UDC 656.7.052(3_Wang_Kharchenko_Chynchenko 045)

Wang Bo[1]
Volodymyr Kharchenko[2]
Yuriy Chynchenko[3]

ESTIMATION OF EFFECT OF UNCERTAINTY FACTORS ON SAFETY OF AIR TRAFFIC FLOWS IN TERMINAL CONTROL AREAS

[1,2]Ningbo University of Technology
201, Fenghua Road, 315211, Ningbo, China
[2,3]National Aviation University
1, Kosmonavta Komarova Avenue, 03680, Kyiv, Ukraine
E-mails: [1]wangbo@nau.edu.ua; [2]kharch@nau.edu.ua; [3]chynchenko@gmail.com

Abstract. *The article deals with the analysis of the researches conducted in the field of influence of complex uncertainty factors on safety of flights and air traffic flows in terminal control areas and adjacent air traffic control zones. Set of models applicable for assessment of uncertainty effect on safety of air traffic flows have been reviewed. Principles of detailed estimation and further analysis of uncertainty effect on air traffic flows in terminal control areas have been proposed.*

Keywords: aeronautical system; air traffic flows; air traffic flow and capacity management; capacity; terminal control area; safety of flights; safety of air traffic flows; uncertainty factors; workload of air traffic controller.

1. Introduction

In the international civil aviation, European countries and Ukraine in recent years there has been a continual increase of flights in controlled airspace. The daily number of aircraft in the European airspace is approximately 25-32 thousands/day (depending on the season), while simultaneously in the air can be up to 10 thousand aircraft. To ensure the management of such large flow of air traffic in the European region has been created the Directorate Network Management (DNM, Directorate Network Management). Similar integrated solutions in air traffic flow management are also being implemented in other regions, such as North America.

In conditions of complex air traffic flow management, but not individual aircraft, is urgent need of increased attention to safety of flights. To take into account all major factors it is necessary to investigate all aspects of the safety of air traffic flows – the totality of aircraft, simultaneously flying in the airspace.

Currently, the management of air traffic flow causes the functioning pan-European air navigation system nearly beyond the limits of its technical and human capabilities. Gradual implementation of the Single European Sky Air Traffic Management Research (SESAR) initiatives in the near future, hopefully, will reduce the load on the national air navigation system, but under current conditions need to maximize (optimise) all the opportunities and internal reserves.

That's why one of very important task is to research the impact of uncertainty on air traffic flows in terminal control areas (TMA) – one of the most significant "bottlenecks" in Air Traffic Management (ATM) system. Associated and important task is detailed analysis of the main threats (hazards) and risks, factors of uncertainty in the air traffic controller work and assessment of their impact on the decision-making process and the final effectiveness of the air traffic controller. Comprehensive study of all aspects of uncertainty will reduce its negative impacts and enhance air traffic flow in TMA and ATM-system as a whole.

A detailed study, classification and synthesis of uncertainties and further efficient management are based on the methodologies of the International Civil Aviation Organisation (ICAO) regarding Safety Management Systems (SMS) [1] and Eurocontrol on problematic aspects in the work of air traffic controllers [2,3]. Their successful implementation will provide an opportunity to increase the overall level of safety of flights in air navigation system of Ukraine [4-10].

2. Description of uncertainty factors effect on safety of air traffic flows in terminal control areas

The definition of "uncertainty" is a general term, which has many descriptions and explanations, applied in different fields, industries and institutions. It is necessary to give adapted definition of uncertainty, which is specific for aeronautical system and relevant for main air traffic flow and capacity management (ATFCM) processes, and, particularly, features of terminal control areas.

While defining (explaining) uncertainty in respect of air traffic flows in terminal control areas, it is very important to classify and assess all its major negative factors and, if possible, propose appropriate practical countermeasures in ATM-system and work of air traffic controllers (ATCOs).

Uncertainty is considered as one of fundamental categories of nature, widely represented in most of processes. Adapted to the ATM-system classification of general types of uncertainty includes 4 elements (with ATM-system examples) (Figure 1):

– ***environment information uncertainty*** (parameters of dynamic air situation, ATFCM measures, adjacent units activities, civil-military coordination, meteorological information, aeronautical information services, airspace structure, short term restrictions and prohibitions of airspace use, aeronautical services provider and airlines internal policies, civil aviation authority regulations, just safety culture implementation, etc.);

– operator decision making uncertainty (qualification level, professional skills and abilities, psychophysiological state, motivation, stress level, and other human-factor related aspects);

– ***uncertainty caused by consequences of decision making*** (unpredictable multiple states (situations) originated in the system after implementation of operator's decisions);

– ***variation uncertainty*** (effects on all three above mentioned, includes multiple and significant changes of fundamental "rules of the game", correction of major constants, namely change of technological procedures of ATCOs and pilots, change of ATFCM regulations, restructuring of aeronautical system on Pan-European and national level, change of airspace structure and its elements, modernisation of workplace equipment and CNS facilities, etc.).

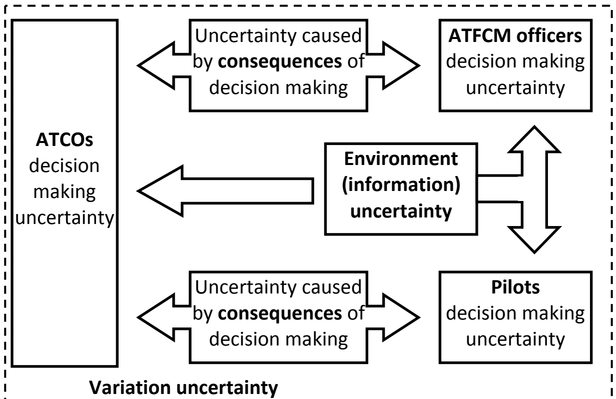

Fig. 1. General classification of uncertainty types

When we consider uncertainty in respect of air traffic flows in terminal control areas, should be taken into account following theses:

– uncertainty is a measure of information (information quality aspects (all available information about the controlled processes, accuracy, completeness, clarity, reliability, relevance, value and volumes of information) and information security aspects (the CIA triad – confidentiality, integrity, availability and additionally the Parkerian Hexad elements – possession, authenticity and utility));

– uncertainty is a difference between prescribed complete information about the processes and actually available information (it's a difference between standard conditions (described in manuals and instructions) and real situations. Such volumes of uncertainty information may be expressed through entropy and express the threshold of controllability of a system);

– uncertainty generated by availability of alternatives at decision making (more options in the disposal of operator, the greater uncertainty in the final. In uncertainty conditions, it's hard to set clear criteria of efficiency and optimality. Also it reflects in uncertainty in ways of decision execution and unexpected final results);

– uncertainty is directly connected with a risks (increase of uncertainty results in growth of risks in controlled processes).

3. Applied models for accounting of the influence of uncertainty factors on air traffic flows and safety of flights in terminal control areas

The uncertainty in ATM-system is defined by means of the absolute error (deviation) Δx from investigated parameter(s). Uncertainty can also be defined as the relative error $\frac{\Delta x}{x}$, which is usually expressed in percentage. The parameter value and its error are represented as $x + \Delta x$. If the statistical probability distribution of the parameter in ATM-system is available to researchers, it is possible to set confidence limits to describe the region of possibly true value of the variable.

Algorithms for accounting the influence of uncertainty factors on air traffic flows and safety of flights in terminal control areas should be performed in following sequence:

The 1st step. Uncertainty definition (a state of having limited knowledge, impossible to exactly describe the actual state) and correlated the 2nd step is uncertainty measurement (a set of possible states or outcomes where probabilities are assigned to each possible state or outcome).

The 3rd step. Risks definition (a state of uncertainty where some possible outcomes have an undesired negative effect) and correlated the 4th step is risk measurement (a set of measured uncertainties where some possible outcomes are losses and the severity of these losses).

The uncertainty measurement (evaluation) includes formulation and calculation, followed by propagation and summarizing tasks.

The formulation task consists of developing a measurement model relating to the input quantities, and on the basis of available knowledge, assigning probability distributions to the input quantities (or a joint probability distribution to those input quantities that are not independent).

The calculation task consists of propagating the probability distributions for the input quantities through the measurement model to obtain the probability distribution for the output quantity, and summarizing by using this distribution.

There are several models in the uncertainty quantification (applicable for TMA):

1. Bias correction model

Bias correction quantifies the model inadequacy, i.e. the discrepancy between the experiment and the mathematical model. The general model updating formula for bias correction is:

$$y^e(x) = y^m(x) + \delta(x) + \varepsilon$$

where $y^e(x)$ denotes the experimental measurements as a function of several input variables x, $y^m(x)$ denotes the computer model (mathematical model) response, $\delta(x)$ denotes the additive discrepancy function, and ε denotes the experimental uncertainty. The objective is to estimate the discrepancy function $\delta(x)$, and as a by-product, the resulting updated model is $y^m(x) + \delta(x)$. A prediction confidence interval is provided with the updated model as the quantification of the uncertainty.

2. Parameter calibration model

Parameter calibration estimates the values of one or more unknown parameters in a mathematical model. The general model updating formulation for calibration is:

$$y^e(x) = y^m(x, \theta^*) + \varepsilon$$

where $y^m(x, \theta^*)$ denotes the computer model response that depends on several unknown model parameters θ, and θ^* denotes the true values of the unknown parameters in the course of experiments. The objective is to either estimate θ^*, or to come up with a probability distribution of θ^* that encompasses the best knowledge of the true parameter values.

3. Bias correction and parameter calibration

It considers an inaccurate model with one or more unknown parameters, and its model updating formulation combines the two together:

$$y^e(x) = y^m(x, \theta^*) + \delta(x) + \varepsilon$$

It is the most comprehensive model updating formulation that includes all possible sources of uncertainty, and it requires the most effort to solve.

The propagation task of uncertainty evaluation is known as the propagation of distributions, various approaches for which are available, including:

- the “Guide to the Expression of Uncertainty in Measurement” uncertainty framework, constituting the application of the law of propagation of uncertainty, and the characterization of the output quantity Y by a Gaussian or a t-distribution;

- analytic methods, in which mathematical analysis is used to derive an algebraic form for the probability distribution for Y;

- a Monte Carlo method, in which an approximation to the distribution function for Y is established numerically by making random draws from the probability distributions for the input quantities, and evaluating the model at the resulting values.

There are several models in uncertainty propagation (applicable for TMA):

1. Linear combinations

Let $\{f_k(x_1, x_2, \dots, x_n)\}$ be a set of m functions which are linear combinations of n variables $x_1, x_2, \dots, x_n$ with combination coefficients $A_{k1}, A_{k2}, \dots, A_{kn}, (k = 1, \dots, m)$. $f_k = \sum_i^n A_{ki} x_i$ or $f = A_x$ and let the variance-covariance matrix on x be denoted by Σ^x:

$$\Sigma^x = \begin{pmatrix} \sigma_1^2 & \sigma_{12} & \sigma_{13} & \cdots \\ \sigma_{12} & \sigma_2^2 & \sigma_{23} & \cdots \\ \sigma_{13} & \sigma_{23} & \sigma_3^2 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} = \begin{pmatrix} \Sigma_1^x & \Sigma_{12}^x & \Sigma_{13}^x & \cdots \\ \Sigma_{12}^x & \Sigma_2^x & \Sigma_{23}^x & \cdots \\ \Sigma_{13}^x & \Sigma_{23}^x & \Sigma_3^x & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

Then, the variance-covariance matrix Σ^f of f is given by

$$\Sigma_{ij}^f = \sum_k^n \sum_l^n A_{ik} \sum\nolimits_{kl}^x A_{jl} : \Sigma^f = A \Sigma^x A^T$$

This is the most general expression for the propagation of error from one set of variables onto another. When the errors on x are uncorrelated the general expression simplifies to

$$\Sigma_{ij}^f = \sum_k^n A_{ik} \sum\nolimits_k^x A_{jk}$$

where $\Sigma_k^x = \sigma_{xk}^2$ is the variance of k-th element of the x vector. Even though the errors on x may be uncorrelated, the errors on f are in general correlated; even if Σ^x is a diagonal matrix, Σ^f is, in general, a full matrix. The general expressions for a scalar-valued function f, are a little simpler:

$$f = \sum_{in}^n a_i x_i : f = ax$$

$$\sigma_f^2 = \sum_i^n \sum_j^n a_i \sum\nolimits_{ij}^x a_j = a \Sigma^x a^{\mathrm{T}}$$

Each covariance term, σ_{ij} can be expressed in terms of the correlation coefficient ρ_{ij} by $\sigma_{ij} = \rho_{ij} \sigma_i \sigma_j$, so that an alternative expression for the variance of f is

$$\sigma_f^2 = \sum_i^n a_i^2 \sigma_i^2 + \sum_i^n \sum_{j (j \neq i)}^n a_i a_j \rho_{ij} \sigma_i \sigma_j$$

In the case that the variables in x are uncorrelated this simplifies further to $\sigma_f^2 = \sum_i^n a_i^2 \sigma_i^2$. In the simplest case of identical coefficients and variances, we find $\sigma_f = \sqrt{n}a\sigma$.

4. Operational activities of Eurocontrol and National Supervisory Authorities in sphere of complex control of uncertainty factors

The main automated systems of Directorate Network Management regulate air traffic flows and reduce the impact of uncertainty at all Air Traffic Flow and Capacity Management (ATFCM) phases in the European region [11,12].

They include the ATS Environment System (CACD or, formerly called ENV), the Repetitive Flight Plan System (RPL), the Integrated Initial Flight Plan Processing System (IFPS), the TACTICAL System (ETFMS), the Data warehouse (DWH or, formerly called ARC) and the Pre-Tactical System (PREDICT) (Figure 2).

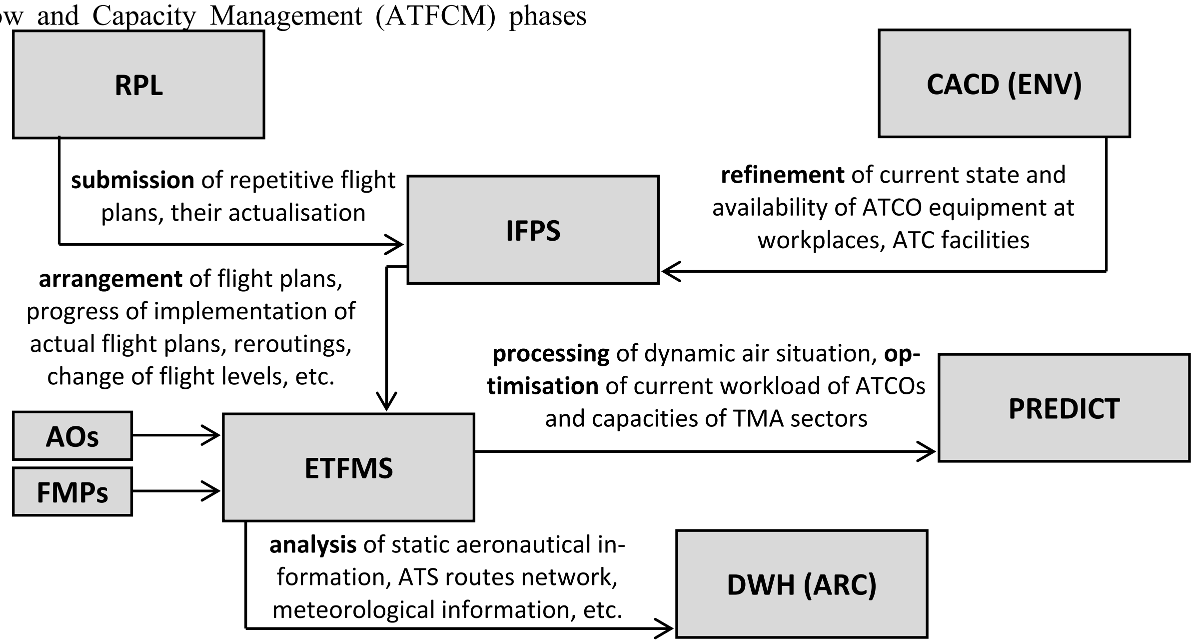

Fig. 2. Interrelated links of major automated systems in structure of the Directorate Network Management and their influence to decrease of uncertainty at all ATFCM phases

The operating unit in the Directorate Network Management, which is responsible for planning, coordination and implementation of strategic, pre-tactical and tactical phases of air traffic flow and capacity management, is the Network Operations Unit. The unit gathers, updates and provides operational information to service users (mainly the ATM) regarding current situation and conditions of flights and the air navigation infrastructure. The effectiveness of the Network Operations Unit fully depends on the actuality, accuracy, reliability and relevance of available operational information (Figure 3).

A recently completed SESAR validation exercise has shown the potential of a new control function and support tool to help clearing air traffic flow and capacity hotspots in Europe's ATM. This new tool can improve air traffic controllers' situational awareness, allowing them to perform early complexity alleviation measures and significantly decrease impact of uncertainty on work of ATCOs. This is part of SESAR drive to refine the role and responsibilities of the controller team organisation in line with the ***Programme's dynamic Demand and Capacity Balancing*** (dDCB) concept. This concept is paving the way to realising SESAR vision of flow-centric operations. In this framework, a number of solutions are being validated, such as the Extended Air Traffic Control Planner (EAP).

The trials validated the introduction of EAP as a new function aimed at bridging the ***gap between Air Traffic Flow and Capacity Management and Air Traffic Control***. When traffic is both high and complex (associated with significant level of uncertainty factors), classic ATFCM/ATC procedures are not responsive enough to alleviate ATFCM hotspots in real-time and to fine-tune mitigation measures. To address this shortcoming, SESAR makes use of the EAP to apply dynamic-ATFCM in its day-to-day operations, within a much shorter time frame than has been possible before. This new function aims at identifying and clearing ATFCM hotspots, and performing early complexity alleviation measures close to Air Traffic Control (ATC) activities.

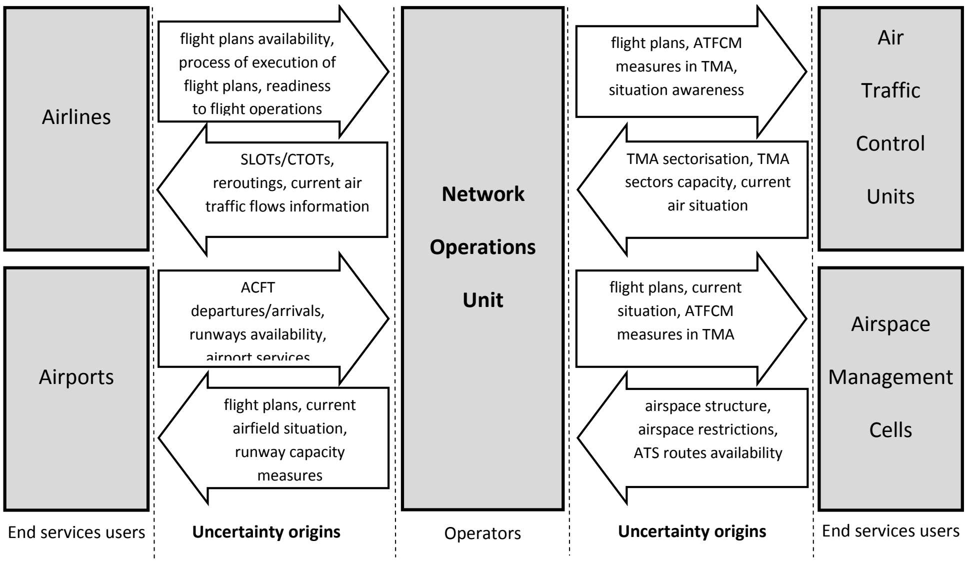

Fig. 3. Operational information flows of the Network Operations Unit and possible areas of uncertainty

To support the EAP function a new tool has been developed that:

– Supports the Local Traffic Manager by identifying ATFCM hotspots and proposes options to clear them;

– Identifies Short Term ATFCM Measures (STAM) candidates; and

– Coordinates and monitors STAM implementation by ATC sectors.

Feedback from industry shows that the supporting tool is ensuring a complete information and coordination process as well as providing ATC sectors with a better situational awareness of the on-going ATFCM situation. As a result, impact of uncertainty factors on work of ATCOs in TMA and adjacent air traffic control zones is decreased to minimum level.

5. Conclusions

Uncertainty is considered as one of the core factor influencing the air traffic flows and safety of flights in terminal control areas. The general sources, which should be taken into consideration are: parameter, structural, algorithmic, experimental and interpolation uncertainty originating areas.

In order to control acceptable uncertainty level in terminal control areas, complex measures and appropriate software tools are developed by Eurocontrol and National Supervisory Authorities.

References

[1] Doc 9859. Montreal, ICAO. 2013. 251 p.

[2] Selected safety issues for staffing ATC operators. Brussels, Eurocontrol. 2007. 32 p.

[3] Study report on selected safety issues for staffing ATC operators. Brussels, Eurocontrol. 2006. 102 p.

[4] *Kharchenko, V.; Chynchenko, Yu.* Integrated risk picture methodology for air traffic management in Europe. Proceedings of the National Aviation University. 2013. N1. P. 15-19.

[5] *Kharchenko, V.; Chynchenko, Yu.* Concept of air traffic flow and capacity management in European region. Proceedings of the National Aviation University. 2013. N3. P. 7-12.

[6] *Kharchenko, V.; Chynchenko, Yu.* Principles of improvement of air traffic flow and capacity management in terminal control areas under uncertainty conditions. Proceedings of the National Aviation University. 2013. N4. P. 12-17.

[7] *Chynchenko, Yu.* Criteria and principles of flight safety assessment at air traffic services in terminal control areas. Bulletin of the Engineering Academy of Ukraine. 2013. N3-4. P. 31-35 (in Ukrainian).

[8] *Kharchenko, V.; Chynchenko, Yu.* Integrated safety management system in air traffic services. Proceedings of the National Aviation University. 2014. N1. P. 6-9.

[9] *Chynchenko, Yu.; Vakhrina, V.; Volianiuk, K.; Kim, I.; Kupaieva, A.; Samartseva, O.* Complex research on improvement of airspace structure and air traffic flows management in terminal control areas. Bulletin of the Engineering Academy of Ukraine. 2014. N2. P. 26-32 (in Ukrainian).

[10] *Kharchenko, V.; Chynchenko, Yu.* Estimation and representation of air traffic flows indices in terminal control areas. Proceedings of the National Aviation University. 2015. N3.

[11] General & CFMU systems. Brussels, Eurocontrol. 2011. 65 p.

[12] Integrated initial flight plan processing system. IFPS user's manual. Brussels, Eurocontrol. 2011. 488 p.

Received 31 August 2015.

Ванг Бо[1],В.П. Харченко[2], Ю.В. Чинченко[3]. Оцінка впливу факторів невизначеності на безпеку потоків повітряного руху в термінальних диспетчерських районах
[1,2]Технологічний університет Нінгбо, дорога Фенхуа, 201, Нінбо, Китай, 315211
[2,3]Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, Україна, 03680
E-mails: [1]wangbo@nau.edu.ua; [2]kharch@nau.edu.ua; [3]chynchenko@gmail.com
У статті проаналізовано дослідження щодо впливу комплексних факторів невизначеності на безпеку польотів та потоки повітряного руху в термінальних диспетчерських районах та суміжних диспетчерських зонах. Розглянуто питання щодо моделей, придатних для оцінки впливу невизначеності на безпеку потоків повітряного руху. Запропоновано принципи детальної оцінки та аналізу впливу невизначеності на потоки повітряного руху в термінальних диспетчерських районах.
Ключові слова: аеронавігаційна система; безпека польотів; безпека потоків повітряного руху; завантаженість авіадиспетчера; організація потоків повітряного руху та пропускної здатності; потоки повітряного руху; пропускна здатність; термінальний диспетчерський район; фактори невизначеності.

Ванг Бо[1] , В.П. Харченко[2], Ю.В. Чинченко[3]. Оценка влияния факторов неопределенности на безопасность потоков воздушного движения в терминальных диспетчерских районах
[1,2]Технологический университет Нингбо, дорога Фенхуа, 201, Нинбо, Китай, 315211
[2,3]Национальный авиационный университет, просп. Космонавта Комарова, 1, Киев, Украина, 03680
E-mails: [1]wangbo@nau.edu.ua; [2]kharch@nau.edu.ua; [3]chynchenko@gmail.com
В статье проанализированы исследования в области влияния комплексных факторов неопределенности на безопасность полетов и потоки воздушного движения в терминальных диспетчерских районах и смежных диспетчерских зонах. Рассмотрены вопросы в отношении моделей, пригодных для оценки влияния неопределенности на безопасность потоков воздушного движения. Предложены принципы детальной оценки и анализа влияния неопределенности на потоки воздушного движения в терминальных диспетчерских районах.
Ключевые слова: аэронавигационная система; безопасность полетов; безопасность потоков воздушного движения; загруженность авиадиспетчера; организация потоков воздушного движения и пропускной способности; потоки воздушного движения; пропускная способность; терминальный диспетчерский район; факторы неопределенности.

Wang Bo (1980). PhD.
Associate Professor, College of Economics and Management, Ningbo University of Technology, China.
Education: National Aviation University, Kyiv, Ukraine.
Research area: presided over a "high-end project" launched by Chinese Bureau of Foreign Experts; presided over and accomplished a longitudinal project launched by the provincial education department; presided over a 800-thousand Yuan horizontal project launched by Ningbo Traffic Detachment; took a major part in a project on international cooperation launched by Ministry of Science and Technology of China (2/6); took part in a municipal project on social sciences and quite a number of horizontal projects in Ningbo.
Publications: 29.
E-mail: wangbo@nau.edu.ua

Kharchenko Volodymyr. Doctor of Engineering. Professor.
Winner of the State Prize of Ukraine in Science and Technology, Honored Worker of Science and Technology of Ukraine.
Acting Rector of the National Aviation University, Kyiv, Ukraine.
Professor of Traffic College of Ningbo University of Technology, Ningbo, China.
Editor-in-Chief of the scientific journal *Proceedings of the National Aviation University.*
Education: Kyiv Institute of Civil Aviation Engineers, Kyiv, Ukraine.
Research area: management of complex socio-technical systems, air navigation systems and automatic decision-making systems aimed at avoidance conflict situations, space information technology design, air navigation services in Ukraine provided by CNS/ATM systems.
Publications: 500.
E-mail: knarch@nau.edu.ua

Chynchenko Yuriy (1976). Candidate of Engineering. Associate Professor.
Department of Air Navigation Systems, National Aviation University, Kyiv, Ukraine.
Education: State Flight Academy of Ukraine, Kirovograd, Ukraine (1998).
Research area: improvement and automation of a professional selection system and development of professional-major skills of civil air traffic controllers.
Publications: 127.
E-mail: chynchenko@gmail.com