Integration of Decision-Making Stochastic Models of Air Navigation System Operators in Emergency Situations

Tetiana Shmelova [1], Kseniia Lohachova[2] and Maxim Yatsko[3]

[1]National Aviation University University, Liubomyra Huzara ave. 1, Kyiv, 03058, Ukraine
[2]National Aviation University University, Liubomyra Huzara ave. 1, Kyiv, 03058, Ukraine
[3]National Aviation University University, Liubomyra Huzara ave. 1, Kyiv, 03058, Ukraine

Abstract

The authors present a new objective-subjective approach to conflict management to ensure proper collaboration of different aviation personnel using decision-making (DM) methods in Certainty, Risk, and Uncertainty. For improvement of outcomes of the collective solutions the collaborative decision-making (CDM) models are used, when is difficult to make the final right decision based on many factors influencing DM of different aviation specialists (pilot, air traffic controller, flight dispatcher) during the development of an emergency in flight. The Integration of Uncertainty Models to the Collective Model of CDM has been presented. An example is presented - the building of individual models and CDM models for the pilot-in-command, flight dispatcher, and air traffic control officer in bad weather conditions (lightning strikes and thunderstorm activity) during the approach of aircraft. The optimal landing aerodrome was chosen for landing in bad weather conditions.

Keywords

Integration of Stochastic and Non-stochastic Models, Collaborative Decision Making, Decision Making under Uncertainty, Emergency, objective-subjective approach, individual and collaborative models, pilot, flight dispatch, air traffic controller, objective and subjective factors

1. Introduction

In the process of aviation industry development, safe air transportation is the core objective of the functioning of the aviation system. But despite the rapid and constant growth from the point of developed technologies applied in the operational processes of air traffic control, flight planning, modern airplanes manufacturing, and improvement of hours flown by pilots and flight performance, the number of aviation accidents does not decrease. Detailed aviation accident statistics are presented in the Annual safety reviews of the European Aviation Safety Agency (EASA) and the guide to European statistics "Statistics Explained" [1; 2]. According to the published data from the EASA, the number of aviation accidents during the last years has grown [2]. There were 789 fatalities in aviation accidents involving European Union (EU) - registered aircraft over the period 2016-2020 [1]. Most of the air accidents dealt with general aviation, near 80% (as known, general aviation consists of all civil aviation aircraft other than commercial air transport) [1]. As per EASA annual safety review, the number of non-fatal accidents in 2019 was higher than the average 10-year period before [2]. The number of occurrences depended on the size and load of the aircraft involved in the accident, and the complexity of emergency situations. Most of the occurrences in 2019 were related to difficult meteorological conditions [2]. Besides, the possible sources for such statistics may have next reasons [3; 4]:

1. Insufficient pre-flight preparation
2. Inadequate training of aviation personnel
3. Gaps in developed procedures and manuals, situational unawareness

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EMAIL: shmelova@ukr.net (T. Shmelova); kseniialogachova@gmail.com (K. Lohachova); maxim_yatsko@i.ua (M. Yatsko)
ORCID: 0000-0002-9737-6906 (T. Shmelova); 0000-0002-3802-5540 (K. Lohachova); 0000-0003-0375-7968 (M. Yatsko)

4. Availability of single guidance for multiple users for non-conflict decision-making (DM), especially in emergency situations
5. The influence of the socio-technical environment and non-professional factors (psychophysiological, individual psychological, socio-psychological) on the person
6. Psycho-emotional states of operators.

Most of these reasons belong to human factor. Human error is considered the first cause of accidents [2; 3; 4]. Indeed, as many safety scholars affirm, human error is only an epiphenomenon, that is a secondary phenomenon that occurs alongside or in parallel to a primary event. The real cause of accidents which induces an error are human performance and limitations, poor teamwork, organizational pressure on the professionals in the team to obtain unreasonable performance, faulty human-machine interaction, and conflict interaction of professionals in important DM too [3; 4]. It's clear, human factor should be included for progressive and sustainable development and safety enhancement of the complex aviation system. Safety is the functioning of certain operational processes in the aviation systems with the objective of controlling the safety risks of the outcomes of hazards during operation. International Civil Aviation Organization (ICAO) developing proactive approaches for the safety provision based on risk and human performance assessment [5]. The one from the modern concepts is the information and intelligent support of collective solutions of different specialists in an emergency [5]. There are a lot of professionals involved in the provision of safety during flight planning and operations process. They are flight dispatchers, flight crews, air traffic controllers, maintenance staff, ground handling personnel, etc. Each of them plays a major role at different stages, as the safe flight starts not only from the aircraft departure. They strictly follow the manuals and legal documents approved in the field of their professional activity [6; 7; 8; 9].

The main actions of aviation specialists in accordance with the stage aircraft operation are presented in the Table 1.

Table 1
The main actions of aviation specialists according to the stage of aircraft operation

Aviation specialist	Stage of flight	Operations
Flight dispatch (FD)	Planning	Responsible for flight planning and organization, for choice of the optimal flight route, alternate aerodromes, and proper fuel amount calculation for definite flights, regulated by international and national documents, orders, and instructions for the normal and abnormal operational environment of aircraft [6]
Pilot-in-command (PIC)	Flight	Is holding the full right of DM before departure and taking all responsibility in flight, following existing aircraft flight and operations manuals, quick reference handbooks (QRH) in case of emergency and abnormal conditions according to the type of aircraft [7]
Air traffic control officer (ATCO)	Safety of flights of aircraft in the control sector of airspace	Ensures required aircraft separation minima established in each sector of airspace and provides flight crews with assistance in emergencies, according to the instructions defined and approved within particular air traffic control sector, by national laws, letters of agreement between neighboring countries, and handbooks in case of aircraft emergencies [8; 9]

Sometimes specialists from other fields, such as emergency and ground services, and medical staff may be involved in joint DM (Figure 1). For example, the digital health and telemedicine in emergencies are applied, allowing to invitie qualified medical personnel for a consultation in case of incapacitation of one of the pilots or one of the passengers [10; 11].

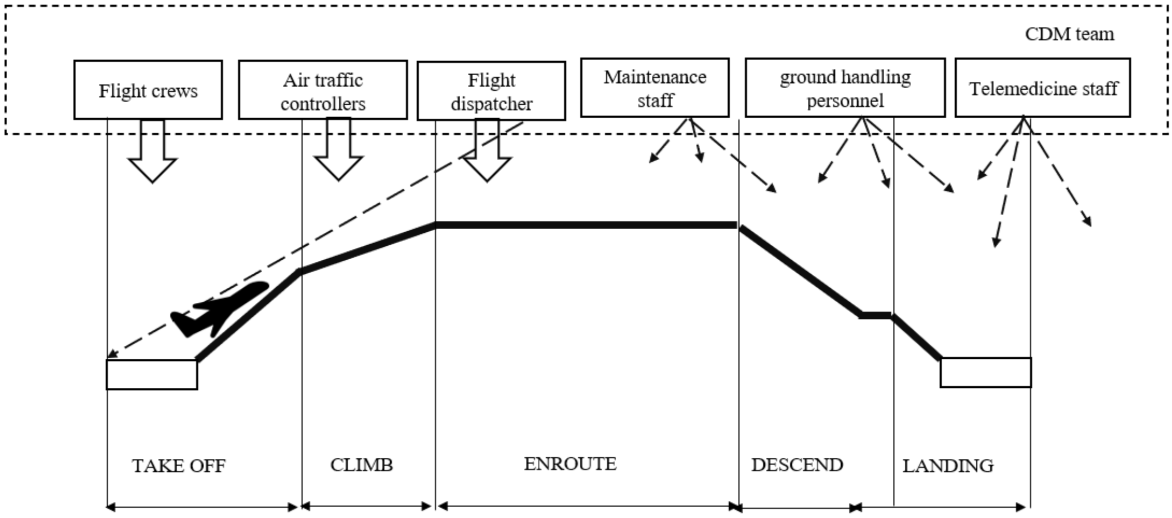

Figure 1: The team of human-operators involved in Collaborative Decision-Making during the flight

Mostly, the complexity, content, particularity of documents, regulations of the professional activity of each aviation personnel are different, which does not allow to develop the general algorithm of actions for all aviation staff in a specific situation, especially for difficult in-flight conditions, where the uncertainty, lack of information and time for DM take place. That's why arises the conflict between actions and decisions of involved staff who making the decisions at the same time for one situation. Therefore, to ensure proper collaboration and conflict resolution between different aviation personnel for improvement of outcomes of group decisions, it is necessary to implement new approaches for conflict management and integrate DM stochastic and non-stochastic models for Air Navigation System (ANS) operators, especially in an emergency [12; 13].

In the concept of the Global Air Navigation Plan developed by ICAO [14], the proper collaboration is possible through the provision of air traffic management system (ATM) members with an environment that ensures enough storage of significant information and its proper usage among ATM system. In this environment, all members closely interact with each other in making common decisions and achieve so-called Collaborative Decision-Making (CDM). This concept foresees the improvement of the whole performance of the ATM system in general taking into consideration the individual performance of ATM system members. This approach allows choosing the direction of action with respect to selected objectives, based on decisions made by each participant, and information exchange influenced those decisions, applying main DM principles [15]. That is why ICAO promotes the global implementation of performance management principles, gradually transferring the existing ATM systems to performance-based global ANS. The performance-based approach (PBA) is a mean of establishing the performance management process and is based on three principles of obtaining effectiveness of solutions [16]:

- A strong and competent focus on desired results of DM
- Conscious and rightly of DM
- Reliance on real facts and data for rational DM.

Hence, according to the ICAO requirements, the meeting of the day-to-day performance in operations may be achieved through the mechanism of Flight and Flow Information for a Collaborative Environment (FF-ICE) Concept [17]. Concept FF-ICE defines air navigation information requirements for flight planning, flow management, air traffic management, and trajectory management, and to be a basis of the performance-based ANS [17].

In the monograph, "Intelligent Automated System for Supporting the Collaborative Decision Making by operators of the Air Navigation System during Flight Emergencies", was researched the PIC and ATCO CDM during flight emergencies using deterministic models in order to achieve the maximum synchronization of operators' technological procedures. Collaborative Decision Models are created for only two operators such as PIC and ATCO [18]. The ability to reach a general consent on the desired outcome to be achieved by all ANS operators (FDs, flight crews, ATCOs, maintenance staff, ground handling personnel) in terms of performance results is the basic condition for the successful application of the approach for conflict management, especially in emergency situations [13]. The application of classical DM criteria under uncertainty makes it possible to take into account the factors influencing the choice and find collective solutions for several participants in the process [19].

The purposes of the work are:

1. Integration of DM stochastic and non-stochastic models of ANS operators in emergency
2. To build the individual DM models for the PIC, FD, and ATCO in an emergency and to determine a collective solution for all operators-participants of the process.
3. To consider an example of building CDM models for the PIC, FD, and ATCO in conditions of uncertainty when it is required to choose an optimal alternate aerodrome in bad weather conditions before the approach.

2. The Integration of Uncertainty Models to Collective Model of Collaborative Decision-Making

For the effectiveness of DM of human-operators (H-O)'s of ANS in emergency situations the integration of Stochastic, and Non-stochastic models has been proposed [4; 12; 13]. There are the next main steps of the Method of the Integration of Stochastic models (DM under Risk and Uncertainty) and Non-stochastic models (DM in Certainty):

1. Analysis of the development of the emergency situation (ES) and synthesis of DM models in accordance with conditions, factors, potential participants, and stages of the development of the event (Figure 2).
2. Building deterministic DM models using Network Planning methods and determining output results (Figure 2):

- critical time T_{cr}; T_{mid}; T_{min}; T_{max}
- critical paths of performance of actions of ANS operators in ES
- ambiguous situations S_1, S_2, and synchronization of H-Os actions using stochastic models
- alternate situations S and optimal CDM using stochastic models.

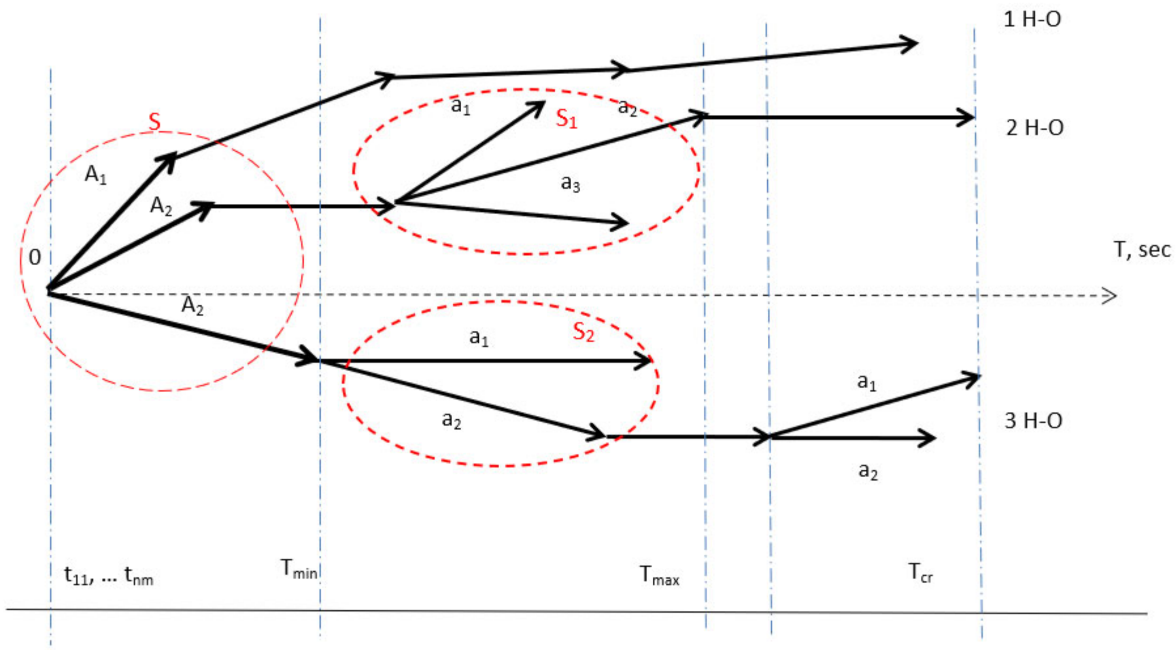

Figure 2: The deterministic DM models in ES for 3 human-operators

3. Analysis of procedures of the main technology, conditions of development of ESs, information about problem and conflict situations, and using the effective integration of DM models:

- If there is statistical information about the conditions of the development of the ES (the presence of probabilities of the development of the ES), then DM models under Risk conditions are applied and a decision tree is built (Stochastic Uncertainty DM models)
- In the case of absence of statistical information and probabilities, there are the factors which influence on the development of the situation, then DM models under Uncertainty are applied and a DM matrix is built (Non-Stochastic Uncertainty DM models)

4. Structural analysis of the ES and building of the Stochastic Uncertainty DM model (decision tree) according to conditions the development situation. Definition of the number of DM stages and time of stage t_i; relevant output data: A_i; p_i; u_i; β_i (alternatives at each stage A_i; probabilities p_i and outcomes u_i for each alternative A_i; added risks β_k influence on DM according to stages of the development situation, increasing threats due DM of H-Os. (Figure 3). Optimal solutions according to conditions of development of ESs. Risk R defined as:

$$R = A_{opt} = min\{Ai\} = min\left\{t_i(\sum_{i=1}^{n} p_i u_i - \beta_k)\right\} \quad (1)$$

where ...

A_i – alternative decisions, $A = \{A_1, A_2, \dots A_i, \dots A_m\}$;

p_j – probability of development situation, $p = \{p_1, p_2, \dots p_i, \dots p_m\}$;

u_{ij} - expected outcomes of alternative actions, $U = \{u_1, u_2, \dots u_i, \dots u_m\}$;

β_i – added risk (increasing threats), depend from stages of the development situation; $B = \{\beta_1, \beta_2, \dots \beta_i, \dots \beta_m\}$;

t_i - time of stage of the development situation, $T = \{t_1, t_2, \dots t, \dots t_m\}$.

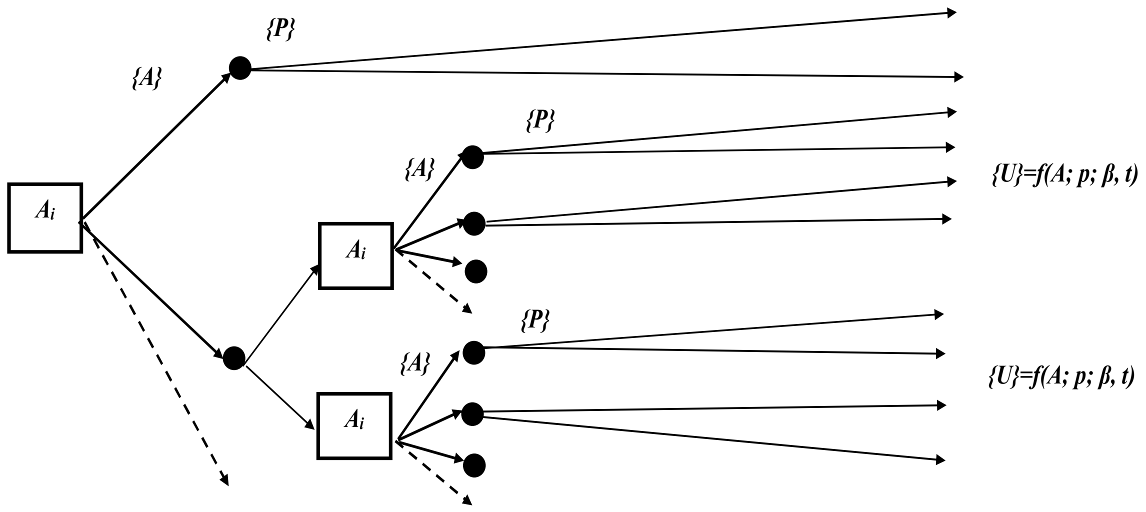

Figure 3: The Stochastic Uncertainty DM models in ES with outcomes *{U}=f (A; p; β, t)*

4. Factor analysis of the ES and building non-stochastic DM model (Table 2) in accordance with factors that influence DM as DM matrix:

- Alternative actions $A = \{A_1, A_2 \dots A_i \dots A_m\}$
- Factors influence on DM according to situation $\Lambda = \{\lambda_1, \lambda_2 \dots \lambda_j \dots \lambda_n\}$, $j = \overline{1, n}$
- Outcomes u_{ij} depending on actions / alternatives A_i , influence of *variable* (u_v) or *static* (u_s) factors - λ_j

For variable factors (u_v) is required to consider the development of the situation - time t_i (from Non-Stochastic DM model) and probability p_j (from Stochastic Uncertainty DM model). For static factors (u_s) is required to consider the normative documents [6 - 9], procedures connected with development of situation, type of aircraft, runway technical characteristics, characteristics of operators [20]. DM matrix $[U(A; \Lambda)]$ with H-O alternative actions $\{A\}$, factors $\{\Lambda\}$ and outcomes $\{U\}$ include (Table 2):

$$\{U(A; \Lambda)\} = \{Us; Uv\} = \Lambda\ (t, p, N),$$

where

U_s – set of outcomes, influenced by the static factors;
U_v – set of outcomes, influenced by the variable factors;
t - time of development of ES;
p – probabilities of development ES;
N – normative documents according to development of ES.

Table 2
Matrix of DM in uncertainty, with variable or static factors

Alternative actions in ES	Variable factors influence DM in critical situation	Static factors influence DM in critical situation
A_1	$u_{v11}, \ ,u_{v1n}$	$u_{s1},\dots u_{sm}$
A_2	$u_{v2},\dots u_{v2n}$	$u_{s2},\dots u_{sm}$
A_3	$u_{v3},\dots u_{v3n}$	$u_{s3},\dots u_{sm}$

5. The optimal solutions are found using classical DM criteria under uncertainty (criterion Wald (maximin), criterion Laplace, criterion Hurwitz, criterion Savage) [19]. The choice of criterion depends on the type of aircraft, type of flight, the conditions for the development of the situation, the nature of the emergency. The short characteristic of criterion and flights:

- Criterion of Wald (maximin) - if this flight is performed for the first time:

$$A^* = \max_{A_i}\left\{\min_{B_j} u_{ij}(A_i, B_j)\right\} \tag{2}$$

where
A_i – alternative solution from set $\{A\}$;
B_j – factor from set of factors $\{A\}$.

- Criterion of Laplace - if this flight is regular:

$$A^* = \max_{A_i}\left\{\frac{1}{m}\sum_{j=1}^{n} u_{ij}(A_i, B_j)\right\} \tag{3}$$

- Criterion of Hurwitz – different approach using optimism-pessimism coefficient α.

For charter flight:

$$A^* = \max_{A_i}\left\{\alpha \max_{B_j} u_{ij}(A_i, B_j) + (1-\alpha)\min_{B_j} u_{ij}(A_i, B_j)\right\} \tag{4}$$

where
α - optimism-pessimism coefficient, $0 \le \alpha \ge 1$, 0 – extreme of pessimism and 1 - extreme of optimism.

- Criterion of Savage – recalculation result after flight:

$$A^* = \min_{B_j}\max_{A_i} r_{ij}(A_i, B_j), \tag{5}$$

where
r_{ij} – loss matrix for recalculations after DM:

$$r_{ij}(A_i, B_j) = \underset{A_i}{\Delta} = \max_{B_k} u_{ij}(A_i, B_j) - u_{ij}(A_i, B_j) \tag{6}$$

6. Integration of the deterministic, stochastic uncertainty (DM in Risk) and non-stochastic uncertainty (DM in uncertainty) models and determining optimal solution.

The flight pattern of an aircraft, the occurrence of an emergency (for example, when approaching the destination airfield, weather conditions have changed, bad weather conditions (BWC) is shown in Figure 4 with the following output data:

- Flight – performed for the first time
- Aircraft – Boeing -737
- Aerodromes – take-off (A_1), landing (A_2) and alternate aerodromes (A_2; A_3; A_4)
- Emergency – BWC (lightning strike and thunderstorm activity)
- The place of the event in-flight – emergency before approach

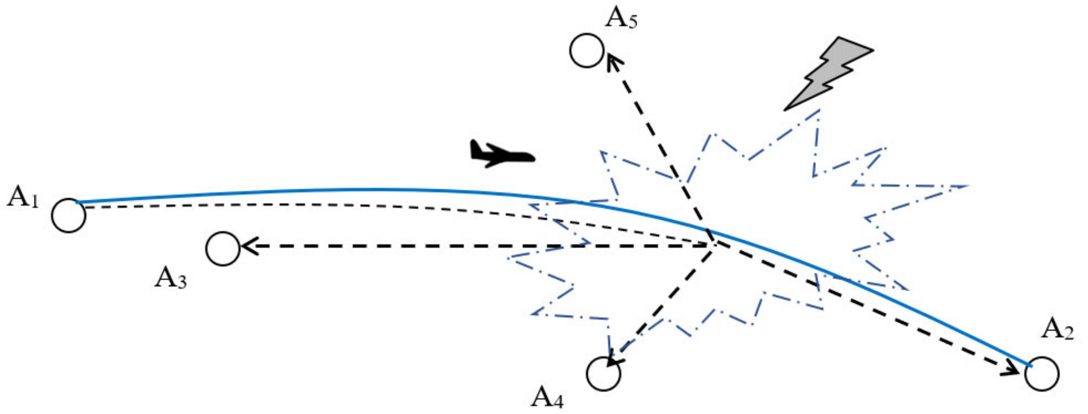

Figure 4: The scheme of aircraft flight route with possible alternative aerodromes

The decision for the selection of the alternate aerodrome in an emergency was implemented with the following output data (Table 3):

- The decision-making matrix
- Alternative actions - $\{A\} = \{A_1, A_2, \dots A_i, \dots A_m\}$ *of DM H-O* in ES and aerodromes of take-off (A_1), landing (A_2) and alternate aerodromes ($A_2; A_3; A_4$)
- States of nature or factors $\{\Lambda\} = \{\lambda_1, \lambda_2, \dots \lambda_j, \dots \lambda_n\}$ – variable or conditionally static factors $\{\Lambda\}$ and outcomes $Us(\Lambda)$ influence on DM in ES. For example, DM in BWC (lightning strike and thunderstorm activity); "variable factor" - are meteorological conditions on aerodromes; "static factor" - available approach systems and aerodrome, crew, aircraft capabilities
- Outcomes of DM matrix $\{U\} = u_{11}, u_{12}, \dots, u_{ij}, \dots, u_{nm}$.
- Conditions of DM under uncertainty if this flight is performed for the first time - Criterion Wald (maximin)

Table 3
Matrix of DM in uncertainty for solution optimal aerodrome in BWC

Alternative aerodromes	Meteorological situation λ_1	Distance λ_2	Fuel reserve λ_3	Aerodrome capability λ_4	Crew capability λ_5	Aircraft capabilities λ_6
Take-off aerodrome A_1	u_{11}	u_{12}	u_{13}	u_{14}	u_{15}	u_{16}
Landing aerodrome A_2	u_{21}	u_{22}	u_{23}	u_{24}	u_{25}	u_{26}
Alternate aerodrome A_3	u_{31}	u_{32}	u_{33}	u_{34}	u_{35}	u_{36}
Alternate aerodrome A_4	u_{41}	u_{42}	u_{43}	u_{44}	u_{45}	u_{46}
Alternate aerodrome A_5	u_{51}	u_{52}	u_{53}	u_{54}	u_{55}	u_{56}

The expected outcomes of the decision matrix are formed based on the influence of factors on DM, and the requirements of regulatory documents [6 – 9; 14 - 17], according to the Aeronautical Information Publication (AIP) too. It is proposed to evaluate the outcomes of the decision matrix using the Expert Judgment Method (EJM) [4; 19]. Each participant in the event - an aviation specialist fills in the decision matrix based on personal opinion. All matrices have the same factors that influence DM.

2.1. The Algorithm of the Collaborative Decision-Making in conflict / emergency situation

The Algorithm of the CDM in conflict/emergency was obtained using the methods of DM under uncertainty for effective collective solutions of different aviation specialists in an emergency:

1. Calculation of route direction
2. Building of DM matrix with:
   - Alternative solutions $\{A\}$
   - Factors, influencing on DM $\{\Lambda\}$
   - Outcomes of choosing of alternative solutions caused by factors influencing on DM $\{U\}$
3. Alternative solutions $\{A\}$ - the list of alternate aerodromes (AA):

$$\{A\} = \{ADest\ U\ ADep\ U\ \{AA\}\} = \{A_1, A_2, \dots A_i, \dots, A_n\},$$

where

alternate aerodrome - an aerodrome of departure (*ADep* - A_1) and it's characteristics;

alternate aerodrome - an aerodrome of destination (ADest – A_2) and it's characteristics;

other alternate aerodromes and it's characteristics according to the calculated route – A_3; A_4; A_5, .

4. Factors $\{\Lambda\}$ influencing on DM for each operator (O_1 - PIC, O_2 - ATCO, O_3 - FD, and O_i - other aviation specialists). These factors may be original or identical and objective (Table 3). For example, next factors:

$$\{\Lambda\} = \lambda_1, \lambda_2 \dots, \lambda_j, \dots, \lambda_m,$$

where

λ_1 – fuel reserve on board;

λ_2 – remoteness of alternate aerodrome;

λ_3 – runway technical characteristics;

λ_4 – meteorological conditions on alternate aerodromes;

λ_5 – the approach lighting system;

λ_6 – available approach system;

λ_7 – available navigation aids;

λ_8 – aircraft performance characteristics;

λ_9 – the presence of radiocommunication;

λ_{10} –air traffic intensity, etc.

5. Outcomes *{U}* - formation of possible consequences $\{U\}$ influencing on the selection of AA in the case of emergency:

$$\{U\} = U_{11}, U_{12}, \dots, U_{ij}, \dots, U_{nm},$$

where

{U} - set of outcomes of DM matrix U_{ij} (i =1, … m; j =1, …, n).

The possible consequences U_{ij} are defined by means of using the EJM according to data from the regulatory documentation and opinions of O_i operators (PIC, FD, and ATCO and other aviation specialists) [4; 6 – 9; 14 - 17].

5. Formation of the matrixes of solutions for each operator. Formation of the matrix 1 of solutions for the first operator (O_1 - PIC) (Table 4).

Table 4

The DM matrix of DM in Uncertainty for operator O_1

The matrix 1	Factors influencing on DM for operator O_1 - PIC						
	{A}	λ_1	λ_2	…	λ_j	…	λ_n
Alternative actions in critical situation	A_1	u_{11}	u_{12}	…	u_{1j}	…	u_{1n}
	A_2	u_{21}	u_{22}	…	U_{2j}	…	u_{2n}
	…	…	…	…	…	…	….
	A_i	u_{i1}	u_{i2}	…	u_{ij}	…	u_{in}
	…	…	…	…	…	…	…
	A_m	u_{m1}	u_{m2}	…	u_{mj}	…	u_{mn}

Analogically, *DM* matrix for the second operator (O_2 - ATCO); the third operator (O_3 - FD) and other operators who are involved in this situation (Figure 1).

6. To choose the methods of DM under uncertainty (equations (2) – (6)) considering the conditions of DM under uncertainty (type of flight, emergency, conditions of development of situation).
7. Finding optimal solutions for each operator using the criteria of DM under uncertainty: Wald, Laplace, Savage, Hurwitz (equations (2) – (6)):

- $A_1^* = A_j(O_1)$ - solutions of PIC $A(O_1)$,
- $A_2^* = A_j(O_2)$ - solutions ATCO,
- $A_3^* = A_j(O_3)$ - solutions FD.

Analogically, DM for other aviation specialists.

8. Formation of the collective matrix of solutions (Table 5), where:

- $\{A\}$ – alternate aerodromes;
- $\{\lambda\}$ – optimal opinions of all operators (O_1 - PIC, O_2 - ATCO, O_3 - FD, and O_i - other aviation specialists) from individual matrixes.
- $\{u\}$ – outcomes - optimal decisions of operators in accordance with the selected criterion / flight conditions from individual matrixes $A_j(O_1)$; $A_j(O_2)$; $A_j(O_3)$

Table 5
The DM matrix of DM in Uncertainty for operators

The collective matrix	Results of optimal solutions by all operators						
	$\{A\}$	$A_j(O_1)$	$A_j(O_2)$	$A_j(O_3)$	$A_j(O_j)$	…	$A_n(O_n)$
Alternate aerodromes	A_1	u^*_{11}	u^*_{12}	u^*_{13}		…	u^*_{1n}
	A_2	u^*_{21}	u^*_{22}	u^*_{23}		…	u^*_{2n}
	…	…	…	…	….	…	….
	A_i	u^*_{i1}	u^*_{i2}	u^*_{i3}	u^*_{ij}	…	u^*_{in}
	…	…	…	…	….	…	…
	A_m	u^*_{m1}	u^*_{m2}	u^*_{m3}		…	u^*_{mn}

9. Finding of optimal solutions for all operators using the criteria of DM under uncertainty: Wald, Laplace, Savage, Hurwitz. For example, for criteria of Wald (2):

$$A^* = \max_{A_i}\left\{\min_{B_j} u_{ij}\left(\min A_i\,, A_j\left(O_j\right)_j\right)\right\}$$

where

A_i – alternative solution from set $\{A\}$;

$A_j\,(O_j)$ – factors $\{A\}$ – opinions of operators from individual matrixes.

The factors in CDM matrix are objective. For each case, depending on the conditions of the situation and priorities of DM, a specific criterion has chosen.

2.1.1. The illustrative example of the Collaborative Decision-Making in emergency situation

Lightning strikes may affect airline operations because of costly delays and serious disruptions to flight schedules [20; 21]. The Aviation Safety Network safety database gives the following lightning strike accident statistics [22]: 29 occurrences with the contributory cause of the lightning strike, including 14 losses of control. A lot of jet airplane lightning strikes occur while in clouds, during the climb and descent phases of flight than in any other flight phase. The reason is that lightning activity is more prevalent between 5,000 to 15,000 feet altitude. The probability of a lightning strike decreases significantly above 20,000 feet. That’s why airplanes flying short routes in areas with a high incidence of lightning activity are likely to be struck more often than long-haul airplanes operating in more benign lightning environments [22; 23; 24; 25].

A lightning strike may result in [25]:

- communication failure
- electrical problems
- emergency descends
- pilot incapacitation.

Expect events:

- pilot may be blinded by a lightning strike
- navigation system problems.

The situation considered in this work**:** bad weather conditions - lightning strike and thunderstorm activity closely to the destination aerodrome.

Initial data:

1. Airplane: Boeing 737
2. Route (Figure 5): Kyiv (Boryspil) (A_1) - Odessa (A_2).
3. Actual and forecasted weather conditions at the time of arrival to Odessa - thunderstorm activity in the vicinity of aerodrome, heavy shower rain, hail.
4. Alternate aerodromes [19]:
   - Chisinau (A_4);
   - Kharkiv (A_5);
   - Alternate aerodrome, which can be chosen along the route: Dnipro (A_3).
5. Factors influencing on DM for each operator:
   - $\{F\}$ - factors considered by operator O_1 (PIC);
   - $\{L\}$ - factors considered by operator O_2 (ATCO);
   - $\{\Lambda\}$ - factors considered by operator O_3 (FD).

Considering the interaction of the PIC, FD, and ATCO, it is necessary to understand their roles and responsibilities. The FD is responsible for the planning of the flight, the PIC is directly responsible for the safe execution of this flight, ATCO provides ATC service, information, and assistance to the crews. Therefore, when making a decision, they analyze a general group of factors, cause the main purpose is the completion of the task (flight from point A to point B), including risk analysis, but from different points of view. And the final decision in flight makes the PIC.

For rational CDM, each operator involved in DM has analyzed and considered the current situation. There are 3 operators in the CDM process: PIC (O_1), ATCO (O_2), FD (O_3) (Figure 1, Table 1). Each operator composed a matrix of decisions, where alternative solutions are alternate aerodromes for the route Kyiv - Odesa, and each operator considers the same factors in the current situation, but with different priorities.

The common factors for each operator (f_j, l_j, λ_j) taken into consideration when making a decision when approaching the destination aerodrome:

- f_1, l_1, λ_1 – fuel reserve on board of the aircraft (always controlled);
- f_2, l_2, λ_2 – meteorological situation (of departure, destination, alternate aerodromes, en-route);
- f_3, l_3, λ_3 – aircraft capabilities (available equipment on board, MEL peculiarities, existing operating limitations);
- f_4, l_4, λ_4 – aerodrome capabilities (available approach systems, technical characteristics of the runways and taxiways, lightning system, service hours restrictions, aerodrome category, firefighting and search and rescue category, emergency service);
- f_5, l_5, λ_5 – crew capability (crew operating minima, crew duty time);
- f_6, l_6, λ_6 – location of obstacles in approach, missed approach and departure sectors;
- f_7, l_7, λ_7 – air situation (intensity of air traffic control sector, radio frequency overload);
- f_8, l_8, λ_8 – commercial point (airport charges, distance from destination aerodrome, passenger and cargo service facilities, the presence of contracts with handlers, the presence of customs, border and migration control service, etc.).

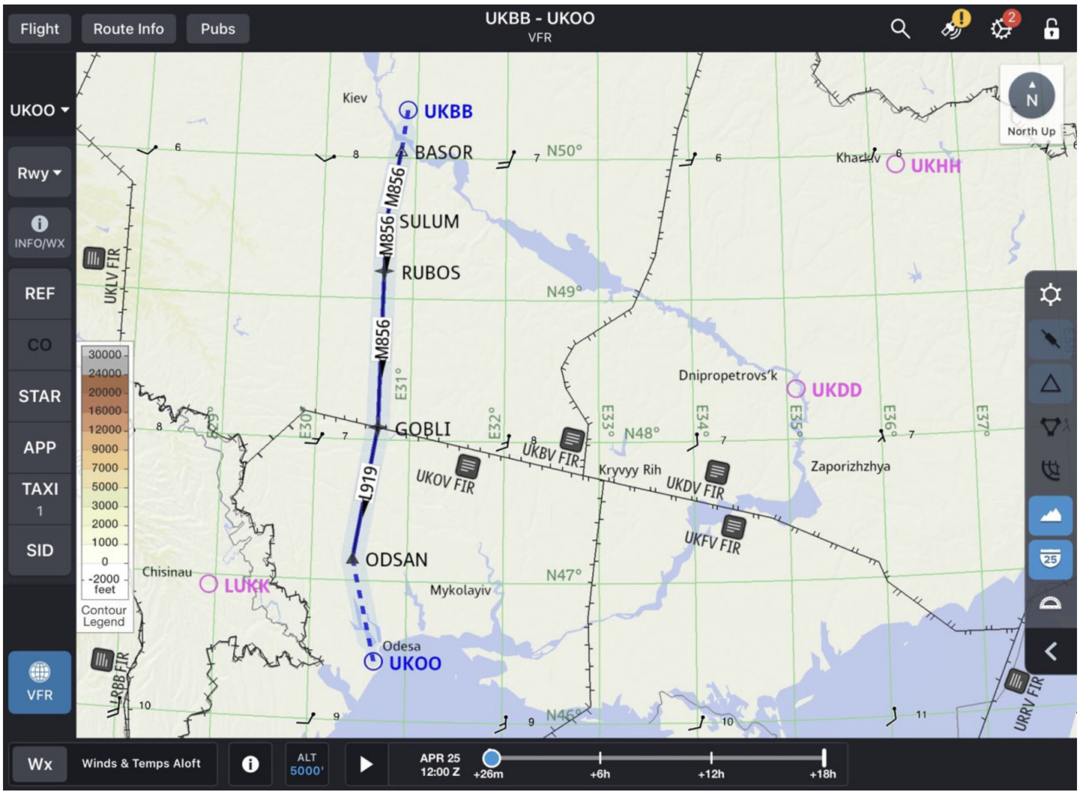

Figure 5: The route of flight Kyiv (Boryspil) - Odessa (UKBB - Kyiv (Boryspil); UKOO – Odesa; LUKK – Chisinau; UKHH - Kharkiv (Osnova); UKDD- Dnipro)

These factors are objective. Composed the operators' DM matrixes when approaching to the destination aerodrome in BWC (Tables 6-9). Expected outcomes considered by the PIC (operator O_1) represented in Table 6. The optimal solutions were determined according to the criteria Wald, Laplace, Horvitz, Savage (2) - (5). The solution according to the criterion of Savage was obtained from the loss matrix (6).

Table 6

The DM matrix of DM in Uncertainty for operator O_1 (PIC)

The matrix 1		Factors $\{F\}$, influence DM for operator O_1 - PIC								Solutions			
Alternative decisions {*A*}		f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	***W***	***L***	***H, α=0,5***	***S***
Departure	*Kyiv (A_1)*	4	10	10	10	8	10	9	9	4	**8,8**	7	6
Destination	*Odessa (A_2)*	10	1	6	7	1	10	2	7	1	5,5	5,5	9
Alternate aerodromes	*Dnipro (A_3)*	5	9	6	7	7	9	6	7	5	7,0	7	4
	Chisinau (A_4)	6	*7*	8	9	8	9	7	*9*	**6**	7,9	**7,5**	**3**
	Kharkiv (A_5)	4	10	7	7	6	5	6	7	4	6,5	7	6

The optimal landing aerodrome during the approach on the route "Kyiv - Odessa" in accordance with the PIC's decision is as follows:

- by Wald criterion - Chisinau (A_4)
- by Laplace criterion - Kyiv (A_1)
- by the Hurwitz criterion - Chisinau (A_4)

- according to the Savage criterion - Chisinau (A_4)

Expected outcomes considered by the ATCO (operator O_2) represented in Table 7.

Table 7

The DM matrix in Uncertainty for operator O_2 (ATCO)

The matrix 2		Factors *{L}*, influencing on decision-making of ATCO (O_2)								Solutions			
Set of alternative decisions {A}		l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8	**W**	**L**	**H, α=0,5**	**S**
Departure	*Kyiv (A_1)*	3	10	10	10	9	10	5	7	3	**8,0**	6,5	7
Destination	*Odessa (A_2)*	10	1	10	10	1	10	8	10	1	7,5	5,5	9
Alternate aerodromes	*Dnipro (A_3)*	4	8	10	10	6	8	6	5	4	7,1	7	6
	Chisinau (A_4)	8	5	10	10	7	7	7	9	**5**	7,9	**7,5**	**5**
	Kharkiv (A_5)	8	4	10	10	7	7	4	8	4	7,3	7	6

The optimal landing aerodrome during the approach on the route "Kyiv - Odessa" in accordance with the ATCO's decision as follows:

- by Wald criterion - Chisinau (A_4)
- by Laplace criterion - Kyiv (A_1)
- by the Hurwitz criterion - Chisinau (A_4)
- according to the Savage criterion - Chisinau (A_4)

Evaluation of optimal alternate aerodrome for landing in difficult meteorological conditions by FD at the stage of flight planning. Matrix of possible outcomes of DM by FD during choosing of alternate aerodromes at the stage of flight planning represented in Table 8.

Table 8

The DM matrix for operator O_3 (FD)

The matrix 3		Factors *{Λ}*, influencing on decision-making of FD (O_3)								Solutions			
Alternative decisions {A}		λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8	**W**	**L**	**H, α=0,5**	**S**
Departure	*Kyiv (A_1)*	3	10	10	10	7	10	7	5	3	**7,8**	6,5	7
Destination	*Odessa (A_2)*	10	1	7	7	1	10	3	10	1	6,1	5,5	9
Alternate aerodromes	*Dnipro (A_3)*	3	8	6	5	5	8	5	8	3	6,0	5,5	**5**
	Chisinau (A_4)	8	9	8	7	5	5	6	9	**5**	7,1	**7**	4
	Kharkiv (A_5)	6	4	9	8	6	8	4	10	4	6,9	**7**	6

The optimal landing aerodrome during the approach on the route "Kyiv - Odessa" in accordance with the FD 's decision is as follows:

- by Wald criterion - *Chisinau (A_4)*
- by Laplace criterion - *Kyiv (A_1)*
- by the Hurwitz criterion - *Chisinau (A_4) and Kharkiv (A_5)*

- according to the Savage criterion - *Dnipro (A_3)*

To determine the consistency of operators, collective matrices were constructed, in which the factors in the decision matrixes for the operators (PIC (O_1), ATCO (O_2), FD (O_3)) are identical, the solutions of the operators and taken from matrices, presented in Tables 6; 7 and 8. In the CDM matrixes used subjective factors – opinions of operators. The optimal CDM if this flight is performed for the first time is presented in the Table 9 (Wald criterion). In this case, the optimal landing aerodrome, determined by objective (fuel reserve on board of the aircraft; meteorological situation; crew, aircraft and aerodrome capabilities; location of obstacles in approach; air situation and commercial point) and subjective factors (PIC, FD, and ATCO) is alternate aerodrome Chisinau (A_4).

Table 9

The CDM matrix for all operators (criteria Wald)

	PIC	ATCO	FD	CDM
Alternate aerodromes	O_1	O_2	O_3	Criterion Wald
Kyiv (A_1)	4	1	5	1
Odessa (A_2)	1	1	1	1
Dnipro (A_3)	5	4	5	4
Chisinau (A_4)	**6**	**5**	**5**	**5**
Kharkiv (A_5)	4	4	4	4

The optimal CDM if this flight is regular (Criterion of Laplace) presented in the Table 10 – is *Kyiv (A_1)*.

Table 10

The CDM matrix for all operators (criteria Laplace)

	PIC	ATCO	FD	CDM
Alternate aerodromes	O_1	O_2	O_3	Laplace
Kyiv (A_1)	***8,8***	***7,8***	**8,0**	***8,2***
Odessa (A_2)	*5,5*	*6,1*	6,1	*5,9*
Dnipro (A_3)	*7,0*	*6,0*	6,0	*6,3*
Chisinau (A_4)	*7,9*	*7,1*	6,8	*7,3*
Kharkiv (A_5)	*6,5*	*6,9*	6,9	*6,8*

The optimal CDM in different approaches using optimism-pessimism coefficient α=0,5 (criterion of Hurwitz) presented in Table 11 – is Dnipro (*A3*).

Table 11

The CDM matrix for all operators (criteria Hurwitz)

	PIC	ATCO	FD	CDM
Alternate aerodromes	O_1	O_2	O_3	Hurwitz
Kyiv (A_1)	*5,5*	*5,5*	5,5	5,5
Odessa (A_2)	*7*	*7*	5,5	6,3
Dnipro (A_3)	***7,5***	***7,5***	**7**	**7,3**
Chisinau (A_4)	*7*	*7*	**7**	7,0
Kharkiv (A_5)	*5,5*	*5,5*	5,5	5,5

Collective decisions were analyzed with varying degrees of optimism-pessimism coefficient α=0,5. The consistency of decisions increases with an increase in the coefficient of optimism, with a decrease in the coefficient in the direction of pessimism, the mismatch increases.

The consistency of decisions determined using the Savage criterion (the recalculation after a flight), were determined for cost initial matrix (Table 12):

$$A^* = \underset{B_j}{min}\underset{A_i}{max} r_{ij}(A_i, B_j) = \underset{B_j}{min}(3; 6; 1; 0; 3) = 0 = A_4,$$

where

$$r_{ij}(A_i, B_j) = \underset{A_i}{\Delta} = u_{ij}(A_i, B_j) - \underset{B_k}{min} u_{ij}(A_i, B_j) = (3; 6; 1; 0; 3)$$

Table 12
The CDM matrix for all operators (criteria Savage) – recalculation)

	PIC	ATCO	FD	CDM
Alternate aerodromes	O_1	O_2	O_3	Savage
Kyiv (A_1)	*6*	7	7	3
Odessa (A_2)	*9*	9	9	6
Dnipro (A_3)	*4*	6	5	1
Chisinau (A_4)	***3***	**5**	**4**	**0**
Kharkiv (A_5)	*6*	6	6	3

The loss matrix presents on the Table 13. The loss matrix shows risks if operators do not choose the optimal collective solution. The maximum risks are selected, which then are minimized.

Table 13
The loss CDM matrix for all operators (criteria Savage))

	PIC / loss	ATCO/ loss	FD / loss	Max loss
Alternate aerodromes	O_1	O_2	O_3	Savage
Kyiv (A_1)	*3*	*2*	*3*	3
Odessa (A_2)	*6*	*4*	*5*	6
Dnipro (A_3)	*1*	*1*	*1*	1
Chisinau (A_4)	*0*	*0*	*0*	**0**
Kharkiv (A_5)	*3*	*1*	*2*	3

The optimal landing aerodrome, determined by objective and subjective factors is alternate aerodrome Chisinau (A_4) as in Wald criterion. The calculations showed a balance between safety and cost of the flight using criteria Wald (maximum safety) and criteria Savage (minimal cost and loss).

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To demonstrate the new method of Integration of Decision-Making Stochastic Models and CDM used the individual science works of aviation students in education (courses “Informatic of DM in ANS” in National Aviation University, Kyiv). Students of different qualifications (PIC, FD, and ATCO, operators of Unmanned Air Vehicles, engineers, and technical personnel) study theoretical courses and then use their knowledge for scientific research. In the chapter "Collaborative Decision Making in Emergencies by the Integration of Deterministic, Stochastic, and Non-Stochastic Models" [13] was presented example of the emergency situation "Lightning strike" from a master's diploma of Zhanna Maksymchuk's “Dynamic models of air traffic controller decision-making in difficult meteorological conditions "Lightning strike" [25]. The diploma considers an example of choosing the optimal landing aerodrome for the ATCO. The authors proposed to find joint solutions for the PIC, FD, and ATCO in an emergency situation.

4. Conclusion

Collaborative Decision-Making is a process of presenting individual and collaborative information and decisions made by various interacting participants, such as PIC, FD, and ATCO in professional solutions, providing synchronization of decisions taken by participants, the exchange of information between them, the effective balancing between safety and cost in collective solutions. It is important to ensure the possibility of making a joint, integrated solution by aviation specialists at an acceptable level of efficiency with minimal risk and maximum safety [5]. This is achieved by the completeness and accuracy of the available information, and by the well-coordinated interaction between specialists, their clear and correct understanding of job duties, and their roles in the process of completing a common task. A Collaborative Decision-Making process in uncertain situations should be provided by using DM stochastic models (stochastic uncertainty and non-stochastic uncertainty models) to improve and simplify the deterministic model.

he objective-subjective approach is effective for determining the optimal solution in important and difficult situations and in conflict interactions between operators. After analysis of the situation firstly the performance of the synthesis (aggregation) of individual models (with objective factors), the next step is to determine collective solutions (with subjective factors). The example of choosing an aerodrome in case of an emergency (for example, in difficult meteorological conditions) using the methods of DM under uncertainty was presented. The calculations showed a balance between safety and cost using criteria Wald (maximum safety) and criteria Savage (minimal cost and loss).

The direction of further research is to develop the DM models for all CDM participants within the Airport CDM (A-CDM) concept may aggregate the solutions of partners (airport operators, manned aircraft operators, unmanned aircraft operators, ground handling agents, and air traffic services) in joint work within non-segregated airspace [26]. For more accurate and timely information provision all partners at the airport are required to create a single operational picture of air traffic [15; 17]. The research was carried out during the simulator training of air traffic controllers [27], it is planned to build the same models for other aviation specialists, operators of manned and unmanned aircraft, flights in integrated airspace [28]. Specialists from other fields, for example, emergency and ground services, and medical staff may be involved in joint DM. Priorities and effectiveness of connecting specialists in the group for CDM will be in the next research. For effective CDM is proposed to include the participant (Artificial Intelligence) in the group of participants in a joint solution and organize the research of a hybrid optimal solution.

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