AEROSPACE SYSTEMS FOR MONITORING AND CONTROL

UDC 656.7.052(045)
10.18372/2306-1472.68.10904

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

PRINCIPLES OF SAFETY MANAGEMENT OF AIR TRAFFIC FLOWS AND CAPACITY UNDER UNCERTAINTY CONDITIONS

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

Abstract

Purpose: *The aim of this study is to investigate the general principles of safety and capacity management in Aeronautical systems regarding air traffic flows operations under uncertainty conditions. In this work the theoretical framework assessing at the same time both the uncertainty model and flight plans model are proposed.* ***Methods:*** *To study features of safety of air traffic flows and capacity under uncertainty conditions were built the original probabilistic models including Bayesian Network for flight plan and air traffic control sector model based on Poisson Binomial Distribution.* ***Results:*** *We obtained models for safety management of air traffic flows and capacity under uncertainty conditions. We discussed appropriate approach for estimating the parameters of safety of air traffic flows and capacity under uncertainty and Markovian uncertainty model for the flight plan.* ***Discussion:*** *We developed the Bayesian Network for flight plan and air traffic control sector models for safety management of air traffic flows and capacity under uncertainty conditions.*

Keywords: aeronautical system; air traffic flow and capacity management; air traffic services; flight safety assessment; safety of flights; uncertainty factors.

1. Introduction

Nowadays, delays and flight cancellations in air traffic management are the significant problems, which are mainly connected with capacity limits, particularly in Europe and Northern America where the flight volumes are high.

The air traffic flow and capacity management (ATFCM) is a service with the objective of managing the balance of demand and capacity by optimising the use of available resources and coordinating adequate responses, in order to enhance the quality of service and the performance of the Air Traffic Management (ATM) system.

In situations, when uncertainty about the future is high, ineffective regulations might be issued. This is the main reason for the introducing of the Short-term ATFCM measures in the process. These are intended to solve small disruptions locally in time and space, and encompass minor ground delays, flight level capping and minor rerouting.

The ATFCM is carried out by Network Manager (NM) in four phases (irrespective influence of uncertainty factors) (Fig. 1).

1. ***Strategic Flow Management*** takes place seven days or more prior to the day of operations and includes research, planning and coordination activities through a Collaborative Decision Making (CDM) process. This phase comprises a continuous data collection with a review of procedures and measures directed towards an early identification of major demand / capacity imbalances. When imbalances are identified, the NM is responsible for the overall coordination and execution of strategic ATFCM planning to optimise all available capacity and achieve performance targets.

2. ***Pre-Tactical Flow Management*** is applied during the six days prior to the day of operations and consists of planning and coordination activities. This phase studies the demand for the day of the operation, compares it with the predicted available capacity on that day, and makes any necessary adjustments to the plan that was developed during the Strategic phase. The main objective of the pre-tactical phase is to optimise efficiency and balance demand and capacity through an effective organisation of resources and the implementation of a wide range of appropriate ATFCM measures.

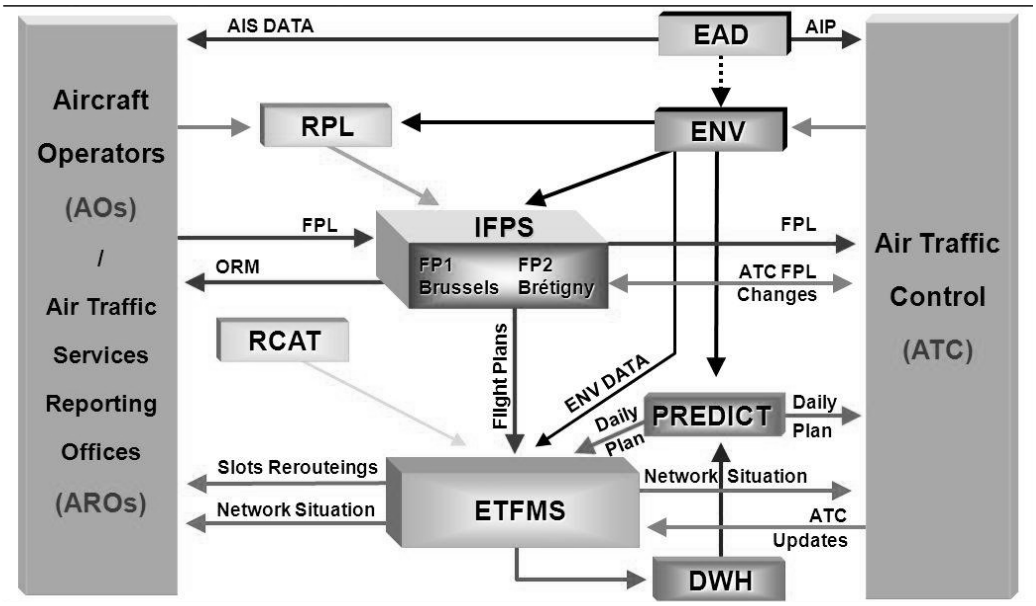

Fig. 1. Network Manager Operations Centre Structure

3. ***Tactical Flow Management*** takes place on the day of operations and involves considering, in real time, those events that affect the ATFCM Daily Plan (ADP) and making the necessary modifications to it. This phase is aimed at ensuring that the measures taken during the strategic and pre-tactical phases are the minimum required to solve the demand / capacity imbalances. The need to adjust the original plan may result from disturbances such as staffing problems, significant meteorological phenomena, crises and special events, unexpected limitations related to ground or air infrastructure, etc. and taking advantage of any opportunities that may arise. The provision of accurate information is of vital importance in this phase, since it permits short-term forecasts, including the impact of any event and maximises the existing capacity without jeopardising safety.

4. ***Post Operational Analysis*** is the final step in the ATFCM planning and management process and takes place following the tactical phase of operations. During the post operations analysis phase, an analytical process is carried out that measures, investigates and reports on operational processes and activities throughout all domains and external units relevant to an ATFCM service. This phase compares the anticipated outcome (where assessed) with the actual measured outcome, generally in terms of delay and route extension, while taking into account performance targets.

The recent technologies and navigation tools open the way to new opportunities for planning during the pre-tactical and tactical phases of ATFCM. Because the ATFCM tactical temporal horizon can go beyond 2 hours, it must deal with the different uncertainties relative to the dynamic air situation and environment. The may be connected with late departure, wind variations, conflict situations between aircraft in the air and on the ground, safety and security issues, avoidance of hazardous meteorological phenomena.

2. Analysis of the latest research and publications

Activities and operations connected with air traffic flow and capacity management described in appropriate Eurocontrol documentation [1-2]. The area of applicability, ATFCM phases, CDM principles and ATFCM solutions for capacity shortfalls are described fully in ATFCM Operations Manual [1]. The applied techniques of ATFCM, processes connected with ATFCM, slot allocation process and are written in the ATFCM Users Manual [2].

Principles of multiobjective tactical planning under uncertainty for air traffic flow and capacity management and original methodology to tackle uncertainty regarding aircraft trajectories and airspace sector crossings are discussed in [3].

The principles of static approach in air traffic flow management rerouting problem, including all phases of flight, ground and air delays, rerouting and flight cancellations are proposed in [4]. Another theses [5] include a stochastic formulation with discrete probabilities associated to scenarios for sectors. In [6] optimisation task to minimize directly the probability of congestion in the sectors is described (used concept of chance constraints).

Principles of multiobjective optimisation applicable to air traffic control were considered in [7] in order to minimize an aggregated complexity metric, designed and validated by Eurocontrol for different sectors. Also, in [8] studied the multiobjective approach to model processes and interactions of sector congestion and air delays (the decision space includes departure time and chosen routes). Multiobjective algorithm generates set of solutions with a diversity measurement in order to distribute them on the Pareto front.

The safety management of air traffic flows and capacity requires solution of set of problems, one of which is taking into consideration the influence of uncertainty factors on Air Traffic Services. Some aspects connected with uncertainty factors analysed in [7-9]. Besides, a research of the uncertainty was conducted by [12] with an analysis of the prediction error of the time of arrival of the aircraft (main hypotheses – a Gaussian distribution of the random variable of the prediction error).

3. Mathematical formulation of models of safety management of air traffic flows and capacity under uncertainty conditions

Let us propose the ***probabilistic model of flight plan*** under uncertainty conditions, where flight plan $f \in F$ with n waypoints denoted by $X_1^f,\dots,X_n^f$ and associated to n random variables $T_1^f,\dots,T_n^f$, where T_i^f represents the time of overfly of flight f over waypoint X_i^f, and let us call p_i^f the probability density of T_i^f, dropping the superscript f when there is no ambiguity. According to standard definition, the marginal probability is [3]:

$$P[T_j \in \Delta t | T_i = t_i] = \int_{\Delta t} p_{i|j}(\tau | t_i) d\tau \qquad (1)$$

where $p_{i|j}(\tau|t_i)$ is the conditional probability that the flight is over X_j during the time interval Δt given that the flight is over the point X_i at time t_i.

Let's define an uncertainty model for any trajectory. To expose easily the concepts presented here, we rely on the graphical model on Fig. 2, namely a Bayesian Network, to represent the interactions between our random variables, illustrated with green circles. An arrow between T_i and T_{i+1} shows that the former influences the latter, or more precisely, that the two random variables are not independent. The joint density function of T_i and T_{i+1} is [3]:

$$p_{i,i+1}(t_i,t_{i+1}) = p_{i+1|i}(t_i,t_{i+1}) \cdot p_i(t_i) \qquad (2)$$

This equality represents the propagation of the information in the same direction than the sequence of waypoints. As a first physical constraint, in order to respect the arrow of time along the sequence, we impose:

$$p_{i,j}(t_i,t_j) = 0, \textit{if } t_i \ge t_j, \forall j > i$$

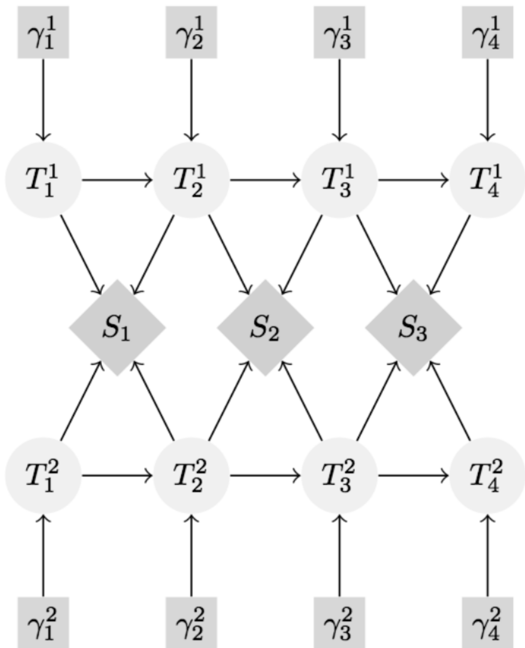

Fig. 2. Model of the Bayesian network for a flight plan

Now, let's generalize the joint distribution for an arbitrary number of waypoints [3]:

$$\begin{aligned} p_{i:N}(t_{i:N}) &= p_{N|1:N-1}(t_N | t_{1:N-1}) \cdot p_{1:N-1}(t_{1:N-1}) \\ &= p_{N|N-1}(t_N | t_{N-1}) \cdot p_{1:N-1}(t_{1:N-1}) \\ &= \prod_{i=2}^{N} p_{i|i-1}(t_i | t_{i-1}) \cdot p_1(t_1) \end{aligned} \qquad (3)$$

The first equality is obtained with the definition of the joint probability; the second equality requires the assumption of conditional independence also known as the Markov assumption. Then, the process is iterated for each T_i from $N-1$ to 1 in order to obtain the last equality. Equation 3 is the markovian uncertainty model for the flight plan.

Here is the ***air traffic control sector model*** under uncertainty conditions based on Poisson Binomial Distribution, where we give the closed-form equation for computing the exact probability that a sector is congested, which requires $S_{s,f}^{t}$, the Bernoulli random variable that the flight f is in the sector s at time t, and $\overline{S_{s,f}^{t}}$ its complementary. Notice that $(S_{s,f}^{t} : t \in \Omega)$ is a stochastic process where Ω is the time horizon.

Then, the probability to not be in the sector during the time interval $\Delta t = (t_{\min}, t_{\max})$ is the probability to enter after $t_{\max}$ or the probability to exit before $t_{\min}$. Because of the arrow of time constraint, these two events are mutually exclusive and one obtain [3]:

$$\begin{aligned} P(\overline{S_{s,f}^{\Delta t}}) &= P(T_i^f > t_{\max}) + P(T_i^f \le t_{\min}) \\ &= [1 - P(T_i^f \le t_{\max})] + P(T_i^f \le t_{\min}) \\ &= 1 - F_i^f(t_{\max}) - F_j^f(t_{\min}) \\ &\Rightarrow P(S_{s,f}^{\Delta t}) = F_i^f(t_{\max}) - F_j^f(t_{\min}) \end{aligned} \quad (4)$$

When $(t_{\max} - t_{\min}) \to 0$, we obtain the values for $S_{s,f}^{t}$. Now, inference on the presence of many flights in a given sector during an interval can be undertaken. To do so, let K_S^t be the random variable of the number of flights in the sector s at time t. Then, by using a multi-index notation, we have [3]:

$$P(K_s^t = n) = \sum_{|a|=n} \prod_{f \in F} P(S_{s,f}^t)^{a_f} \cdot P(\overline{S_{s,f}^t})^{1-a_f} \quad (5)$$

where $a = (a_1, \ldots, a_{N_S^t}) \in \{0,1\}^{N_S^t}$, $|a| = a_1 + \cdots + a_{N_S^t}$ and $N_S^t = \left|\{i \middle| P(S_{s,f}^t) \ne 0\}\right|$.

Again, $\{K_S^t : t \in \Omega\}$ corresponds to a stochastic process and these are depicted with diamonds on the graphical model.

4. Conclusions

In this work we proposed the theoretical framework assessing at the same time both uncertainty factors model and flight plans/ air traffic control sector parameters. The factors of uncertainty should be considered as one of the most important contributors influencing safety management of air traffic flows and capacity. The uncertainty origins, which should be taken into consideration are: staffing problems, significant meteorological phenomena, crises and special events, unexpected limitations related to ground or air infrastructure, etc. The solution of uncertainty triggered problems will result in increasing safety level by application of practical models and algorithms of safety management of air traffic flows and capacity.

References

[1] ATFCM Operations Manual. Network manager. Brussels, Eurocontrol. 2015. 196 p.

[2] ATFCM Users Manual. Network operations. Brussels, Eurocontrol. 2015. 122 p.

[3] *Caron G.M., Savéant P., Schoenauer M.* Multiobjective tactical planning under uncertainty for air traffic flow and capacity management. IEEE Congress on Evolutionary Computation. 2013. P. 1548-1555.

[4] *Bertsimas D., Lulli G., Odoni A.R.* An Integer Optimization Approach to Large-Scale Air Traffic Flow Management. Operations Research. 2011. Vol. 59, N1. P. 211-227.

[5] *Clare G., Richards A.* Air Traffic Flow Management Under Uncertainty: Application of Chance Constraints. 2nd International Conference on Application and Theory of Automation in Command and Control Systems (ATACCS'2012). 2012. P. 20–26,

[6] *Oussedik S., Delahaye D., Schoenauer M.,* Air Traffic Management by Stochastic Optimization. 2nd USA/Europe Air Traffic Management Research and Development Seminar. 1998. P. 1–10.

[7] *Flener P., Pearson J., Ågren M., Garcia Avello C., Celiktin M., Dissing S.*, Air-Traffic Complexity Resolution in Multi-Sector Planning using Constraint Programming. 7th USA/Europe Air Traffic Management Research and Development Seminar, 2007.

[8] *Delahaye D., Oussedik S., and Puechmorel S.* Airspace Congestion Smoothing by Multi-Objective Genetic Algorithm. 20th Annual ACM Symposium on Applied Computing (SAC 2005). 2005. P. 907–912.

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

[10] *Kharchenko, V.; Chynchenko, Yu.* Estimation of effect of uncertainty factors on safety of air traffic flows in terminal control areas. Proceedings of the National Aviation University. 2015. N4.

[11] *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.

[12] *Gilbo E.P., Smith S.B.* New Method for Probabilistic Traffic Demand Predictions for En Route Sectors Based on Uncertain Predictions of Individual Flight Events. 9th USA/Europe Air Traffic Management Research and Development Seminar, 2011.

Received 27 September 2016.

Ванг Бо[1], В.П. Харченко[2], Ю.В. Чинченко[3]

Принципи управління безпекою потоків повітряного руху та пропускною здатністю в умовах невизначеності

[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]vanbo@ nau.edu.ua; [2]kharch@nau.edu.ua; [3]chynchenko@gmail.com

Мета: Метою цього дослідження є вивчення загальних принципів управління безпекою та пропускною здатністю в аеронавігаційних системах щодо потоків повітряного руху в умовах невизначеності. У цій роботі запропоновано теоретичні основи спільної оцінки моделі невизначеності і моделі планів польоту. **Методи дослідження:** Для вивчення особливостей забезпечення безпеки потоків повітряного руху та пропускної здатності в умовах невизначеності було побудовано оригінальні імовірнісні моделі, включаючи Байєсову мережу для планів польотів і модель сектора повітряного руху на основі біноміального розподілу Пуассона. **Результати:** Було отримано моделі для управління безпекою потоків повітряного руху та пропускної здатності в умовах невизначеності. Розглянуто відповідний підхід для оцінки параметрів безпеки потоків повітряного руху та пропускної здатності в умовах невизначеності і Марковську модель невизначеності для плану польоту. **Обговорення:** Розроблено Баєсову мережу для плану польотів і модель сектора повітряного руху для управління безпекою потоків повітряного руху та пропускною здатністю в умовах невизначеності.

Ключові слова: аеронавігаційна система; безпека польотів; обслуговування повітряного руху; оцінка безпеки польотів; управління потоками повітряного руху та пропускною здатністю; фактори невизначеності.

Ванг Бо[1], В.П. Харченко[2], Ю.В. Чинченко[3]

Принципы управления безопасностью потоков воздушного движения и пропускной способностью в условиях неопределенности

[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]vanbo@ nau.edu.ua; [2]kharch@nau.edu.ua; [3]chynchenko@gmail.com

Цель: Целью данного исследования является изучение общих принципов управления безопасностью и пропускной способностью в аэронавигационных системах в отношении потоков воздушного движения в условиях неопределенности. В данной работе предложены теоретические основы совместной оценки модели неопределенности и модели планов полета. **Методы исследования**: Для изучения особенностей обеспечения безопасности потоков воздушного движения и пропускной способности в условиях неопределенности, были построены оригинальные вероятностные модели, включая байесовскую сеть для планов полетов и модель сектора воздушного движения на основе биномиального распределения Пуассона. **Результаты**: Были получены модели для управления безопасностью потоков воздушного движения и пропускной способности в условиях неопределенности. Рассмотрены соответствующий подход для оценки параметров безопасности потоков воздушного движения и пропускной способности в условиях неопределенности и Марковская модель неопределенности для плана полета. **Обсуждение**: Разработаны байесовская сеть для плана полета и модель сектора воздушного движения для управления безопасностью потоков воздушного движения и пропускной способности в условиях неопределенности.

Ключевые слова: аэронавигационная система; безопасность полетов; обслуживание воздушного движения; оценка безопасности полетов; управление потоками воздушного движения и пропускной способностью; факторы неопределенности.

Wang Bo (1980). PhD. Professor.
College of Economics and Management of Ningbo University of Technology, China.
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: 38.
E-mail: vanbo@ nau.edu.ua

Kharchenko Volodymyr. Doctor of Engineering. Professor.
Vice-Rector on Scientific and Research Work, 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.
Winner of the State Prize of Ukraine in Science and Technology, Honored Worker of Science and Technolgy of Ukraine.
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: 510.
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: Faculty of Air Traffic Services, 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: 140.
E-mail: chynchenko@gmail.com