Collaborative-Factor Models of Decision-Making by Operators of the Air Navigation System in Conflict or Emergency Situations

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Abstract. The authors present a new approach to conflict management to ensure proper collaboration between different aviation personnel using decision-making methods in uncertainty. To improve the results of collective decisions, a dual risk assessment of decision-making in an emergency is used. Initially, the operators' decision is influenced by the factors of occurrence and development of an emergency. The next collective matrix is formed from the individual rational decisions of the operators. The reliability and optimality of the result solutions are provided by the individuals and collaborative solutions of operators. The optimal solutions in emergency "Failure of one engine on a twin-engine aircraft" using collaborative-factor decision-making models for the pilot, flight dispatcher, and air traffic controller are obtained.

Keywords: Air traffic controller · Collective model · Flight dispatcher · Hurwicz criterion · Individual model · Laplace criterion · Pilot · Savage criterion · Uncertainty · Wald criterion

1 Introduction

The human-operator in the aviation system is the most flexible part, but despite advanced technologies applied throughout the aviation system, it is the most vulnerable part, which can be influenced by multiple factors such as environmental factors, conditions of the flight situation development, interaction, and decision-making by operators of Air Navigation System (ANS). The efficiency of aviation systems and flight safety still depend primarily on the reliability of aviation professionals and the results of individual and collective decisions.

International Civil Aviation Organization (ICAO) has defined Key Performance Areas (KPAs) to classify system components concerning goals and expected results of decision-making such as [1, 2]: access and equity; capacity; cost-effectiveness; efficiency; environment; flexibility; global interoperability; participation in the air traffic

O. Ignatenko et al. (Eds.): ICTERI 2021 Workshops, CCIS 1635, pp. 391–409, 2022.
https://doi.org/10.1007/978-3-031-14841-5_26

management (ATM); community; predictability; safety; security. ICAO considered the concepts to refine flight safety, the lasts of which are the cultural interaction and the cross-cultural factors influencing flight safety [3]. They present the safety case for cultural interaction in flight safety concerning early conceptual safety models: Reason's model of latent conditions, SHEL model, and Threat and Error Management (TEM) model [4]. Culture means the interface of the people collectives with their environment which develops and changes due to the occurring social, physical, and technological processes in the environment.

Nowadays one of ICAO's top priorities is developing a strong, stable, and effective aviation security culture. "Security culture" is a central component of the ICAO Global Aviation Security Plan (GASeP) that gives justification for the Year of Security Culture 2021 [5]. The security culture is the rules, standards, persuasions, values, views, and assumptions that affect the daily activity of all departments and staff in the organization.

In the scope of the Global Air Navigation Plan developed by ICAO [6], the proper collaboration is possible via the provision of ATM system members with an environment that ensures enough storage of significant information and its proper usage in ATM system. The Global ATM Operational Concept proposes to realize collaborative decision-making (CDM) between all operational partners [7, 8]. Implementation of the CDM requires the use of a modern information environment based on the concepts of System Wide Information Management (SWIM) [9] and Flight & Flow Information for a Collaborative Environment (FF-ICE) [10].

The analysis of the requirements presented by ICAO concepts to improve the reliability of operators (cross-cultural factors, collaborative decision-making, and security culture) and synthesis of collaborative-factor models of decision-making by operators of the ANS in conflict situations and emergencies are the relevant tasks.

2 A State-of-the-Art Literature Review

From the beginning of aviation, safe air transportation is the core objective of the functioning of the aviation system. However, despite the rapid and constant growth from the point of developed technologies of the air traffic control, flight planning process, modern airplanes, hours flown by pilots, the number of aviation accidents (AA) each year is not tending to decrease.

According to [11], among the main causes of AA include:

- human factor – 68% of cases: pilot errors account for about 47% of all cases (crew violation of standard piloting procedures; fatigue and pilots' health problems; crew errors in difficult weather conditions; errors in contradictory instrument performance; flight disorientation in an unfamiliar area; violation of interaction between crew members; insufficient qualifications for this type of aircraft); errors of ground services – 13% of cases (errors of the air traffic controller; improper operation, repair, maintenance of the aircraft); terrorist acts – 8% of cases (seizure of control, which leads to the fall of the aircraft; bookmark explosive device in the aircraft; destruction of the aircraft from the earth's surface);
- failure of equipment – 18% of cases (aging; structural defects of equipment);

- other reasons – 14% of cases.

Analysis of the PlaneCrashInfo.com database [12], which presents 1085 AA, allowed determining the main causes of aviation accidents in previous decades. The records about AA that meet the following conditions were studied: AA happened from 01.01.1950 to 30.06.2019; AA happened to planes capable of carrying at least 19 passengers; at least two people died in the AA; AA with military and private planes, helicopters are excluded. The causes of the crashes were divided into five categories: pilot errors, technical factors, weather conditions, sabotage, and other causes. The distribution of the causes of aircraft crashes by decades is given in Table 1. The vast majority of AA occurs due to the human factor (Fig. 1).

Table 1. Distribution of causes of aircraft crashes by decades, %.

Causes	1950s	1960s	1970s	1980s	1990s	2000s	2010s	On the average
Pilot errors	50	53	49	42	49	50	57	49
Technical factors	26	27	19	22	22	23	21	23
Weather conditions	15	7	10	14	7	8	10	10
Sabotage	4	4	9	12	8	9	8	8
Other causes	5	9	13	10	14	10	4	10

A lot of professionals are involved in the provision of safety during the flight planning and operations process. There are flight crews, air traffic controllers, flight dispatchers, maintenance staff, ground handling personnel, etc. Each of them plays a major role at different stages, as the safe flight starts not only from aircraft departure. They are strictly following the manuals and legal documents approved in the field of their professional activity. The *flight dispatcher* is involved in planning and supporting the flight. At the stage of flight planning the actions of flight dispatcher, who are responsible for the choice of the optimal flight route, alternative aerodromes, and proper fuel amount calculation for definite flight, are regulated by international and national documents, orders, instructions at the workplace for the normal and abnormal operational environment [13]. *Pilot-in-command* is holding the full right of decision-making before departure and taking all responsibility in flight, follows existing aircraft flight and operations manuals, quick reference handbooks (QRH) in case of emergency and abnormal conditions [14]. *Air traffic controller* (ATCO), who ensures required aircraft separation minima established in each sector of airspace and provides for flight crews assistance in emergencies, guided by instructions defined and approved in particular air traffic control sector, national laws, letters of agreement between neighboring countries and handbooks in case of aircraft emergencies [15].

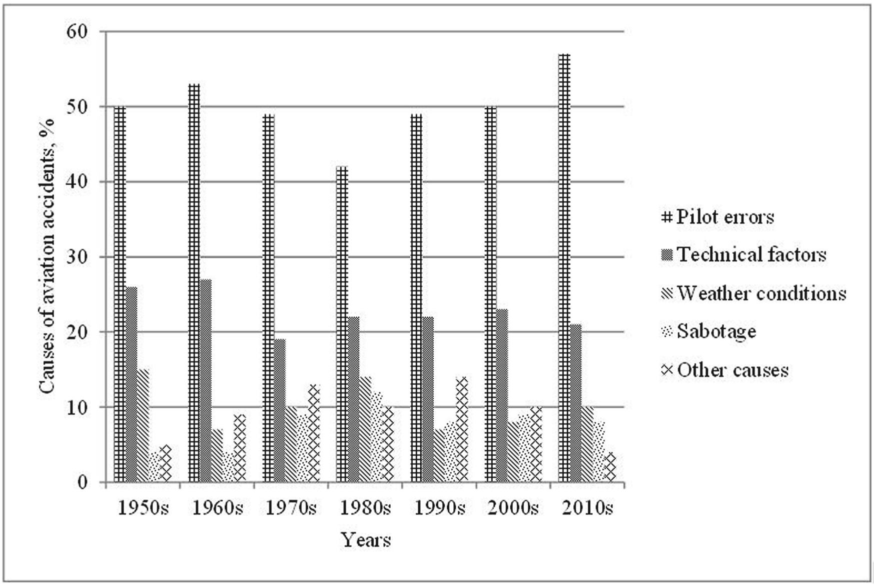

Fig. 1. Distribution of causes of aircraft crashes by decades, %.

The pilot is responsible for the flight in conflict and emergencies; it becomes necessary to provide the aircraft crew with timely information from other operators, such as the flight dispatcher, ATCO, and others. It is necessary to create joint collaborative decision-making to ensure a safe flight. Very often the complexity, content, particularity of documents, regulating the activity of each aviation personnel, are different, which does not allow the developing of a general algorithm of actions for all aviation staff for a specific situation, especially in difficult flight conditions, where the uncertainty, lack of information and time for decision-making take place. That's why the conflict arises between actions and decisions of involved staff who made the decisions at the same time for one situation. Therefore, to ensure proper collaboration and conflict resolution between different aviation specialists for improvement of outcomes of group decisions, it is necessary to implement approaches of conflict management and enhanced models of decision-making in uncertainty, where is difficult to make one and right decision based on many factors influencing on final personal and group decision [7].

ATM system members are closely interacting with each other in making common decisions, and achieve CDM. CDM concept foresees the improvement of the general performance of the ATM system in general taking into consideration the individual performance of ATM system members. It allows choosing the direction of action concerning selected objectives, based on decisions making by each participant, and information exchange influenced those decisions, applying main decision-making principles [8]. To achieve the best collaboration, ATM system members are required to cooperate in a performance-based way. That is why ICAO promotes the global implementation of performance management principles, gradually transferring the existing ATM system to performance-based global ANS. The performance-based approach (PBA) is a means of establishing a results management process and is based on the next principles [2]: a maximum emphasis on desired results; conscious decision-making; facts/data in the basis of decision making. The ability to reach common consent on the desired outcome in terms of performance results to be achieved is a basic condition for the successful application of the approach in conflict/emergency management.

CDM increasingly finds application in business [16], transport [17], logistic [18], management [19], ATM for obtaining effective information environment (FF-ICE) [10] etc. The implementation of CDM in aviation nowadays occurs in the form of Airport-CDM and has the following strategic high-level objectives [20, 21]: efficient overall airport operation and sustainable growth for airline operators; reduction of operational and non-performance/service recovery costs in flight and airport operations; maximize traffic throughput by effective use of airport infrastructure and resources; reduction of delays in flight and handling processes at the airport; minimize effects of major disruptions and temporary reductions incapacity; effective allocation of people and equipment for operational decision-making and flight handling; increased reliability of transfer flows, for passengers, baggage, cargo, and crew; reduction of aircraft fuel burn.

The authors have developed deterministic and non-deterministic individual decision-making models for ANS operators (pilots, ATCOs, flight dispatchers, UAV operators, etc.) in emergencies [22]. In addition to professional factors (knowledge, skills, abilities, experience), these models also take into account non-professional factors (individual-psychological, psychophysiological and socio-psychological) [23]. Integrated decision-making models for several operators are proposed [24]. The problem of optimizing the pilot, flight dispatcher, and air traffic controller operational interaction in flight emergencies with the help of consolidated deterministic, stochastic, and non-stochastic models is studied [25]. For assessing the risk of CDM by the ATCO and pilot in the emergency, a multilayer recurrent artificial neural network in the composition of the Intelligent System for Supporting Collaborative Decision-Making was developed [26].

The purpose of the work is to build the individual and CDM models for the pilot, ATCO, and flight dispatcher in uncertain conditions for choosing the optimal landing aerodrome in flight emergencies.

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

The decision about the selection of the optimal landing aerodrome in flight emergency by the means of Wald, Laplace, Savage, Hurwicz criteria of decision-making under uncertainty is implemented with the following output data:

1. The individual decision-making (payoff) matrix and collaborative decision-making (payoff/loss) matrix.
2. Alternative actions $\{A\} = \{A_1, A_2, \ldots A_i, \ldots, A_m\}$ – are the alternative landing aerodromes.
3. States of nature or factors influence decision-making $\{\lambda\} = \{\lambda_1, \lambda_2, \ldots \lambda_j, \ldots, \lambda_n\}$.
4. Outcomes of DM matrix $\{U\} = \{U_{11}, U_{12}, \ldots, U_{ij}, \ldots, U_{mn}\}$ – are the solutions of operators in emergency.

5. Conditions of decision-making under uncertainty, and characteristic of the emergency, type of flight, kind of aircraft, characteristic of aerodromes.

The algorithm of the CDM during the selection of the optimal landing aerodrome in flight emergency (engine failure, for example) using the methods of decision-making under uncertainty is obtained.

3.1 The Algorithm of the Collaborative Decision-Making in Conflict/Emergency Situation

1. Calculation of route direction.
2. Building of individual decision-making matrix with:

- alternative solutions $\{A\}$ – are the alternative landing aerodromes;
- factors influencing DM $\{\lambda\}$ – are the states and influence of natural factors in an emergency;
- expected outcomes of choice of alternative solutions caused by factors influencing decision-making $\{U\}$ – are the solutions of operators in an emergency.

3. Alternative solutions $\{A\}$ – is the list of suitable aerodromes (SA) (1):

$$A = \{ADest \text{ U } ADep \text{ U } \{SA\}\} = \{A_1, A_2, \ldots A_i, \ldots, A_n\}, \quad (1)$$

where ADep $= A_1$ – is an alternative aerodrome – departure aerodrome and its characteristics;

$ADest = A_2$ – is an alternative aerodrome – destination aerodrome and its characteristics;

A_n – are the other suitable aerodromes and their characteristics according to the calculated route.

4. Factors $\{\lambda\}$ influencing on DM for each operator (2):

$$\{\lambda\} = \left\{\lambda_1, \lambda_2 \ldots, \lambda_j, \ldots, \lambda_m\right\}, \quad (2)$$

where λ_m – are the original or identical factors.

5. Outcomes $\{U\}$ – is a formation of possible consequences influencing the selection of SA in an emergency (3):

$$\{U\} = \left\{U_{11}, U_{12}, \ldots, U_{ij}, \ldots, U_{mn}\right\}, \quad (3)$$

where $\{U\}$ – is a set of outcomes of decision-making matrix U_{ij} ($i = 1, \ldots, m$; $j = 1, \ldots, n$).

The possible consequences U_{ij} are defined based on the Expert Judgment Method (EJM) [27] according to data from the regulatory documentation and opinions of O_i operators: O_1 – pilot, O_2 – ATCO, O_3 – flight dispatcher, O_i – other aviation specialists.

Formation of the individual matrices of solutions for each operator (Table 2).

Table 2. The individual decision-making matrix in uncertainty.

The matrix	{A}	Factors influencing decision-making in emergency					
		λ_1	λ_2	…	λ_j	…	λ_n
Alternative actions in emergency	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}

The matrix for the first operator (O_1 – pilot) solutions is in Table 3.

Table 3. The decision-making matrix in uncertainty for operator O_1.

The matrix 1	{A}	Factors influencing decision-making for operator O_1 – pilot					
		λ_1	λ_2	…	λ_j	…	λ_n
Alternative actions in emergency	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, decision-making matrices for the second operator (O_2 – ATCO), the third operator (O_3 – flight dispatcher), and other operators, who are involved in this situation, are formatting.

6. Consideration of conditions of decision-making under uncertainty (type of flight). Choosing the methods (criteria for analyzing the decision problem) of decision-making under uncertainty with maximum safety:

- Wald criterion (maxmin/minmax) – if the flight is performed for the first time (4):

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

where A_i – is an alternative solution from set *{A}*;

B_j – is a factor from the set of factors *{λ};*

- Laplace criterion – if the flight is regular (5):

$$A^* = \max_{A_i}\left\{\frac{1}{n}\sum\nolimits_{j=1}^{n} u_{ij}\left(A_i, B_j\right)\right\}, \tag{5}$$

where n – is a number of possible influencing factors;

- Hurwicz criterion – is using optimism-pessimism coefficient α (6):

$$A^* = \max_{A_i}\left\{\alpha \max_{B_j} u_{ij}\left(A_i,\ B_j\right) + (1-\alpha)\min_{B_j} u_{ij}\left(A_i,\ B_j\right)\right\}, \tag{6}$$

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

- Savage criterion – is recalculating result after the flight (7):

$$A^* = \min_{B_j}\max_{A_i} r_{ij}\left(A_i,\ B_j\right), \tag{7}$$

where r_{ij} – is a loss matrix for recalculations after individual decision-making with maximum safety (8):

$$r_{ij}\left(A_i,\ B_j\right) = \underset{A_i}{\Delta} = \max_{B_k} u_{ij}\left(A_i,\ B_j\right) - u_{ij}\left(A_i,\ B_j\right). \tag{8}$$

7. Finding optimal solutions for each operator using the Wald, Laplace, Savage, Hurwicz criteria of decision-making under uncertainty:

- $A_1{}^* = A_j(O_1)$ – solutions of pilot $A(O_1)$ – $\{C_{o1}\}$;
- $A_2{}^* = A_j(O_2)$ – solutions of ATCO – $\{C_{o2}\}$;
- $A_3{}^* = A_j(O_3)$ – solutions of flight dispatcher – $\{C_{o3}\}$.

8. Formation of the collective matrix of solutions (Table 4), where:

- *{A}* – are the alternative aerodromes*;*
- *{λ}* – are the optimal opinions of all operators (O_1 – pilot, O_2 – ATCO, O_3 – flight dispatcher, and O_j – other aviation specialists) from the individual matrices;
- *{u}* – are the outcomes – optimal decisions of operators following the selected criteria/flight conditions from the individual matrices $A_j(O_1)$; $A_j(O_2)$; $A_j(O_3)$.

9. Finding of optimal solutions for all operators using the Wald, Laplace, Savage, Hurwicz criteria of decision-making under uncertainty with maximum safety and minimal loss:

- for Wald criterion (9):

$$A^* = \max_{i}\left\{\min_{l} c_{oij}^{l}\right\}, \tag{9}$$

Table 4. The decision-making matrix in uncertainty for operators.

The collective matrix	{A}	Results of optimal solutions by all operators					
		$A_j(O_1)$	$A_j(O_2)$	$A_j(O_3)$	$A_j(O_j)$	…	$A_n(O_n)$
Alternative 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}

where $c^l_{oij} = \min_j \left\{ u^l_{oij} \right\}$ – are the optimal solutions of operators from the individual matrix with minimal loss;

- for Laplace criterion (10):

$$A^* = \max_i \left\{ \frac{\sum_{l=1}^{L} c^l_{oij}}{l} \right\}; \tag{10}$$

where $c^l_{oij} = \min_j \left\{ \frac{\sum_{j=1}^{n} u^l_{oij}}{n} \right\}$ – are the optimal solutions of operators from the individual matrix with minimal loss;

- for Hurwicz criterion (11):

$$A^* = \max_i \left\{ \beta \max_l c^l_{oij} + (1 - \beta) \min_l c^l_{oij} \right\}; \tag{11}$$

where $c^l_{oij} = \alpha \max_j u^l_{ij} + (1 - \alpha) \min_j u^l_{ij}$ – are the optimal solutions of operators from individual matrix, $0 \leq \alpha \leq 1$; $0 \leq \beta \leq 1$;

- for Savage criterion (12):

$$A^* = \min_j \max_l c^l_{oij}; \tag{12}$$

where $c^l_{oij} = u^l_{oij} - \min_j u^l_{oij}$ – is a loss matrix of recalculations after collective solutions with minimal loss.

For each case, depending on the conditions of the situation and priorities of decision-making, a specific criterion is chosen. It is important to fulfill the condition for constructing individual matrices: the similarity of factors influencing decision-making in individual matrices (f_j, l_j, λ_j).

The Illustrative Example of the Collaborative Decision-Making in Flight Emergency. There is presented an example of CDM in flight emergency "Failure of one engine on a twin-engine aircraft". Engine failure is one of the most common and complicated failures (Fig. 2) that occupies 13% of the total aviation incidents [28].

Engine failure can lead to serious consequences such as loss of aircraft controllability, stall, problems with electrical power supply, aircraft pressurization problems, etc. On pilot responsibility, this situation may be urgent or emergency. The initial communication, and if considered necessary, any subsequent transmissions by an aircraft in distress should begin with the signal MAYDAY. The signal PAN-PAN should be used in the same manner for an urgency condition [29]. As a result, engine failure can force to land at the nearest suitable aerodrome. In the process of decision-making to choose the alternate aerodrome, several ANS specialists are involved, such as flight dispatcher, pilot, and air traffic controller.

At the planning stage, the flight dispatcher is responsible for calculating the route and selecting suitable aerodromes. Engine failure at various stages of flight is taken into account. It is necessary to select an alternate aerodrome for take-off when it is impossible to return to the departure aerodrome. A take-off alternate is selected from the following criteria:

- at a distance of one hour of flight with one failed engine in calm conditions, which for B737 is approximately 390 nautical miles;
- the weather must correspond to a minimum not lower than CAT 1.

Category I (CAT I) approach operation' means a precision instrument approach and landing using an instrument landing system ILS (microwave landing system). En-route alternate and destination alternate are selected within a radius of about 420 nautical miles and weather not lower than CAT 1. The choice of alternates is made according to the requirements of existing regulatory documents, such as operating manuals and the requirements of the State Aviation Authorities.

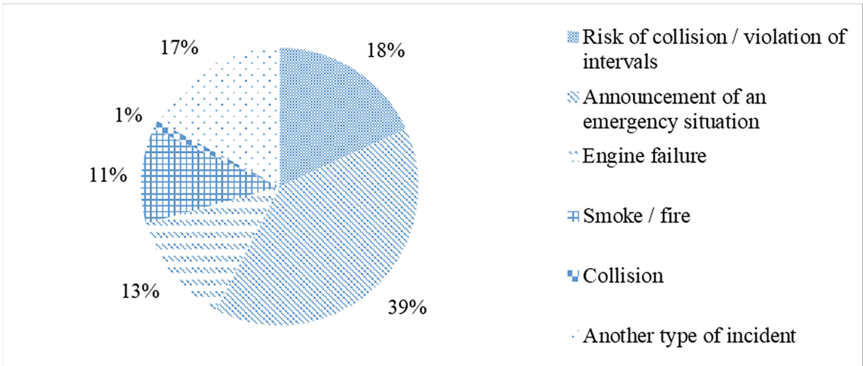

Fig. 2. Distribution of aviation incidents by types, %.

The *flight crews* evaluate the proposed route calculation based on weather conditions and the operational suitability of the aircraft and aerodromes. The *ATCO* performs the function of traffic control and provides all possible assistance in the event of an emergency on board, and is also responsible for providing actual information, aircraft separation, lateral and vertical, at the required intervals. The *flight dispatcher* is involved in supporting the flight in conflict and emergency for change of flight trajectory.

Engine failure at high altitudes leads to an inevitable descend due to a significant reduction in thrust. Since the available thrust produced by one engine is much less than required to maintain the required speed and altitude. As a result, the "drift down procedure" must be executed [30]. The essence of the procedure lies in the fact that for running engine should be set the maximum continuous thrust that can be used without restrictions, and with a minimum speed that provides a steady level flight with one engine, smoothly descend to an altitude where such a flight will be possible. A flight in mountainous areas, where the minimum safe altitude is much higher than the maximum flight altitude with one engine inoperative, can pose great danger. This will require pilots to make a more balanced assessment of the situation, which will lead to a deviation from the route in direction with less terrain height.

Initial data:

1. Aircraft: Boeing 737-800, heavy aircraft (mass is near maximum landing mass 66360 kg).
2. Route (Fig. 3): Lviv (UKLL) (A_1) – Kharkiv (UKHH) (A_2).

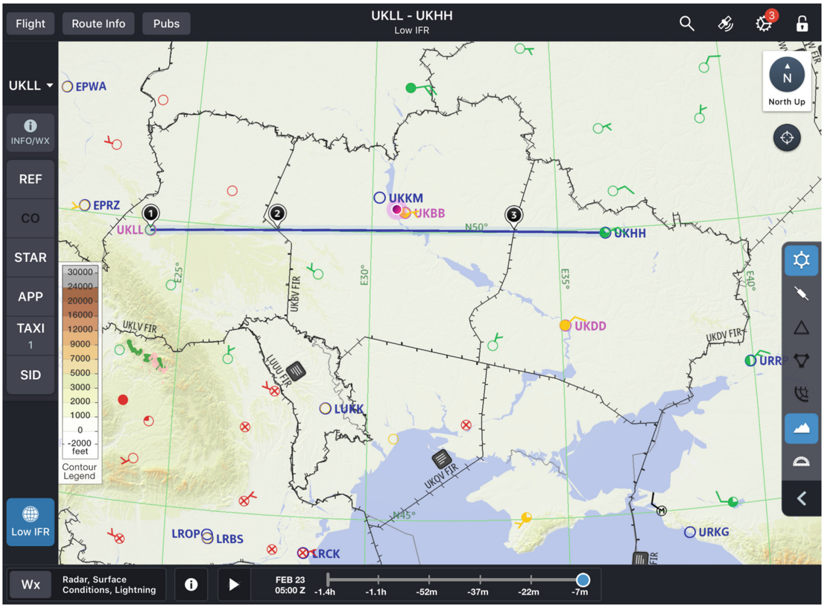

Fig. 3. The flight route Lviv (A_1) – Kharkiv (A_2) in the navigation map.

3. Flight level 350.
4. Alternate aerodromes:

- Dnipro (UKDD) (A_3);

- Boryspil (UKBB) (A_4).

5. The weather at Lviv, Kharkiv, Boryspil, Dnipro corresponds to the minimum CAT 1 (not lower than the following criteria: visibility 800 m, visibility range on the runway 550 m, decision height 200 ft (60 m)). Wintertime, precipitation, braking action is medium, the temperature near zero.
6. Factors influencing decision-making for each operator:

- $\{f\}$ – factors considered by operator O_1 (pilot);
- $\{l\}$ – factors considered by operator O_2 (ATCO);
- $\{\lambda\}$ – factors considered by operator O_3 (flight dispatcher).

For rational CDM, each operator has analyzed and considered the current situation. There are three operators in the CDM process: pilot (O_1), ATCO (O_2), flight dispatcher (O_3).

Each operator has composed a matrix of decisions, where alternative solutions are alternative suitable aerodromes for the route "Lviv – Kharkiv" (Fig. 4), and each operator has taken into account the same factors in the current situation, but with different priorities.

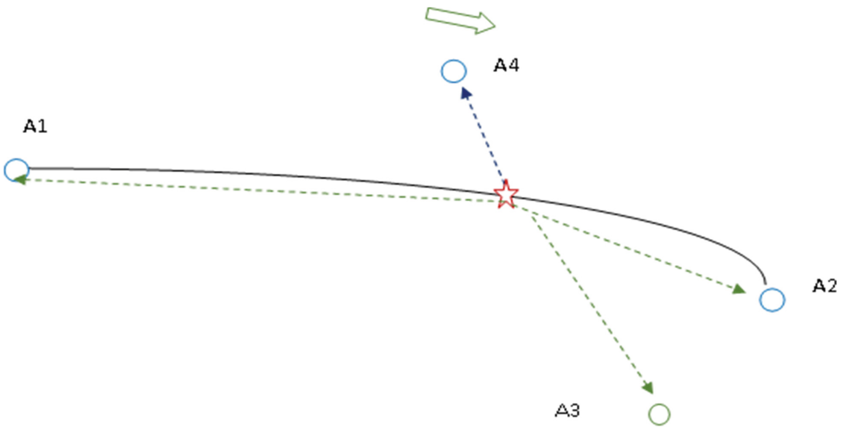

Fig. 4. Schematic presentation of the flight route Lviv (A_1) – Kharkiv (A_2).

When choosing an optimal alternate, each operator (f_j, l_j, λ_j) is guided by the common factors [22]:

- f_1, l_1, λ_1 – fuel reserve on board;
- f_2, l_2, λ_2 – remoteness of alternate aerodrome;
- f_3, l_3, λ_3 – runway technical characteristics;
- f_4, l_4, λ_4 – meteorological conditions on alternate aerodromes;
- f_5, l_5, λ_5 – the approach lighting system;
- f_6, l_6, λ_6 – available approach system;

- f_7, l_7, λ_7 – available navigation aids;
- f_8, l_8, λ_8 – aircraft performance characteristics;
- f_9, l_9, λ_9 – connection communication (radio);
- f_{10}, l_{10}, λ_{10} – air traffic intensity;
- f_{11}, l_{11}, λ_{11} – commercial point.

These factors are objective. The decision-making matrices for operators in flight emergency "Failure of one engine on a twin-engine aircraft" are in Tables 4, 5 and 6. Expected outcomes considered by the pilot (operator O_1) are represented in Table 5. Factors prioritize for the pilot f_3, f_4, f_8 (blue color in Table 5).

Table 5. The decision-making matrix in uncertainty for operator O_1 (pilot).

The matrix 1		Factors influence decision-making for operator O_1 – pilot											Solutions			
Alternative decisions {*A*}		f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	*W*	*L*	*H*, $\alpha=0.5$	*S*
Departure	*Lviv* (A_1)	4	1	9	5	8	8	8	7	7	7	8	1	6.5	8.2	8
Destination	*Kharkiv* (A_2)	8	7	3	5	7	8	8	5	7	7	10	3	6.8	9.3	7
Alternate	*Dnipro* (A_3)	6	5	3	5	7	7	8	6	7	5	7	3	6.0	7.5	5
aerodromes	*Boryspil* (A_4)	7	8	10	5	10	10	10	10	7	9	9	5	8.6	9.5	5

The optimal landing aerodrome during the approach on the route "Lviv – Kharkiv" in accordance with the pilot's decision is as follows (red color in the matrix): by Wald criterion – Boryspil (A_4); by Laplace criterion – Boryspil (A_4); by the Hurwitz criterion – Boryspil (A_4); according to the Savage criterion – Boryspil (A_4) or Dnipro (A_3).

Expected outcomes considered by the ATCO (operator O_2) are represented in Table 6.

The optimal landing aerodrome during the approach on the route "Lviv – Kharkiv" in accordance with the ATCO's decision is as follows: by Wald criterion – Boryspil (A_4); by Laplace criterion – Boryspil (A_4); by the Hurwitz criterion – Boryspil (A_4); according to the Savage criterion – Kharkiv (A_2), Dnipro (A_3) or Boryspil (A_4).

Evaluation of optimal alternate aerodrome for landing in flight emergency is performed by flight dispatcher at the stage of flight planning. The matrix of possible outcomes of decision-making by flight dispatcher during choosing the optimal landing aerodrome at the stage of flight planning is represented in Table 7.

The optimal landing aerodrome during the approach on the route "Lviv – Kharkiv" in accordance with the flight dispatcher's decision is as follows: by Wald criterion – Boryspil (A_4); by Laplace criterion – Boryspil (A_4); by the Hurwitz criterion – Boryspil (A_4); according to the Savage criterion – Dnipro (A_3).

Table 6. The decision-making matrix in uncertainty for operator O_2 (ATCO).

The matrix 2		Factors influence decision-making for operator O_2 – ATCO											Solutions			
Alternative decisions {*A*}		l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8	l_9	l_{10}	l_{11}	*W*	*L*	*H*, α=0.5	*S*
Departure	*Lviv* (A_1)	4	3	8	6	9	10	9	10	8	2	7	2	6.9	6.0	8
Destination	*Kharkiv* (A_2)	8	8	6	2	8	8	8	9	7	4	8	2	6.9	5.5	7
Alternate	*Dnipro* (A_3)	4	8	7	3	9	8	8	9	8	2	6	2	6.5	5.5	7
aerodromes	*Boryspil* (A_4)	7	8	10	3	10	10	10	10	9	4	8	3	8.1	6.5	7

Table 7. The decision-making matrix in uncertainty for operator O_3 (flight dispatcher).

The matrix 3		Factors influence decision-making for operator O_3 – flight dispatcher											Solutions			
Alternative decisions {*A*}		λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8	λ_9	λ_{10}	λ_{11}	*W*	*L*	*H*, α=0.5	*S*
Departure	*Lviv* (A_1)	3	5	8	6	9	8	8	7	8	7	6	3	6.8	6.0	6
Destination	*Kharkiv* (A_2)	10	10	6	6	8	8	8	5	8	6	10	5	7.7	7.5	4
Alternate	*Dnipro* (A_3)	6	7	7	6	8	7	7	6	8	5	5	5	6.5	6.5	3
aerodromes	*Boryspil* (A_4)	7	8	10	6	10	10	10	10	9	8	8	6	8.7	8.0	4

To determine the consistency of operators, collective matrices were constructed, in which the factors in the decision matrices for the operators (pilot (O_1), ATCO (O_2), flight dispatcher (O_3)) and are identical, the solutions of the operators and are taken from matrices, presented in Tables 5, 6 and 7. In the CDM matrices, the subjective factors – opinions of operators are using.

The optimal CDM if this flight is performed for the first time (Wald criterion) is presented in Table 8. In this case, the optimal landing aerodrome is determined by objective factors (fuel reserve on board; remoteness of the alternate aerodrome; runway technical characteristics; meteorological conditions on alternate aerodromes; the approach lighting system; available approach system; available navigation aids; aircraft performance characteristics; connection communication (radio); air traffic intensity, and commercial point) and subjective factors (pilot, ATCO, flight dispatcher) is alternative aerodrome is Boryspil *(A_4)*.

Table 8. The CDM matrix for all operators (Wald criterion).

Alternate aerodromes	Pilot	ATCO	Flight dispatcher	CDM
	O_1	*O_2*	*O_3*	Wald criterion
Lviv (A_1)	1	2	3	1
Kharkiv (A_2)	3	2	5	2
Dnipro (A_3)	3	2	5	2
Boryspil (A_4)	5	3	7	3

The optimal CDM if this flight is regular (Laplace criterion) is presented in Table 9 – is Boryspil *(A_4)*.

Table 9. The CDM matrix for all operators (Laplace criterion).

Alternate aerodromes	Pilot	ATCO	Flight dispatcher	CDM
	O_1	*O_2*	*O_3*	Laplace criterion
Lviv (A_1)	6.5	6.9	6.8	6.5
Kharkiv (A_2)	6.8	6.9	7.7	6.8
Dnipro (A_3)	6.0	6.5	6.5	6.0
Boryspil (A_4)	8.6	8.1	8.8	8.1

The optimal CDM in different approaches using optimism-pessimism coefficient $\beta = 0.5$ (Hurwicz criterion) is presented in Table 10 – is Boryspil (A_4). The consistency of decisions increases with an increase in the coefficient of optimism, with a decrease of the coefficient in the direction of pessimism, the mismatch increases.

Table 10. The CDM matrix for all operators (Hurwicz criterion).

Alternate aerodromes	Pilot	ATCO	Flight dispatcher	CDM
	O_1	*O_2*	*O_3*	Hurwicz criterion
Lviv (A_1)	8.2	6.0	6.0	6.0
Kharkiv (A_2)	9.3	5.5	7.5	5.5
Dnipro (A_3)	7.5	5.5	6.5	5.5
Boryspil (A_4)	9.5	6.5	8.5	6.5

The consistency of decisions using the Savage criterion (the recalculation after a flight), is determined for loss initial matrix (Table 11).

Table 11. The CDM matrix for all operators (Savage criterion – recalculation).

Alternate aerodromes	Pilot	ATCO	Flight dispatcher	CDM
	O_1	O_2	O_3	Savage criterion
Lviv (A_1)	8	8	6	3
Kharkiv (A_2)	7	7	4	2
Dnipro (A_3)	5	7	3	0
Boryspil (A_4)	5	7	3	0

The loss matrix is presented in Table 12. It shows risks if operators do not choose the optimal collective solution. The minimal risks are selected, which are then minimized.

Table 12. The loss CDM matrix for all operators (Savage criterion).

Alternate aerodromes	Pilot	ATCO	Flight dispatcher	Max loss
	O_1	O_2	O_3	Savage criterion
Lviv (A_1)	3	1	3	3
Kharkiv (A_2)	2	0	1	2
Dnipro (A_3)	0	0	0	0
Boryspil (A_4)	0	0	0	0

The optimal landing aerodrome, determined by objective and subjective factors, is alternative aerodrome Boryspil (A_4) as in Wald, Hurwitz, Savage, and Laplace criterion. The calculations showed a balance between safety and cost of the flight using Wald criterion (maximum safety) and Savage criterion (minimum loss).

4 Results

The algorithm of CDM by different aviation operators during the selection of the optimal solution in an emergency is developed. The example of choosing the optimal landing aerodrome in flight emergency "Failure of one engine on a twin-engine aircraft" using the methods of decision-making under uncertainty is presented.

The optimal landing aerodrome during the approach on the route "Lviv – Kharkiv" in flight emergency "Failure of one engine on a twin-engine aircraft" determined by objective factors (fuel reserve on board; remoteness of the alternate aerodrome; runway technical characteristics; meteorological conditions on alternate aerodromes; the approach lighting system; available approach system; available navigation aids; aircraft performance characteristics; connection communication (radio); air traffic intensity, and commercial point) and subjective factors (pilot, ATCO, flight dispatcher) is: by Wald criterion (if this flight is performed for the first time) – Boryspil (A_4); by Laplace criterion (if this flight is regular) – Boryspil (A_4); by the Hurwitz criterion (using optimism-pessimism coefficient $\beta = 0.5$) – Boryspil (A_4); according to the Savage criterion (the recalculation after the flight) – Boryspil (A_4). The calculations showed a balance between safety and cost using Wald criterion (maximum safety) and Savage criterion (minimum loss.)

5 Conclusion

Collaborative decision-making is a process of presenting individual and collaborative information by various interacting participants, such as pilots, flight dispatchers, and ATCOs in professional solutions. The effective use of CDM is 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 with partners at an acceptable level of efficiency. This is achieved by the completeness and accuracy of the available information, and by the well-coordinated interaction between aviation specialists, their clear and correct understanding of job duties, and their roles in the process of completing a common task. The reliability of the CDM process in uncertain situations should be provided by using different decision-making models and performance of dual assessment risky. After analyzing the situation, synthesis (aggregation) of decision-making individual models and the determination of the optimal CDM is necessary.

The direction of further research is working out decision-making models for all CDM participants within the Airport CDM (A-CDM) concept that can unite the interests of partners (airport operators, aircraft operators, ground handling agents, and air traffic services) in joint work, to create the basis for effective decision-making through more accurate and timely information that provides all partners at the airport a single operational picture of air traffic.

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