ASSESSMENT OF ACCIDENT AND COLLISION RISKS IN PRESENCE OF FUZZY THREATS TO FLIGHT SAFETY

E.A. Kuklev
Saint-Petersburg State University of Civil Aviation, 38 Street Pilots,
St. Petersburg, 196210, Russia

V.S. Shapkin, S.V. Daletsky, S.S. Demin, A.I. Pleshakov
The State Scientific Research Institute of Civil Aviation,
22-2 Street Planernaja, Moscow, 125481, Russia

ABSTRACT

The article substantiates the principles of developing a single approach to solving the problem of evaluating the risks of accidents and collisions not only in the field of aircraft safety, but also in areas of military operations, ecology, finance, industrial projects, in air traffic control systems and in counter-terrorism activities. The interpretation of the notion of “risk” as formulated by NASA as “a measure of the forecasted amount of danger” (similar to the Russian Academy of Sciences) is adopted on the basis of the provisions of the risk-oriented approach in the development of the ICAO-recommended safety management systems for aviation safety such as the Safety Management System (SMS). Adjustments have been made to the probabilistic interpretation of rare events. Classical probabilistic indicators may be unreliable in case of insufficient amounts of statistical data on events; therefore a scheme for the analysis of rare events from the Berkeley School (USA) – the Fuzzy Sets approach – has been adopted. The concept of “indicator” provides some tools for “weighing risks and chances”. It is shown that promising developments are based on the Boolean logic of constructing event chains in systems when creating a “collision equation” for a system with a given structure and a predictable risk event, for creating an SMS without the Monte Carlo method and using a new NASA interpretation of the risk of negative consequences. The tool for solving these problems is the method of fuzzy sets for assessing the aviation safety levels without probabilistic indicators. This enables development of procedures and mathematical models for determining integrated levels of safety based on the concept of the functional failure risk. The paper provides examples of constructing the collision equation and defining the risk area and vulnerability points.

Key words: accidents, collisions, threats, flight safety, aircraft, integrated risk, fuzzy measure.
1. INTRODUCTION

Classical probabilistic safety indicators of technical systems may be unreliable in case of insufficient amounts of statistical data as in rare events with regard to accidents and collisions with aircraft or, for example, in a situation with terrorist threats [1]. Therefore, it is necessary to correct the probabilistic interpretation of the features of rare events. The Civil Aviation Center (the Netherlands) stated that the probabilistic concept of safety and risk in rare events is erroneous and should be reviewed [2]. A scheme is given in [3] for analyzing the features of rare events based on the results of the Berkeley School (Zadeh L., USA) using the Fuzzy Sets approach.

The new concept of “risk” (following the NASA wording) as a “measure of predicted danger” or harm with a certain threat to the safety of aviation and technical systems makes it possible to assess the criticality of the detected paths leading to a collision, with off-nominal aircraft operating conditions [3]. At the same time, it seems promising to apply uniform indicator assessments of the state of complex aviation and technical systems including technical and economic, financial, environmental, natural complexes, military operations, air traffic control (ATC) and air traffic management (ATM) systems.

Some safety experts assess safety through “safety indicators”, and only “hazard indicators” (without reservations) are studied [4]. This position is quite understandable and traditional for Russian civil aviation, because the state of the aviation safety is verified through the name of opposite events/failures, but this is incorrect from the standpoint of formal logic, as was noted in [5]. The application of the risk-oriented approach [6] for the formation of proactive (preventive) control actions on the technical system provides a reduction in the risks of negative consequences and makes it possible to increase the chances of success in aviation activities with the uncertainty of information on dangerous situations.

In this paper, the theoretical and methodological aspects of the ICAO concept are studied announced in Annex 19 [1, 7] regarding the need to recognize the “risk” formula as a mathematical category; and the proposed methodological approach correctly eliminates the contradictions in the definitions of “safety” and “risks” in SMS audits in the investigation of collisions and is more consistent with established traditions in various fields of activity associated with manifestations of dangerous or risk factors [7, 8, 9]. Therefore, the subject of the article is topical.

The background and key issues of the risk-based approach are as follows. It is necessary to eliminate a number of contradictions arising from the use of certain definitions in solving the problems of “rare events” in the tasks of evaluating “risks” as a measure of the predicted “danger” in solving the corresponding tasks [10].

It is known that “risk” is “the probability of ... a negative event with some damage” [8]. But in this definition there some points of ill-posedness as follows:
a) inapplicability for “rare events” [1, 2];
b) infeasibility of applying the concepts of “risk probability” [11].
According to the NASA wording [7, 12], “risk” is a “measure of the amount of danger” taking into account the “probability of occurrence for a predicted event with damage”. Such an interpretation requires clarification, especially in connection with the existence of the well-known ICAO formula from Annex 19 [1, 7], which has been proposed to be (and is) used in this paper from the standpoint of fuzzy logic. But one must accept the “risk matrix and indicators” [3, 12]. In this regard, it is necessary to establish a hierarchy of a number of definitions from the theory of system security (TSB) and “risk” [3, 5, 11] of:
- threats, hazards, risk factors, threat factors [13-15];
- the identification of vulnerability points of the systems, risk points, risk events, bifurcation points of processes [16], the possibility of occurrence of dangerous events such as “risk events” [13, 14].

2. OBJECTIVE AND TASKS

The objective is to develop a methodical and mathematical apparatus that allows a priori to find chains of events [3, 7] sought in the technical systems in the form of paths leading to negative events and collisions. The chain is searched taking into account the criticality of the consequences in the form of a risk measure resulting from the features of a special event in the form of “destruction of the system functionality” [1, 10, 13].

The following problems formulated in [3] are considered in the paper:
- mathematical correction of the risk assessment for rare events according to NASA;
- prevention of threats taking into account fuzzy hazards [11, 14];
- deciphering the ICAO term: “System Security Management” (through the “risk”), management of processes and activities using the “safety” criterion [5, 14, 15];
- development of tools for “weighing risks and chances”.

For the mathematical formulation of the problem, a generalized indicator of the system quality $K_\Sigma$ is introduced on the basis of identifying the “vulnerability window” determined by the method of multicriteria estimates of “weak points” in the features of complex technical systems. Significant indicators are: efficiency, reliability, security, vulnerability, acceptability, effectiveness, ergonomics, competitiveness [3, 8]. These parameters should be considered together in order to be integrally reduced to simple (in physical meaning) indicators of the type “dangerous” – “not dangerous”, “acceptable” as recommended by the FAA (USA) [3, 7].

With this approach, the generalized indicator $K_\Sigma$ will have the form of a tuple (not a function):

$$K_\Sigma = \langle K_1, K_2 | \Sigma_0 \rangle,$$

(1)

where $K_1$ are indicators characterizing the reliability of aircraft structures [3, 5];

$K_2$ are indicators that determine the operation safety of the aviation technical system [3, 7, 8];

$\Sigma_0$ are specified operating conditions of the aviation technical system.

The main problem of solving the formulated problem (1) is that the traditional method of searching for weighted $K_\Sigma$ averages is not applicable. This is because of the fact that even on the set of additive indicators $K_1, K_2$ affecting the integral assessment of system features, the
quality indicators and type factors $K_1$, as well as indicators $K_2$ do not form a topological space. Here (1) is a tuple, but not a vector of interdependence for heterogeneous indicators.

These indicators are defined in heterogeneous inconsistent functional spaces. However, the assessment of the choice of the best integral indicator $K_2$ must be solved. In particular, it is necessary to establish what is the “risk” in (1), since $K_1$ reflects the average “trouble-free” time – “almost infinity”, and $K_2$ for rare events in “probability” is “almost zero” [3]. These indicators may contain fuzzy parameters like “preferably”, “unacceptable”, etc. Moreover, the integral indicator $K_2$ in (1) is most often specified as fuzzy (“effective-ineffective-dangerous ...”, which can be investigated most simply by using special computational methods based on Fuzzy Sets [3].

Formulations of the problem as in the form (1) always arise in projects for determining the appearance of aviation systems, for example, in the design of prospective aircraft, taking into account the multitude of contradictory (and even conflicting) multiparameter requirements in the form of ensuring high reliability and flight safety. Similar tasks are typical for the activities of such organizations as the State Scientific Research Institute of Civil Aviation [17-21].

For example, in modern projects it is sometimes necessary to solve complex issues of quality and efficiency in conditions depending on human factors both onboard the aircraft, and in the ATM system, at the airport, and during the organization of maintenance and repair works while saving financial resources. Previously, the most constructive method was linear programming in a classical, rather complex and multidimensional but correctly formulated problem with clear numerical criteria for evaluating the optimality in a closed topological space of arguments.

In (1), indicators $K_1$, $K_2$ are functionally heterogeneous. It is quite difficult to apply numerical estimates for (1) on the basis of the probability theory, especially for large dimensions of the problem. However, these problems are solved on the basis of the Berkeley school methods. Obviously, it is advisable for Russia’s civil aviation to develop similar approaches discussed in this paper. Therefore, it is proposed to seek a solution for (1) within the framework of the Fuzzy Sets approach [3]. To do this, the mathematical and physical concepts of a dangerous or otherwise risk event are introduced in the current situations of complex systems operation [1, 3, 5, 12] and the existence of fuzzy subsets of various parameters is assumed.

The formulated provisions make it possible to find ways to manage the safety of aircraft operations including those on the ATC routes [22, 23], and to establish the unity of the provisions of risk-oriented approaches to evaluating the safety of technical systems in various fields of activities.

3. METHODS AND MATERIALS
Identification of hazards in aviation activities is proposed with the help of the Safety Management System (SMS) using the technology of a proactive risk mitigation process technology. The scheme for solving the problem considered in this paper is implemented in accordance with the ICAO recommendations [9, 12] by creating a new generation of safety management systems (SMSs) in civil aviation enterprises and organizations.
When solving the task of evaluating the flight safety using an SMS, the main problem of the system safety theory (SST) formulated in [1, 3] was successfully solved under the following conditions:

- no mathematical expectations and variances of quantities regarding the bifurcation of processes required;
- no need to use probability distribution density functions, since in problems with rare events there are no analytical forms or histograms for these functions;
- the general classifier of uncertainty types for features of events [16] is used, a scenario analysis [5, 16] is applied and “vulnerability points” and “vulnerability windows” [1, 4] are searched for according to the new “risk formula” [3, 5].

The basic procedures in SMS when modeling functional failures on Boolean lattices are as follows. When evaluating the safety level, the SST tools are used to assess the risks and chances with a measure of hazard in the presence of threats according to the following scheme:

- Simulation of scenarios of events [1] based on the “collision equation” [3], FMEA and ECAST [13];
- Use of a risk analysis matrix in the form of $\hat{R}$ to assess the criticality of the chain of events leading to a collision (ICAO scheme in civil aviation), that is, without “probabilities”;
- Application of the NASA algorithm for flight safety management [7, 12];
- Weighing the “risks and chances” at the vulnerability point in pure safety management strategies based on the new SMS structure, in which there are corresponding databases required for applying the above assessment matrices.

The relationship between the “risks and chances” indicators for the Fuzzy Sets in the binary outcome space on the event tree is characterized by symbols reflecting the technology of proactive management of the system state using the NASA algorithm with databases for the risk matrix. Indicator estimates of the safety level (or protection level), as recommended in ICAO Annex 19 can be introduced in the form: safe system - with indicator “1”, dangerous system – with indicator “0”.

The main method is to identify and search only such discrete states of the technical system, which denote the loss of features of the system functionality. The hazard model is developed in the form of a logical chain of events in the system, where the processes leading to people’s death can be weighed as risks and chances of occurrence for consequences in dangerous situations in the form of chains of events leading to a collision. Criticality of the results is estimated on the basis of the Fuzzy Sets (“fuzzy sets” according to L. Zadeh [7]) with the help of logical “collision equations” [3].

These equations are constructed in accordance with the FMEA event tree structure [3] according to the logical algebra rules (I.A. Ryabinin’s method described in [3]). The search for the shortest paths to a possible collision is made without probability indicators of the significance of the detected paths, without mathematical expectations and variances, without probability distribution density functions and other parameters of Gaussian models due to information uncertainty and unreliable statistics on rare events.

The main SST tools are as follows:

- a new universal definition of the concept of risk (based on game theory in countable sets of elements) – without probability indicators for rare events with probabilities of “almost-zero”;
Assessment of Accident and Collision Risks in Presence of Fuzzy Threats to Flight Safety

- clear and fuzzy functions of the logical algebra;
- “collision equation” by the minimum section method;
- matrix of risk significance analysis by ICAO, NASA.
- The SMS structure in the SST is determined by the standard ICAO and NASA modules:
- assessment of integral levels of risks and chances;
- SMS definitions and functional scheme including (SMS-B structure – the SMS core for the safety of any ICAO subsystems).

The list of main SMS modules per Annex 19 includes also the uncertainty classifier, risk assessment matrix, procedures for weighing (evaluating) risks and chances. The risks and chances in SMS-B when searching for optimal solutions to mitigate the consequences of risk factors are weighed according to the NASA approach following the procedure:

- the “risk-probability” concept is completely rejected with the “almost-zero” probability of rare events, since it is almost impossible to calculate (and guess) it;
- Fuzzy Sets determine fuzzy measures for the occurrence of unpredictable dangerous events and a scale for measuring integrated risks $\hat{R}$ and chances $\hat{B}$, for example, using known risk analysis matrices. Fuzzy levels of risk are determined on the basis of the traditional NASA and ICAO matrix, which was originally published in the works of the “Boeing” company [3, 14, 15];
- “acceptable solutions” are taken by “weighing the risks and chances” for the forecasted events in binary outcome spaces in fuzzy subsets $E(\Omega)$ in evaluating the significance of integrated risks – according to the NASA and ICAO matrices [7, 12].

An important detail must be noted. Especially it concerns users working with ICAO Annex 19 and those who design SMSs for their aviation enterprises.

4. RESULTS AND DISCUSSIONS
The main result of these studies can be considered the creation of the SST baseline on the basis of NASA recommendations and the ICAO risk concept.

Risk is understood (as a definition) in the following interpretations:
a) risk is the predicted “amount of danger” corresponding to the identified detected threat. This amount should be (in our method) found in advance before the time of the bifurcation onset, that is, the event $R$;
(b) risk is not an event, but an extent and measure of the perceived danger and projected harm with a well-defined (specified) threat with a set of hazards.

The degree of the predicted level of danger in the form of a measure of danger or harm that may arise in the system is assessed by an integral level of risk of the consequences that may present a certain risk event occurring in the presence of the indicated threat.

The basis of the SMS structure is the NASA algorithm [3, 7, 13, 24, 25] for identifying risks and hazards and forming management principles for changing the current state of technical systems controlled by the safety factor.

The NASA algorithm is unified for all SMS types described in the ICAO references – Annex 19 [7, 9, 12] and has the following form:

Sources of danger – threat – risk event –
dangerous state – risk assessment – control action.

In the above algorithm, of the primary significance is the detection or existence of a source of danger that determines threats in the form of certain physical objects and conditions in the presence of which a negative unpredictable (in time) occurrence of the risk event $R$ is possible.

Event $R$ has not yet occurred, but if it does, there will be damage with serious consequences in this “vulnerability window”. The degree of danger is assessed on the basis of the methodology for calculating risk for fuzzy boundaries of areas or similar vulnerability windows (according to Kulba V.V. and Malinetsky G.G. [16]). But only the Fuzzy Sets approach is successfully applied [3, 7] with rare events $R$ of the specified type [1, 3] with “almost-zero” probability.

This approach can be applied in the air traffic control (ATC) theory in assessing the flight safety of aircraft. For ATC systems, it is suggested to treat the concept (definition) of “risk” also in a new way – as a measure of danger with a fuzzy measure [1]. So, in the publication of M. Fujito (Japan) [22] performed under the ICAO grant project, it was shown that conflicts (collisions, collisions...) in the ATC system are rare. The probabilities of these events lie in the area of the “tails” of the probability distribution density functions (pddf), the laws of which are not known and cannot be described analytically; and the calculated probabilities of rare events cannot be reliably found.

It was a success to find and prove that it is impossible to determine and calculate reliably the probabilities of events in the indicated area by means of Reich’s models [22], if there is no exact corresponding analytic formula. Moreover, in NASA works it was proved [7] that the “behavior of the pddf tail” is unpredictable even after a vast nimbr of statistical tests of a very large volume. Moreover, it was proved in [26] that events of the “AT collision” type lie precisely in the “tails” of the pddf distributions, but there are no formulas for the pddf “tail” and they cannot be found. Practically the above probabilities in ATC are negligibly small and are of the order of $10^{-17}$. One can point to the TLS parameter by ICAO given in [2, 3]. These probability levels reflect only the requirements for the size of the runway or the flight level at which a certain level of flight safety is guaranteed taking into account the errors in the measurement of the aircraft coordinates by the radar and the uncertainty of errors in determining the values of the parameters for the operating systems in flight situations.

It is proposed to adopt the following new adjusted axiomatics of NASA risk models on the basis of a mathematical description of the general risk concept in ICAO works [1, 7, 24]:

Risk Concept: Likelihood & Severity of Harm.  

On the basis of (3) the predicted risk event $R$ with negative fuzzy consequences in the form $\mu$, $\mu$ should be defined as [3]:

$$R = R(\zeta | \mu, H_R, L_R, \Sigma_0),$$

where $\zeta$ is the uncertainty of the given type $\gamma_j$ from the classifier [3, 16]; $\mu$ is a fuzzy measure of the possibility of occurrence for a risk event, for example, in the form of system function loss by [3, 4]; $H_R$ is damage; $\Sigma_0$ are the conditions for the occurrence of the situation (scenario); line ( | ) is the feature of the events in the form of conditions.
characterizing these events, $L_R$ is the chain of events from the $\sigma$-sigma of the algebra $E(\Omega)$ of some function space of outcomes $\Omega$ [3] given in $\Sigma_0$.

An event (4), as was shown above, is predictable at the time of the threat. Its physical features are described in (4), but the measure $\mu$ of the possibility of occurrence for this event is fuzzy (untrue and indefinite). Therefore, the significance of the predicted consequences can also be estimated only with the aid of a fuzzy measure of the magnitude of the integral risk $\hat{R}_0$ [3] according to the following scheme:

- a set $\tilde{R}$ of fuzzy elements in the form of a tuple $\tilde{R}$ is introduced to assess the risk of a dangerous situation for the predicted risk event $R$:

$$\tilde{R} = (\mu, H_L, L_R, \Sigma_0).$$

(5)

where $\mu$ measure from (4), the $L_R$ chain as an event and even damage $H_L$ are fuzzy in the sense of Fuzzy Sets [3];

- the value of the assessment $\hat{R}$ is introduced – the integratd risk, the magnitude or value of the predicted hazard level for fuzzy estimates (5) as a fuzzy amount of danger in a given state.

This estimate will have the form [3]:

$$\hat{R} = \hat{f}(\tilde{R}|\Sigma_0) = \hat{f}(\mu, H_L| \Sigma_0, L_R).$$

(6)

where $\hat{R}$ – an integral assessment of the risk level (“amount of danger”) is a function of a two-element fuzzy set (5). It is obvious that the notion of “average risk” according to (4) is a scalar quantity and its traditional calculation is incorrect with rare events.

According to the features (3), the average risk cannot be calculated using the probability safety assessment (PSA) tools in the absence of statistics about $\mu$ from (4) or (5).

However, the fuzzy measure $\hat{R}$ of the occurrence of a risk event $R$ can be correctly, though unclear, given by linguistic variables [3, 7, 12]:

“rarely”, “very rarely”, “often”, “seldom”, “sometimes”.

(7)

Any fuzzy terms of the form (7) and fuzzy narrative sentences introduced in risk models as predicates are fairly simply and automatically processed in software systems on the basis, in particular, of fuzzy implication procedures [3].

The proposed scheme for solving problems makes it possible, when assessing the levels of risks, to avoid the incorrect concept of “predictable” probability of an event. It follows from (6) that the use of a safety criterion such as the “probability of collision non-occurrence” is erroneous. Instead of the probability of the occurrence (of events) of chains (J. Reasons’ chains), the criticality indicators of these chains or the corresponding outcomes of the systems tests are determined for their operation in the form of risk levels or some indicators: hazard, safety, etc. Thus, estimates of type (6) can be obtained on the basis of fuzzy indicators in the form of (6) with allowance for (5) without applying the probabilistic indicators of the criticality of the event chains. Criticality [24] is objectively incorporated in (6) as a model of
the structure of the system and its functional features and is determined by comparison of $\hat{R}$ with the level of acceptable risk $\hat{R}^*$ for a given system under threats and disturbances.

Proposals for the choice of the universal appearance of the SMS structure for safety management systems and ATC are substantiated considering the ICAO recommendation based on the risk-oriented approach and fuzzy logic with Fuzzy Sets.

Thus, estimates of type (6) can be obtained on the basis of fuzzy indicators of type (5) without applying the probabilistic indicators of the criticality of the event chains.

The hazard model is built on the basis of the new concept of “risk” in NASA wording [7, 13] in the following sequence (approach):

a risk event $R$ is defined as in [3];

a “collision equation” is constructed according to the rules of the algebra of the logic of events;

relationships of hazards are established as in [13, 24];

scenarios are defined in the form of logical chains of events according to J. Reason [7, 13].

Here are some examples of the use of the mathematical apparatus and the methodological approach proposed in the paper.

Example 1. Reducing the risk level for conflicts between the aircraft in the ATC area.

The conflict manifests itself in the form of possible collisions or dangerous and critical closures depending on the set of dangerous factors characterizing the safety hazards in the ATC system [5]. The question is that P. Reich’s models [22] should be corrected, as presented in this paper. Therefore, it is advisable to implement the Fuzzy Sets approach in the ATC system.

The transition in the aviation community to the application of a risk-oriented approach in the ATC system is justified. In the new NASA interpretation, the safety state is also assessed through the “risk” in the form of the value of the forecasted hazard level and the corresponding measure of this hazard – in the form of the integrated risk value [3, 7].

NASA [7] developed a risk concept based on the idea of identifying and searching (in ATC and ATM systems) such discrete states, which denote the system functionality loss.

In the theory of “risk” defined in fuzzy sets (4)-(6), the paramount task is to analyze the structures of the chain of events leading to a possible collision. This means that it is necessary to apply the derivation of the “collision equation” (the conditions for the occurrence of a collision) depending on the type and kind of safety threats including a set of hazard factors. After identifying the source of the threat $ZR$ and the danger factors $\varphi \in ZR$ for the flight safety (FS), the “collision equations” must be constructed using the disjunction and conjunction functions based on the analysis of the interrelationship of the elements of a clear set that is the carrier of reliable information about the physical features of the predicted risk event. Then risks and chances can be estimated on the basis of “risk event” models (4)-(7).

Example 2. Analysis of J. Reason’s chains for the flight situation analyzed in [2]. The article describes the new construction of a model for the dangerous closure of aircraft in a
Assessment of Accident and Collision Risks in Presence of Fuzzy Threats to Flight Safety

flight situation on the basis of the NASA concept of “risk” within the framework of the theory of function spaces and “sigma-algebra” [3] in the function space of desired flight outcomes. This approach was not previously known, but indirectly the approach proposed below was also conceptually developed in NASA publications [7, 25].

The significance of the example in question is that it is possible to study the conflicts that arise in the ATC system with the help of a clear and fuzzy logic for analyzing the consequences of combinations of various factors, taking into account the uncertainty of the measure of their possible occurrence.

In the given conflict diagram between two aircraft, conflict models M1 and M2 were initially constructed for two sides A and B. Then, the “collision equations” were constructed according to the logical algebra rules on sets of hazards with the detected threats. The relationships of hazard factors were established and scenarios or chains of events (Reason-like) leading to a possible collision were identified.

In the M1 model (the initial normal flight of the B-side aircraft), the following hazard factors were considered as elements of the “collision threat”:

- \( \varphi_0 \) is a “challenge” to the side B in the form of “collision warning” following the alarm signal from the A-side radar;
- \( \varphi_1 \) is the entry of the B-side aircraft into the dangerous closure area in the A-side “alarm zone” (according to the radar data);
- \( \overline{\varphi_2} = 0 \) means there is no “collision risk factor” for sides A and B (logical negation of factor \( \varphi_2 \)), because the A-side dangerous object has not yet appeared in the conflict area, although the “challenge” has already been announced (for example, through the communication link with the ATC controller).

The M2 model (risk flight with the collision threat) contains the hazards \( \varphi_i \) that determine the real threat in the following form:

- \( \varphi_0 \) is a “challenge” (collision threat warning) – the same factor as in M1;
- \( \varphi_1 \) is the entry of the aircraft into the dangerous closure area with the collision threat – the same factor as in M1, but more dangerous, since there is a real collision threat from side A;
- \( \varphi_2 \) is a “collision threat factor” for side A;
- \( \varphi_3 \) is the fact of occurrence of the “collision threat”.

The threat \( Z_R \) to the flight safety lies in the possibility of the occurrence of a risk event (the collision threat) by factors \( (\varphi_2 \land \varphi_3) \) (conjunction). These factors yield a risk event (predicted) \( R \) in the form of the Reason’s chain \( LR \) from the combination of factors \( \varphi_i \) from the collision equation \( U_R \) with damage \( HR \) according to (3), \( \omega_R \) is an elementary event (case) with an uncertainty argument of general form \( \xi_1 \) or \( \xi_2 \) from (4):

\[
R = R(\xi_1, \Pi_R, Z_R, \Sigma_0, U_R).
\] (8)
The collision equation $UR$ for $M2$ will be:

$$UR = (\varphi_0 \land \varphi_1 \land \varphi_3 | Z_R, \Sigma_0) = 1.$$ 

This equation defines the chain of events $LR(UR)$ leading to a possible collision. Integral assessments of risk $\hat{R}$ and chance $\hat{B}$ (acceptability, criticality) are obtained as follows:

$$\hat{R} = \hat{f}_R(\mu_1, H_R | \Sigma_0, Z_R) - "\text{risk} \ \hat{R} \ \text{is great}" \ \text{at} \ UR = 1.$$ 

Here, the damage $HR$ ($\Pi_R \neq 0$) is non-zero and with $\mu_1 \sim \mu_p$ – the “almost zero probability” – $\mu_p \cong 0$.

Weighing $\hat{R} >> \hat{B}$ in M2 gives a minimum estimate of the chance, that is $\hat{B}$ is min, but achieving the max risk $\hat{R}$ is greatly possible:

$$\min \hat{R} = \hat{R} | \Sigma_0 = H_R \ \text{or indicator} \ L_{R*} = [\hat{R}_0] \ \text{from the NASA matrix.}$$ 

The necessary management of the system state for the projected event R in the presence of the collision threat $ZR$:

- to maneuver the aircraft according to the procedure for bypassing the vulnerability (collision) point;
- to use on-board and other means of warning about a possible aircraft collision.

Conclusion on the M1 situation: in the M1 model, the collision “risks” are small.

Conclusion on the M2 situation: in the M2 model, the “risk” of a possible collision is great.

It is required in advance for the predicted event R in the presence of the threat $ZR$ to implement proactive management of the system state: reduce the collision risk $\hat{R}$ by maneuvering the aircraft at the vulnerability point.

The value of the results: The Fuzzy Sets hazard models necessary for building flight safety control and assessment systems can be created on the basis of a risk-based approach.

In assessing the reliability of the developed mathematical models for assessing the risks of accidents and collisions with aircraft, a fairly stable reproducibility of the models developed in various practical operational conditions was found, and a qualitative coincidence of the authors’ research results set forth in this paper with the results presented in [6, 17-21] was established.

5. CONCLUSIONS

Classical probabilistic flight safety indicators become unreliable with insufficient amounts of statistical data in rare events with regard to accidents and collisions of aircraft. The probabilistic concept of safety and risk in case of rare events is erroneous and should be reviewed. Adjustments were made to the probabilistic interpretation of rare events and a scheme for the analysis of rare events from the Berkeley School (USA) was adopted.
The paper substantiates the principles of developing a single approach to solving the problem of assessing the risks of accidents and collisions not only in the field of flight safety, but also in the areas of military operations, ecology, finance, industrial projects, in air traffic control systems and in counter-terrorism activities.

The newly introduced concept of “risk” (following the NASA wording) as a “measure of predicted danger” or harm with a certain threat to the safety of aviation and technical systems makes it possible to assess the criticality of the detected paths leading to a collision, with off-nominal aircraft operating conditions.

The application of the risk-oriented approach for the formation of proactive (preventive) control actions on the technical system provides a reduction in the risks of negative consequences and makes it possible to increase the chances of success in aviation activities with the uncertainty of information on dangerous situations.

The concept of “indicator” provides a tool for “weighing risks and chances”. Indicator estimates of the safety level (or protection level), as recommended in ICAO Annex 19 can be introduced in the form: safe system - with indicator “1”, dangerous system – with indicator “0”. The Fuzzy Sets method allows the development of procedures and formulas for determining the integral levels of safety with a fuzzy level of threats and the risks of functional failures in various systems in the presence of disturbing factors.

The objective is achieved to develop a methodical and mathematical apparatus that allows a priori to find chains of events sought in the technical systems in the form of paths leading to negative events and collisions. The chain is searched taking into account the criticality of the consequences in the form of a risk measure resulting from the features of a special event in the form of destruction of the system functionality.

Identification of hazards in aviation activities is proposed with the help of the Safety Management System (SMS) using the technology of a proactive risk mitigation process technology. The scheme for solving the problem considered in this paper is implemented in accordance with the ICAO recommendations [9, 12] by creating a new generation of safety management systems (SMSs) in civil aviation enterprises and organizations.

The main method is to identify and search only such discrete states of the technical system, which denote the loss of features of the system functionality. The hazard model is developed in the form of a logical chain of events in the system, where the processes leading to a possible collision can be weighed as risks and chances of occurrence for consequences in dangerous situations (in the form of chains of events leading to a collision). Criticality of the results is estimated on the basis of the Fuzzy Sets with the help of logical “collision equations”.

The basis of the SMS structure is the NASA for identifying risks and hazards and forming management principles for changing the current state of technical systems controlled by the safety factor. The NASA algorithm unified for all SMS types is described in the ICAO Annex 19.

The proposed scheme for solving problems makes it possible, when assessing the levels of risks, to avoid the incorrect concept of “predictable” (“guessed”) probability of an event. The use of a safety criterion such as the “probability of collision non-occurrence” is erroneous. Instead of the probability of the occurrence (of events) –J. Reasons’ chains, the criticality indicators of these chains or the corresponding outcomes of the systems tests are determined for their operation in the form of risk levels or some indicators of hazard (safety). Thus,
estimates can be obtained on the basis of fuzzy indicators for event chain criticality. Proposals for the choice of the universal appearance of the SMS structure for safety management systems and ATC are substantiated considering the ICAO recommendation based on the risk-oriented approach and fuzzy logic. The concept of “indicator” provides some tools for “weighing risks and chances”. It is shown that promising developments are based on the Boolean logic of constructing event chains in systems when creating a “collision equation” for a system with a given structure and a predictable risk event. The tool for solving these problems is the method of fuzzy sets for assessing the aviation safety levels without probabilistic indicators. This enables development of procedures and formulas determining integrated levels of safety based on the concept of the functional failure risk concept.

As an illustration of the proposed methods, examples of the construction of the collision equation are considered: reducing the risk level for conflicts between the aircraft in the ATC area; Analysis of J. Reason’s chains for the flight situation while preventing the aircraft collision. At the same time, a new approach is to build a hazard model based on the NASA “risk” concept within the framework of the theory of functional spaces of desired flight outcomes without probabilistic interpretations of events.

In assessing the reliability of the mathematical models described in the paper and used for assessing the risks of accidents and collisions with aircraft, a fairly stable reproducibility of the models developed in various practical operational conditions was found, and a qualitative coincidence was established for the authors’ research results set forth in this paper with the results presented in other authors’ works in the same area of research.

REFERENCES
Assessment of Accident and Collision Risks in Presence of Fuzzy Threats to Flight Safety


