Collaborative Decision-Making Models in Flight Emergency "Landing Gear Failure on Takeoff"

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Abstract

Previous FAA incident reports show that in the USA retractable landing gear accidents account for more than 50% of all accidents involving piston retracts, often as many as 6-7 per week. Timely, correction and coordinated collaborative actions of aviation specialists in flight emergencies for prevention the catastrophic situation development is the relevant task. The block diagram of the collaborative decision-making algorithm in an emergency, managing the development of a situation using the integration of non-stochastic, stochastic, and deterministic decision-making models is given. The diagrams of cause-and-effect relationships for the emergency "Landing gear failure on takeoff" in the form of semantic models are presented. A flowchart of the algorithm of the pilot's actions in the case of landing gear failure is designed. The non-stochastic, stochastic, and deterministic collaborative decision-making models by the operators of the Air Navigation System in emergency "Landing gear failure on takeoff" under certainty, risk, and uncertainty conditions are developed. The non-stochastic models are built with the help of a decision matrix based on the Wald, Laplace, and Hurwitz criteria; stochastic models are built with the help of a decision tree based on the expected value criterion; deterministic models are built with the help of network planning based on the critical way calculated. The worked-out models can be used in the Intelligent Decision Support System to improve the efficiency of the joint actions of aviation personnel.

Keywords 1

Cause-and-effect relationships, certainty, decision matrix, decision tree, event tree, flowchart, network graph, risk, uncertainty

1. Introduction

Airbus Global Market Forecast [1] foresees a doubling of global air traffic over the forthcoming 15 years. This significant increase in aviation activity means that cooperation is needed to strengthen flight safety efforts to reduce accident rates.

Over the past 20 years, the accident rate in the aviation industry has decreased approximately eight times for catastrophes and approximately three times for all aviation accidents. During the same period, traffic increased by approximately 150%. This demonstrates that investments in safety are paying off, safety is being improved and accidents are largely being prevented.

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However, the rate of fleet growth is enormous, with traffic doubling every 15 years and the aviation industry delivering around 2 000 new aircraft per year. A commensurate rising in the number of professional aviation personnel, including crewmembers, air traffic controllers, engineers, flight attendants, etc., must provide this growth. Therefore, if the accident rate remains the same, the increase in accident risk in the aviation industry is numerically directly proportional to this rise in activity. That is, a greater number of flights will mean more accidents, so it is necessary to work continuously on reducing the level of accidents.

Figure 1 shows the total number of fatalities and fatal accidents during 2012-2021 with jet and turboprop aircraft [2]. It can be seen that the biggest peak of fatalities and fatal accidents occurs in 2014 and 2018 years.

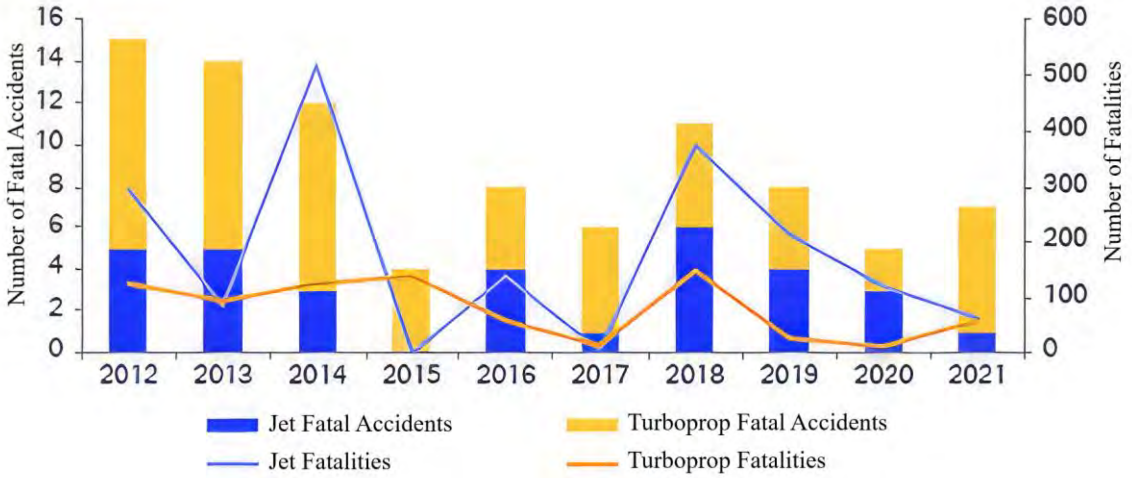

Figure 1: Number of fatalities and fatal accidents during 2012-2021 [2]

Figure 2 presents the relationship between the accident category frequency and the fatality risk, measured as the number of full-loss equivalents per one million flights, within 2017-2021 [2]. It can be seen that the most dangerous accident is the loss of control of the aircraft, and the most frequent – is runway/taxiway excursion.

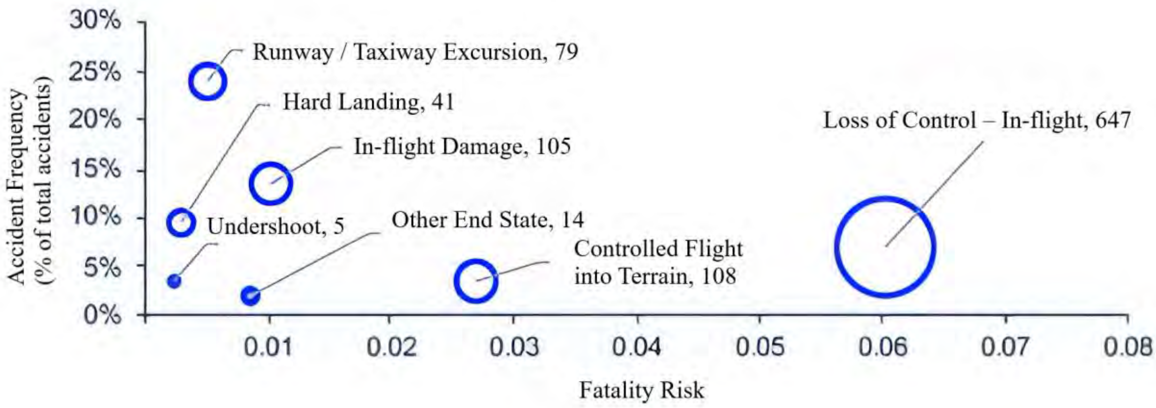

Figure 2: Relationship between the accident category frequency and the fatality risk in 2017-2021 [2]

According to the Boeing study [3], 11% of aircraft accidents occur during flight at cruising altitude, 3% during descent, 22% during final approach for landing, and 28% – during landing. At the beginning of the flight, according to statistics, there are fewer problems: 17% of aircraft crashes occur during takeoff and initial climb, 11% – during the climb (with flaps up), and another 8% – on the ground during towing, taxiing, loading/unloading/overloading, etc. (Figure 3).

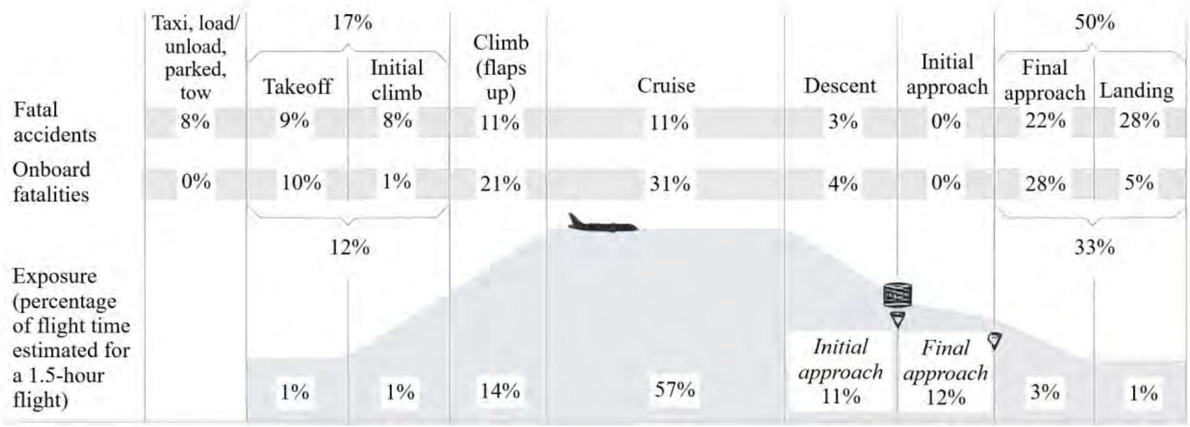

Figure 3: Percentage of fatal accidents and onboard fatalities during 2012-2021 [3]

Today, around 80% of aircraft accidents are caused by human error and 20% – by technical malfunctions [4]. About 70% of aviation accidents causes due to the human factor are the pilot errors: crew violations of standard piloting procedures; fatigue, pilot health problems; crew errors in difficult weather conditions; errors in conditions of conflicting instrument indicators; disorientation when flying in an unfamiliar area; disruption of the interaction between by crewmembers; insufficient qualification for this type of aircraft. The other 30% are related to the errors of the personnel of various ground services: air traffic controller (ATCO) errors; improper operation, repair, and maintenance of aircraft, etc.

Therefore, decreasing the human factor's effect on the causality of aviation accidents is a relevant problem.

2. A state-of-the-art literature review

To enlarge the level of flight safety, practical and scientific research on the problem of interaction of aviation specialists is increasingly being realized. Collective work studies in aviation were first initiated by NASA (National Aeronautics and Space Administration of USA) based on improving the interaction between the flight crewmembers. Later this approach was further developed and became one of the most successful tools for preventing human errors [5; 6].

Following the advanced requirements of ICAO, for the effectiveness of solutions, it is relevant to use the collaborative decision-making (CDM) models [7–9].

Today, within the framework of the Airport Collaborative Decision-Making (A-CDM) concept, specific solutions are being implemented that can join the interests of participants (airport, aircraft, air traffic, ground services operators, etc.) in coordinated work. A-CDM concept is based on the principles of transparency and information sharing; it is aimed at air traffic enhancement and airport capacity control by delay reduction, the predictability of situation improvement, and the use of resources optimization [7–9]. Moreover, the required daily efficiency of operations may be achieved through the mechanism of Flight and Flow Information for a Collaborative Environment (FF-ICE) [10]. FF-ICE concept defines requirements for air navigation information for flight planning, air traffic, flow, and trajectory management; it is the basis of the performance-based Air Navigation System (ANS) [10].

In [11] the issue of synchronizing the technological procedures of the Pilot Flying and Pilot Monitoring during the cross-monitoring in the flight emergency (FE) is considered. In [11–14] the research of deterministic, stochastic, non-stochastic, and neural-network modeling, optimization, and intellectualization of CDM by the commands of ANS operators (pilots, air traffic controllers, UAV operators, flight dispatchers, engineers, etc.) in various FE.

Nevertheless, the problems of operational interaction between ANS operators in FE [15; 16] and low formalization of the CDM process, which does not allow applying the performance-based approach for its improvement [17], are still undecided.

The purposes of this work are:

- To consider the peculiarities of the functioning of ANS as a sociotechnical system
- To design the CDM algorithm by the ANS operators in FE, managing the development of the situation
- To build collaborative decision-making models by the ANS operators in the case of FE (for example *landing gear failure on takeoff*), which will be used in the Intelligent Decision Support System (IDSS) to improve the efficiency of the collaborative actions of aviation personnel

3. Peculiarities of Functioning of Sociotechnical Air Navigation System

According to the principles of functioning, ANS refers to sociotechnical systems [11], within the framework of which there is close cooperation between human and technological components. A distinctive feature of sociotechnical systems is the presence of dangerous activities, as well as the use of high-tech technologies in production. Ensuring flight safety in ANS with the help of high-level technological processes depends primarily on the reliability of human-operator (H-O), which includes his ability to make timely and correct decisions under the influence of professional (knowledge, skills, skills, experience) and non-professional (individual-psychological, psychophysiological, and social-psychological) factors [11].

Let's consider ANS as a control system, where the main link is H-O, which perceives information, processes it, makes decisions, and influences control bodies or transfers information. The subsystems of the ANS are the control object (CO) – the aircraft (ACFT), the control subject (CS) – the pilot of the aircraft, and the external environment (including the ground services personnel), which interact with each other and are themselves complex systems. ANS is an aviation complex purposeful sociotechnical highly organized stochastic system with a hierarchical control structure, the distinguishing features of which can be considered the presence of the following components [11]:

- The goal of the operation is to ensure flight safety by maintaining at the required level or improving the performance characteristics of CO – ACFT, regularity, and efficiency of air transportation
- H-O, which acts as a control link that evaluates the compliance of the system's work results with the set goal and decision-making regarding the need for control actions
- Subsystems for collecting, transmitting, and processing information about the state of the CO, H-O, the external environment, the nature of control actions and their results, the nature of the influence of the external environment on H-O and vice versa
- Control bodies
- Decision-making support subsystems in the form of Intelligent Decision Support System (IDSS), the presence of which is an indispensable property of aviation sociotechnical systems of the new generation due to a complex of uncertainties of various natures and types (informational, situational, strategic, structural, parametric, statistical, methodical, combinatorial uncertainties, etc.)

Considering the mentioned distinctive features of ANS as an aviation sociotechnical system has the following structure (Figure 4):

- "Aircraft" subsystem
- "Pilot of the aircraft" subsystem
- "External environment" subsystem
- "Decision support" subsystem
- "Flight situation" subsystem

The work of aviation personnel is a type of operator activity related to receiving and processing information, making responsible decisions under time constraints. If ordinary H-O deals with technical devices and their operation parameters, and addresses control actions to them, then the ATCO controls the ANS through its operators – the pilots of the ACFT and the recipients of his commands are people. The pilot of the ACFT in his professional activity communicates with other operators of the ANS through the ATCO. That is, the principle of a dual operator "pilot – ATCO" operates in the ANS, the pilot and ATCO interact equally with each other (Figure 4) [11].

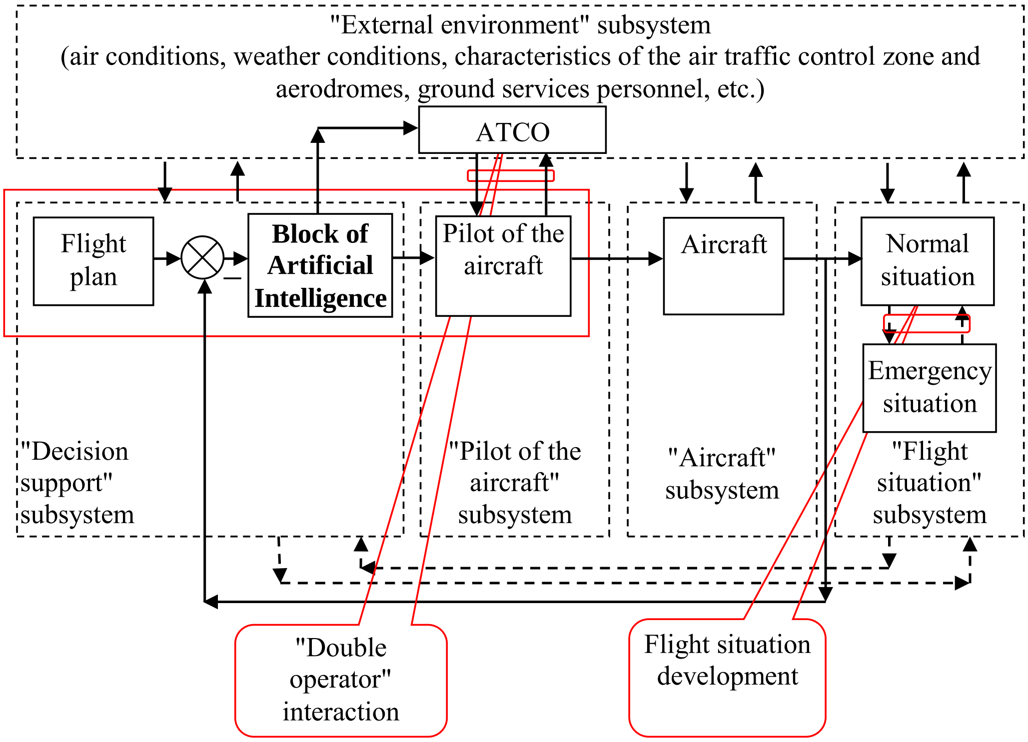

Figure 4: Subsystems in ANS [11]

A feature of ANS is that H-O makes decisions in conditions of environmental uncertainty, with incompletely set goals, and conflicting performance indicators for determining a multi-criteria control goal. Depending on the stage of functioning of the ANS, like any other system, it has CO – ACFT, flows of ACFT, organizational structure and control elements (CE) – decision-makers, technical means, IDSS, etc. [11].

The goal of control is to produce the H-O (CE) (pilot of the aircraft) such optimal actions Y_{opt} to ensure the execution of the aircraft (CO) specified flight plan Y_s on the condition of receiving timely, competent, and justified recommendations of the ATCO and other ANS operators Y_r in case of various disturbing actions Y_d, that is, changes in the dynamic air situation or flight situation (normal, complicated, difficult, emergency, catastrophic), using the feedback channel Y_{fb}, and reducing the inconsistency $\Delta Y = Y_a - Y_s$ to a minimum. Production of effective solutions is possible if the parameters of the deviations of the actual values of the CO from the specified flight plan are known (Figure 5).

During the flight, the pilot and the ATCO are in constant interaction, during which there is the coordination of actions, planning of compatible/joint activities, distribution of functions, etc. In addition to the pilot and the ATCO other ANS operators are also involved to assist the pilot in the FE: the flight dispatcher – when the flight plan is changed; the technical staff – in the event of a malfunction of the ACFT; emergency and rescue services specialists – in the event of an FE; ground services personnel – in the event of a flight delay; units of the state safety – in the event of a terrorist threat; telemedical personnel – in the event of deterioration of the health of passengers or crewmembers, etc. (Figure 6).

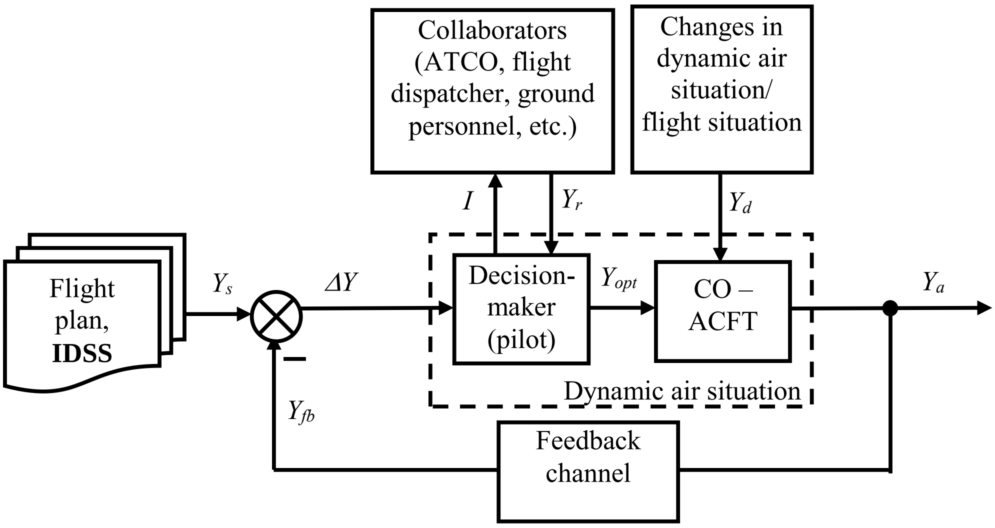

Figure 5: Functional diagram of ANS: Y_s – specified flight plan; Y_{opt} – optimal actions of H-O; I – information about changes in the dynamic air situation or flight situation; Y_r – recommendations of H-O; Y_a – actual actions of H-O; Y_d – disruptive actions; Y_{fb} – feedback channel

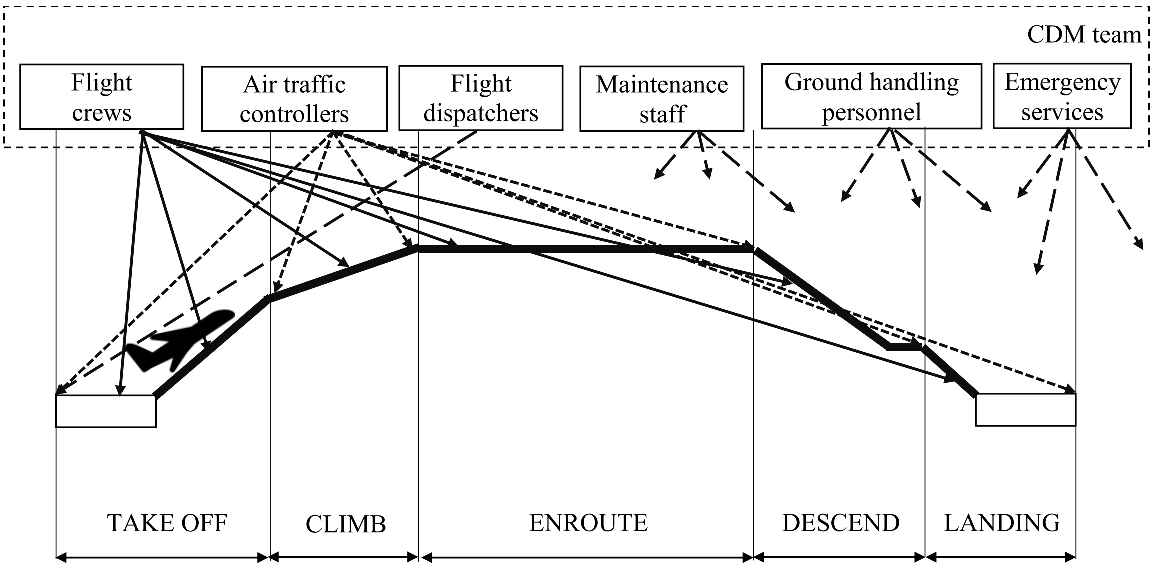

Figure 6: Interaction of ANS operators

At the same time, the synergism of a group of aviation specialists can have both a positive effect – countering the development of FE, and a negative effect – the development of the flight situation in the direction of deterioration. Since the main common goal is to accomplish the flight plan, in the CDM process operators analyze the current situation based on a common set of factors, albeit from different points of view. However, the pilot of the aircraft makes the final decision in flight.

Each of the ANS operators plays an important role at different stages because a safe flight begins not only with the departure of the aircraft. Aviation specialists strictly follow the manuals and regulatory documents approved in the field of their professional activity. Very often, the complexity, content, and features of the documents that regulate the activities of each aviation specialist are different, which does not allow for the development of a general algorithm of actions for all aviation personnel for specific conditions, especially in FE, when there is uncertainty, lack of information and time for decision-making. At the same time, there is a conflict between the decisions and actions of the personnel involved, who jointly make decisions.

4. General Algorithm of Collaborative Decision-Making by the Operators in the Flight Emergency

The general algorithm of CDM by the ANS operators in FE is presented in Figure 7.

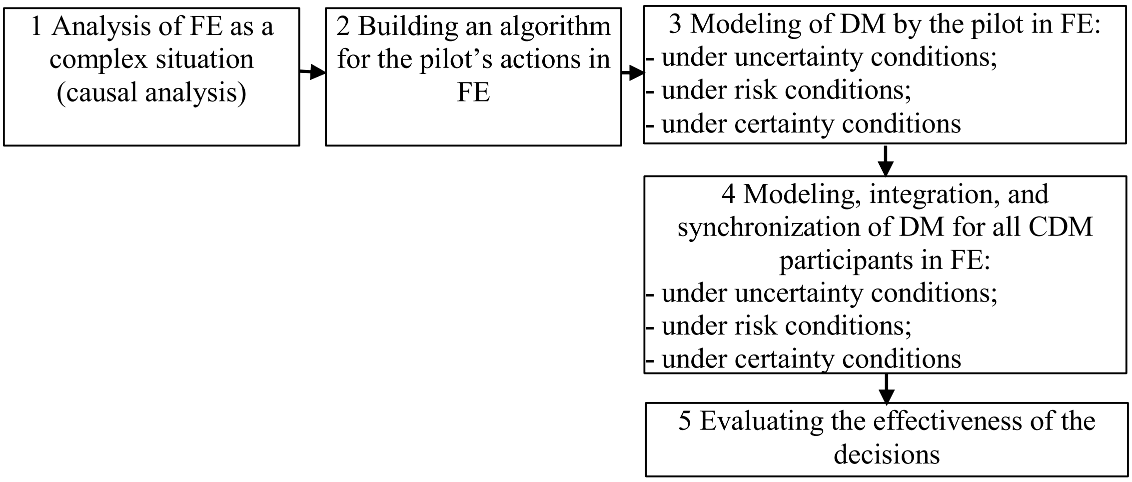

Figure 7: The general algorithm of CDM by the ANS operators in FE

Components of the CDM algorithm by the ANS operators in FE are:

1. **Characteristics of the flight situation {*G*}**:
- G_1 – normal situation
- G_2 – complicated situation
- G_3 – complex situation
- G_4 – emergency
- G_5 – catastrophic situation

2. **Factors {λ}** influencing decision-making for each operator. These factors may be original or identical and objective. For example, describing general factors:
- Fuel stock on board (always monitored; fuel systems differ in ACFT due to their relative size and complexity. Each tank may be equipped with internal fuel pumps and have appropriate valves and piping to power the engines, supply fuel, isolate individual tanks, and, in some cases, drain fuel or optimize the ACFT gravity center)
- The remoteness of the emergency landing aerodrome
- Meteorological conditions (at departure, destination, alternate aerodromes, enroute, etc.)
- ACFT capabilities (available equipment on board, features of the Minimum Equipment List (MEL), existing operational limitations)
- Aerodrome capabilities (approach systems available, technical characteristics of runways and taxiways, lighting system, available navigation aids, available navigation aids, restrictions on service hours, aerodrome category, firefighting, search and rescue category, emergency service)
- Crew capacity (crew operational minimums, crew duty time)
- Air situation (tension of the air traffic control (ATC) sector, radio frequency overload, presence of radio communication, the intensity of air traffic enroute and at landing aerodrome, etc.)
- Commercial point (airport fees, distance from the destination airport, passenger and cargo services, availability of contracts with handlers, availability of customs, border, and migration control services, etc.)
- Fuel supply on board, etc.

3. **Alternative solutions {*A*}** – the list of alternate aerodromes:
- Alternative aerodrome – an aerodrome of departure and its characteristics
- Alternative aerodrome – an aerodrome of destination and its characteristics

- Other alternative aerodromes and its characteristics according to the calculated route

4. **Operators involved in decision-making (CDM team) {*O*}.** Many specialists are engaged in ensuring the safety of aircraft flights during flight planning, flight execution, and implementation of operational processes, especially when the flight is complicated. These are flight crews, ATCO, flight dispatchers, maintenance staff, ground handling personnel, and emergency services. Each of them plays an important role at different stages because a safe flight begins not only from the moment the aircraft takes off. They strictly follow the instructions and regulatory documents approved in the field of their professional activity.
5. **The possible consequences {*U*}** are defined using the Expert Judgment Method (EJM); Fuzzy Logic; Artificial Intelligence block of IDSS according to data from the regulatory documentation and opinions of O_l operators (pilot, ATCO, and other aviation specialists).
6. Time of CDM ***T*:**

- T_{min} – minimum time
- T_{max} – maximum time
- T_{cr} – critical time

Figure 8 is given the block diagram of the CDM algorithm in an emergency, managing the development of the situation using the integration of decision-making models: non-stochastic, stochastic, and deterministic models.

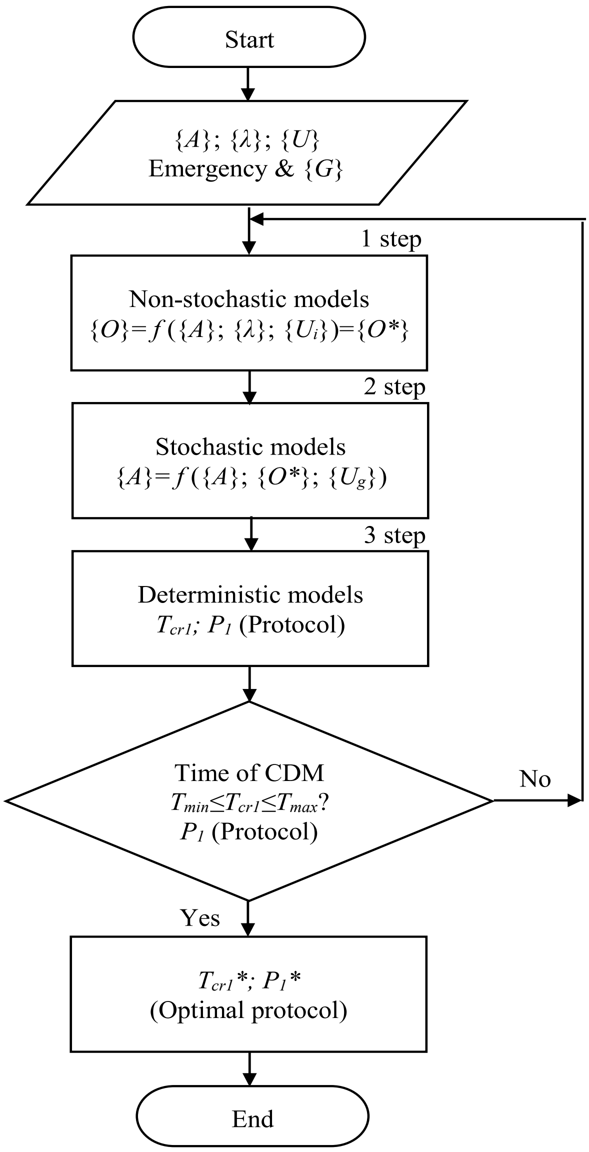

Figure 8: The block diagram of the CDM algorithm in emergency

5. The Diagrams of Cause-and-Effect for the Emergency “Landing Gear Failure on Takeoff”

Landing gear accidents are common in aircraft with the retractable landing gear. Previous FAA incident reports show that in the USA they account for more than 50% of all accidents involving piston retracts, often as many as 6-7 per week [18]. Because they rarely cause injuries or damages that are reportable to the NTSB, they uncommonly show up in the statistics used to calculate overall aviation safety.

There may be reasons *for landing gear failure on takeoff* [19; 20]:

- Mechanical damage
- Failure of the hydraulic system
- Failure of the electrical system
- Fire
- Failure of the indicators
- Errors of maintenance staff
- Errors of ground services personnel when towing
- Errors of the pilot
- Intentional actions of criminals
- Entry of a foreign object
- Obstacles on the runway
- Irregularities on the runway surface
- Precipitation
- Strong wind, etc.

The *landing gear failure on takeoff* leads to a violation of the aircraft aerodynamics [19; 20], which, in turn, causes a decrease in horizontal flight speed and vertical rate of climb, a decrease in cruising altitude, and an increase in fuel burn – approximately twice compared to normal speed. Therefore, it is extremely undesirable to continue the flight to the destination aerodrome with the landing gear retracted. Better to direct the aircraft to the holding area at the departure aerodrome or follow to the nearest alternate aerodrome. Before landing, the pilot must reduce the weight of the aircraft to the maximum landing weight (MLW) by burning fuel according to the scheme in the holding area or by quickly dumping it in specially designated areas at set altitudes (above 5 000-6 000 feet).

Diagrams of cause-and-effect relationships for the FE "*Landing gear failure on takeoff*" in the form of semantic models of the P-type and S-type event trees, which are branched, connected, and finite graphs that do not have cycles or loops, have been developed (Figures 9–10).

A good example of a situation when there is a problem with the *landing gear on takeoff* and the pilot decides to return the aircraft to the departure aerodrome and perform the fuel dump procedure occurred with a Wizz Air Airbus A320-200, registration HA-LPU, which was performing flight W6-1023 from Katowice (Poland) to Zaporizhzhia (Ukraine) on 06/15/2021 [21]. The pilot was taking off from Katowice airport and on the instrument panel, he noticed that the doors responsible for closing the nose landing gear were not closed. It happened at an altitude of 5 000 feet. The pilot decided to dump fuel and land at the departure airport. After 75 minutes from the start of the flight, the aircraft successfully landed at Katowice Airport.

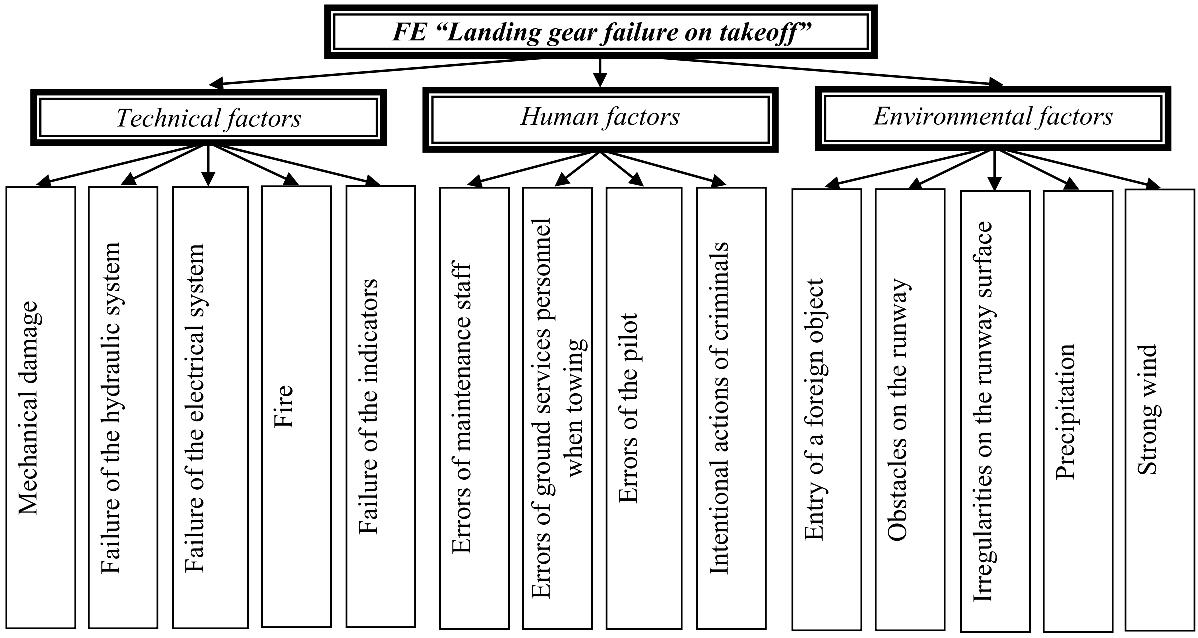

Figure 9: P-type event tree for the FE "Landing gear failure on takeoff"

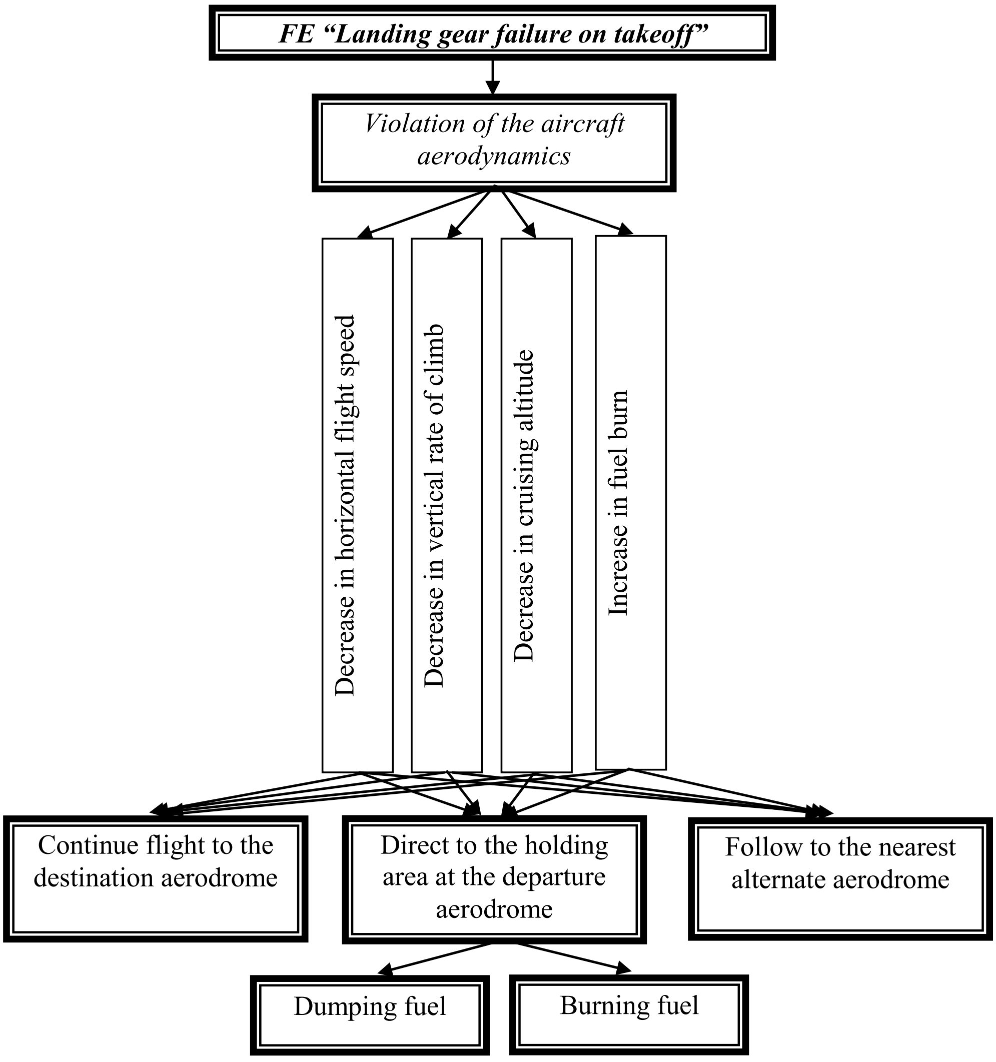

Figure 10: S-type event tree for the FE "Landing gear failure on takeoff"

Let's consider another example when the pilot decided to land at an alternate aerodrome. It was a THY Turkish Airlines Airbus A330-300, registration TC-JNI, which was performing flight TK-45 from Cape Town (South Africa) to Istanbul (Turkey) on 01/02/2020 [22]. The pilot received a fault message from the instrument panel about the left main landing gear gaining FL080 after takeoff. After contacting the ATCO, the pilot decided to dump the fuel and make a landing at the alternate Johannesburg airport, because this airport had better maintenance services. The aircraft landed at the alternative airport. The aircraft taxied to the apron with emergency services in a trail.

To describe the third example when the aircraft lands at the destination aerodrome, let's take the situation that occurred on 10/29/2022 with the aircraft a LATAM Cargo Boeing 767-300 freighter, registration N532LA, which was performing flight L7-2516 from Zaragoza (Spain) to New York JFK (USA) with four crew on board [23]. The aircraft was making the final approach to the destination airport when the pilot transmitted the message to the ATCO about a problem with the landing gear. The pilot decided to go around. At an altitude of 2 000 feet, the pilot additionally reported the impossibility of extending of the right landing gear and declared an emergency. The ATC service offered the longest runway for landing. The aircraft landed but rolled off the runway.

6. Algorithm of Decision-Making by the Pilot in Emergency "Landing Gear Failure on Takeoff"

Emergency flight must only be undertaken in accordance with the procedures and limitations in the Quick Reference Handbook (QRH), Aircraft Flight Manual (AFM), or Operations Manual.

The decision task lies in the necessity to execute an enroute diversion due to lack of fuel.

If a crew has declared gear problems, the main input factors that we consider can be divided into four groups:

1) Flight considerations (aircraft structural limitations):
- Maximum gear down speed V_{maxgd}
- Maximum gear down speed for climbing KIAS (knots of indicated speed) $KIAS_{maxgd}$
- Cruise altitude capability with gears down CAC_{gd}
- Fuel consumption with gears down FC_{gd}
- Actual weight (AW) and maximum landing weight (MLW)

2) Crew considerations:
- Noise
- Increased vibration
- Crew fatigue

3) Aerodrome considerations:
- Runway characteristics
- Length
- Width (to prevent lateral runway excursion)
- Rescue and fire services (for aircraft evacuation)

4) ATC issues:
- Transferring to another frequency
- Have direct contact with the aircraft operator's technical representative (if possible)
- Maintain close coordination with ground emergency units
- Provide a wider range of information to the crew on request
- Use the proper ICAO phraseology, such as "The landing gear appears down"
- Consider the impact of reduced speed and expected arrival time at the potentially alternate aerodrome

The Flight Management System (FMS) that is used by the majority of commercial aircraft has several functions and flight information. However, under circumstances of abnormal aircraft conditions, the fuel calculations will not be correct. Most FMS will not give accurate fuel predictions in these situations.

Failure to realize the incorrect information may lead to false assumptions about the further route of wrong decisions that cause accidents and incidents on board.

By finite flight conditions, we perform a creation of step-by-step decision-making model that includes various aspects under pressure.

The following model will provide a solution starting from the time of the condition's detection and ending with a correct decision based on a range of variables that impact a finite flight.

Assume that the FMS can contain the following model's data.

Therefore, the FMS data is up to date and correct for the finite aircraft. In that way, the information on the selected considerations and rates integrated into FMS will be used to compare the current amount of fuel, remaining distance, flight level limitations, and other aspects that impact on the current flight in an unpredictable situation with landing gears down.

An attempt to reach a closer aerodrome is made.

According to the QRH of the Boeing 737-400, Boeing 747-800, Boeing 747-400, and IL-76T it is not mandatory to return to the departure aerodrome.

Following the B-737 QRH [24], a flowchart of the algorithm of the crew actions in the case of *landing gear failure on takeoff* is built (Figure 11).

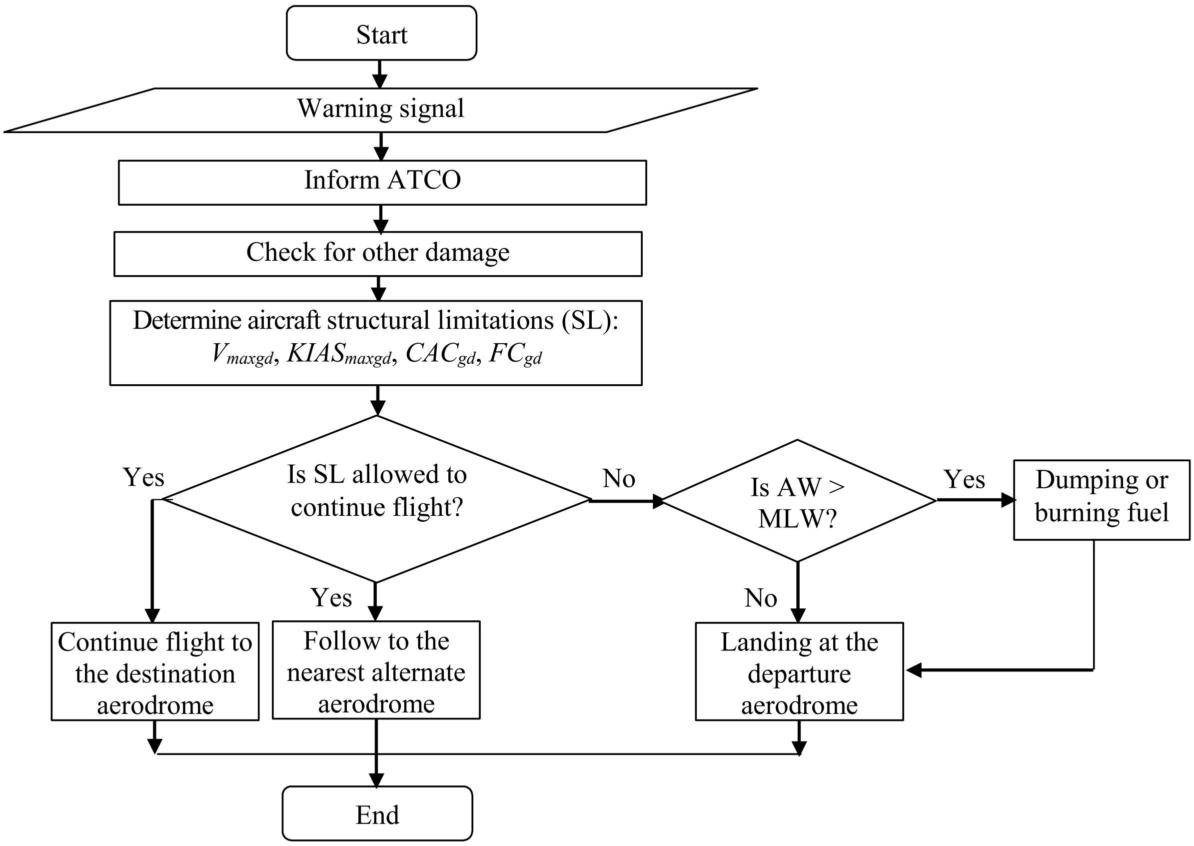

Figure 11: The flowchart of the algorithm of the pilot actions in the case of landing gear failure on takeoff

Examples of crew actions in the case of *landing gear failure on takeoff* are given in SKYbrary [25].

7. Non-Stochastic Collaborative Decision-Making Models by the Operators in Emergency "Landing Gear Failure on Takeoff"

The sequence of CDM by the ANS operators in FE "*Landing gear failure on takeoff*" is:

1. Selection of main factors affecting DM in FE "*Landing Gear Failure on Takeoff*" $\{\lambda\}$:
- λ_1 – distance to the landing aerodrome, time in flight
- λ_2 – technical characteristics of the aircraft, amount of fuel
- λ_3 – technical characteristics of the landing aerodrome
- λ_4 – ground (emergency) services
2. Alternative decisions $\{A\}$ and analysis of alternative decisions:
- A_1 – return to the departure aerodrome
- A_2 – continuation the flight to the destination aerodrome
- A_3 – landing at the alternate aerodrome
3. Operators involved in decision-making $\{O\}$ (CDM team):
- O_1 – pilot of the aircraft
- O_2 – air traffic controller
- O_3 – ground (emergency) services operator
- O_4 – Artificial Intelligence block (IDSS is available)
4. The possible consequences $\{U\}$ (Table 1).

Table 1
The matrix of DM in FE "Landing gear failure on takeoff"

Alternative decisions		Factors influencing CDM in FE				
		λ_1	λ_2	λ_3	λ_4	Solutions by DM criteria, *D*
A_1	Departure aerodrome	u_{11}	u_{12}	u_{13}	u_{14}	D_1
A_2	Destination aerodrome	u_{21}	u_{22}	u_{23}	u_{24}	D_2
A_3	Alternate aerodrome	u_{31}	u_{32}	u_{33}	u_{34}	D_3

The schematic presentation of the location of departure, destination, and alternate aerodromes is in Figure 12.

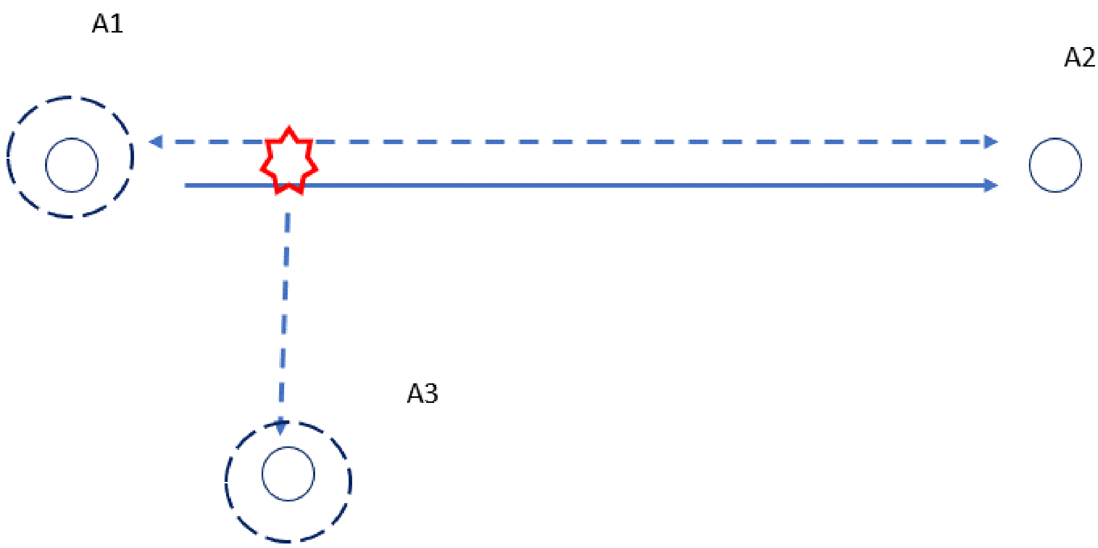

Figure 12: Schematic presentation of the location of departure, destination, and alternate aerodromes

The matrix of individual DM for one of the ANS operators – pilot – in FE "Landing gear failure on takeoff" is in Table 2.

Table 2
The matrix of individual DM for the pilot (O_1) in FE "Landing gear failure on takeoff"

Alternative decisions		Factors influencing DM in FE						
		λ_1	λ_2	λ_3	λ_4	Solution by Wald criterion, *W*	Solution by Laplace criterion, *L*	Solution by Hurwitz criterion, *H*, α=0.5
A_1	Departure aerodrome	0.80	0.40	0.80	0.80	0.40	0.70	0.60
A_2	Destination aerodrome	0.30	0.70	0.80	0.80	0.30	0.65	0.55
A_3	Alternate aerodrome	0.50	0.50	0.70	0.80	0.50	0.63	0.65

The optimal decision for the pilot (O_1) in FE "*Landing gear failure on takeoff*" according to the Wald and Hurwitz criteria is landing at the alternate aerodrome, by the Laplace criterion – is the return to the departure aerodrome.

DM for all process participants (pilots, ATCO, flight dispatchers, maintenance staff, ground personnel, etc.) fills in individual matrices.

The results of individual matrices of process participants are factors in the collective matrix (Table 3), that allows for finding the optimal group solution.

Table 3
The matrix of collective DM for all participants

Alternative decisions		Factors influencing DM in FE						
		O^*_1	O^*_2	…	O^*_l	…	O^*_L	Solutions by CDM criteria, *D*
A_1	Departure aerodrome	u_{11}	u_{12}		u_{1l}	…	u_{1L}	D_1
A_2	Destination aerodrome	u_{21}	u_{22}		u_{2l}	…	u_{2L}	D_2
A_3	Alternate aerodrome	u_{31}	u_{32}		u_{3l}	…	u_{3L}	D_3

In the case of data accumulation, Artificial Intelligence data is obtained with the help of an Artificial Neural Network. IDSS (Figure 5) uses a combination of algebraic methods, decision-making models, and Artificial Intelligence. The following calculations were obtained for ATCO (decision-making in risk and certainty).

8. Stochastic Collaborative Decision-Making Models by the Operators in Emergency "Landing Gear Failure on Takeoff"

Decision-making by the ANS operators in FE "*Landing gear failure on takeoff*" is included:

1. Next alternatives:

- A_1 – following to the nearest alternate aerodrome
- A_2 – landing at the departure aerodrome
- A_3 – dumping fuel

- A_4 – without dumping fuel
- A_5 – direction to holding zone with burning fuel
- A_6 – immediately emergency landing

2. Next stages of the decision:

[1] – choosing between an alternate or departure aerodrome
[4] – choosing between dumping or not dumping fuel
[7] – choosing between the direction to the holding zone with burning fuel or immediate emergency landing

The probabilities p_j for each outcome u_{ij} were identified: p_1=0.4 – normal landing; p_2=0.6 – complicated landing.

The optimal decision is based on the expected value criterion (1) and would that be corresponding to the condition (2):

$$R_m = F_m(t_m; \{A, \alpha, p, u\}) = t_m(\sum_{k=1}^{n} p_k u_k + \alpha_k); \quad (1)$$

$$A_{opt} = \min\{R_m\}, \quad (2)$$

where $R_m < R_{m-1}$;
α_k – is an additional risk of FE development, in our example $\alpha_k = 0$;
t_m – is a time of the decision-making stage, in our example $t_m = 1$;
$A_{ij} = \sum_{j=1}^{m} p_j u_{ij}, i = \overline{1,n}; j = \overline{1,m}.$

The decision tree in the case of *landing gear failure on takeoff* is presented in Figure 13.

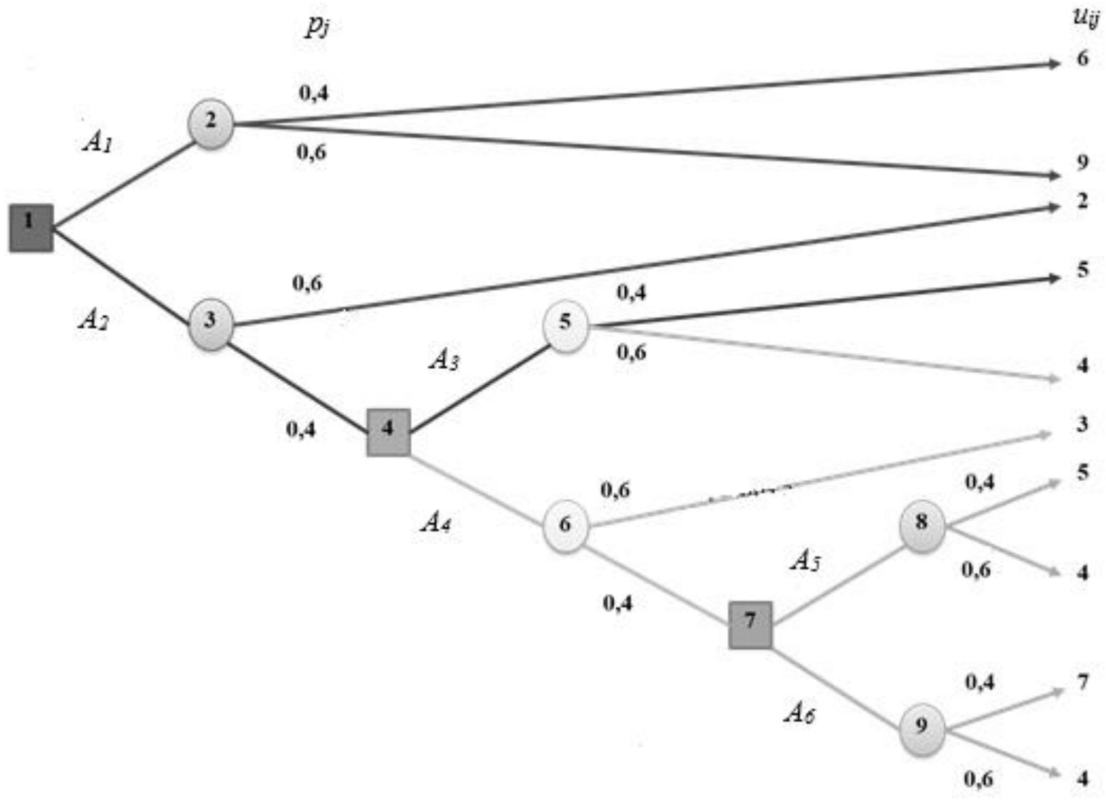

Figure 13: Decision tree of FE "Landing gear failure on takeoff"

Risks calculation for the decision tree of FE "*Landing gear failure on takeoff*", conventions units (c.u.):

$R_{78}=p_1*U_{81}+p_2*U_{82}$=0.4*5+0.6*4=2+2.4=4.4

$R_{79}=p_1*U_{91}+p_2*U_{92}=0.4*7+0.6*4=2.8+2.4=5.2$
$R_{78}<R_{79}$, so $A_5=R_{78}=4.4$

$R_{45}=p_1*U_{51}+p_2*U_{52}=0.4*5+0.6*4=2+2.4=4.4$
$R_{46}=A_{78}+p_1*U_{61}+p_2*U_{62}=4.4+0.4*4+0.6*3=4.4+2+1.6+1.8=7.8$
$R_{45}<R_{46}$, so $A_3=R_{45}=4.4$

$R_{12}=p_1*U_{21}+p_2*U_{22}=0.4*6+0.6*9=2.4+5.4=7.8$
$R_{13}=A_{46}+p_1*U_{31}+p_2*U_{32}=4.4+0.4*4+0.6*2=4.4+1.6+1.2=7.2$
$R_{12}>R_{13}$, so $A_2=R_{13}=7.2$

An optimal solution in the FE "*Landing gear failure on takeoff*" is landing at the departure aerodrome with dumping fuel, where $R_{min}=7.2$ c.u.

9. Deterministic Collaborative Decision-Making Models by the Operators in Emergency "Landing Gear Failure on Takeoff"

The technology of work performance by the ATCO in FE "*Landing gear failure on take-off*" following ASSIST principles (**A** – Acknowledge, **S** – Separate, **S** – Silence; **I** – Inform, **S** – Support, **T** – Time) is submitted in Table 4.

Table 4
The technology of work performance by the ATCO in FE "Landing gear failure on take-off"

Operations of ATCO, a_i,	Name, a_i	Previous operations, a_i,	Time, t_i, sec.
Receive a message from the crew about landing gear problems	a_1	-	9.6
Confirm the landing gear problem	a_2	a_1	9.4
Ask about the crew's intentions when the situation allows	a_3	a_1, a_2	19.8
Determine if the crew can retract the landing	a_4	a_3	15.4
Determine the number of people on board, determine the fuel on board and its amount in minutes	a_5	a_4	38.8
Separate the aircraft from other traffic	a_6	a_5	62.4
Set the silence mode if necessary	a_7	a_3	15.2
Inform airport emergency services and all interested parties by the established procedures	a_8	a_6	20.0
Support a flight with any information requested and deemed necessary (e.g. approach type, runway length, and aerodrome details)	a_8	a_3	27.0
Give the crew time to assess the situation	a_{10}	a_3	13.4

Based on the experts' opinion the deterministic model of work performance by the ATCO in the FE "Landing gear failure on takeoff" in the form of the network graph is designed (Figure 14).

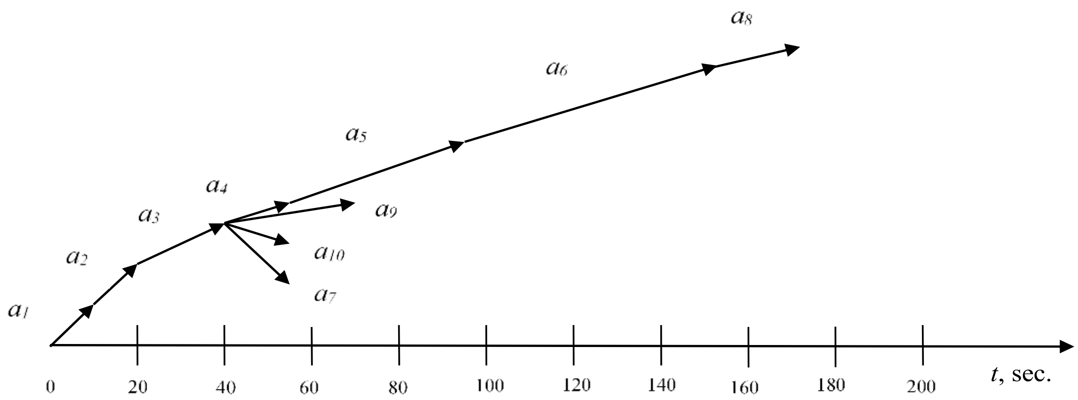

Figure 14: Network graph of work performance by the ATCO in FE "Landing gear failure on take-off"

The critical way for the ATCO is the operations a_1, a_2, a_3, a_4, a_5, a_6, a_8 located one after the other without time gaps and overlapping. The critical time t_{cr} of work by the ATCO in FE "Landing gear failure on takeoff" is 175.4 sec.

To solve the task of finding a compromise between the time of DM by the ANS operators under the influence of various factors in uncertainty conditions and the critical time of FE parry in certainty conditions it is proposed to use Artificial Neural Networks with Machine Learning and analyzing tools of Big Data. To control Artificial Intelligence solutions by the ANS operators it is necessary to introduce Hybrid Intelligence Systems that use both human and machine competence [26; 27].

10.Results

The block diagram of the CDM algorithm by the ANS operators in FE for managing the situation development based on the integration of non-stochastic, stochastic, and deterministic decision-making models is designed. Diagrams of cause-and-effect relationships in the form of semantic models of the P-type and S-type event trees, which are branched, connected, and finite graphs that do not have cycles or loops, are developed for the FE "*Landing gear failure on take-off*". A flowchart of the algorithm of the pilot actions in the case of *landing gear failure on takeoff* by the QRH B737 is built.

The main factors affecting DM in FE "*Landing gear failure on takeoff*" are determined: distance to the landing aerodrome, time in flight; technical characteristics of the aircraft, amount of fuel; technical characteristics of the landing aerodrome; ground (emergency) services. The optimal decision for the pilot in FE "*Landing gear failure on takeoff*" is defined: according to the Wald and Hurwitz criteria it is landing at the alternate aerodrome, by the Laplace criterion – it is the return to the departure aerodrome. The collective matrix allowed for finding the optimal group solution for all process participants (pilots, ATCO, flight dispatchers, maintenance staff, ground personnel, etc.). An example of risk calculation in FE "*Landing gear failure on take-off*" based on the expected value criterion with the help of the decision tree is given. An optimal solution is landing at the departure aerodrome with dumping fuel, where R_{min}=7.2 c.u. The technology and the network graph of work performance by the ATCO in FE "*Landing gear failure on take-off*" following ASSIST principles are submitted. The critical time t_{cr} of work by the ATCO in FE "*Landing gear failure on take-off*" is 175.4 sec.

11.Conclusion

The peculiarities of the functioning of ANS as a sociotechnical system are considered, the presence of IDSS has recognized as an indispensable property of aviation sociotechnical systems of the new generation due to a complex of uncertainties of various nature and types (informational, situational, strategic, structural, parametric, statistical, methodical, combinatorial uncertainties, etc.). Proved that each of the ANS operators plays an important role at different stages of flight and they are in constant interaction. The block diagram of the CDM algorithm by the ANS operators in FE, managing the development of the situation using the integration of non-stochastic, stochastic, and deterministic decision-making models is given.

Landing gear accidents are common in aircraft with the retractable landing gear. Previous FAA incident reports show that in the USA they account for more than 50% of all accidents involving piston retracts, often as many as 6-7 per week. Timely, correction and coordinated collaborative actions of aviation specialists in flight emergencies for prevention the catastrophic situation development is the relevant task.

The diagrams of cause-and-effect relationships in the case of landing gear failure on takeoff in the form of semantic models of the P-type and S-type event trees are presented. The flowchart of the algorithm of the pilot actions in the case of *landing gear failure on takeoff* following the QRH B737 is designed.

The non-stochastic, stochastic, and deterministic collaborative decision-making models by the operators of Air Navigation System in emergency "*Landing gear failure on takeoff*" under certainty, risk, and uncertainty conditions are developed. The non-stochastic models are built with the help of a decision matrix based on the Wald, Laplace, and Hurwitz criteria; stochastic models are built with the help of a decision tree based on the expected value criterion; deterministic models are built with the help of network planning based on the critical way calculated. The worked-out models can be used in the IDSS to improve the efficiency of the joint actions of aviation personnel.

The direction of further research is developing the method of intelligent collaborative-factor assessment of the consequences of CDM allows to predict risk by considering the common objective factors of the decision-making environment and the subjective advantages of ANS operators in conditions of incompleteness, uncertainty, and a large amount of data based on a multilayer recurrent Artificial Neural Network. In the future, to solve the task of finding a compromise between the time of DM by the ANS operators under the influence of various factors in uncertainty conditions and the critical time of FE parry in certainty conditions it is proposed to use Artificial Neural Networks with Machine Learning and analyzing tools of Big Data. To control Artificial Intelligence solutions by the ANS operators it is necessary to introduce Hybrid Intelligence Systems that use both human-operator (aircraft crew, UAV operator, ATCO, flight dispatcher, ground services operator, engineer, etc.) and machine competence.

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