Decision-Making Models by the Aircraft Crew in Emergency "Depressurization"

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Abstract

According to statistics, an average of about 35 occurrences of aircraft depressurization are happening a year. Sudden depressurization at a high altitude (more than 24 000 feet) is a very dangerous flight emergency, and with incorrect, and most importantly, untimely actions of the aircraft crew, it leads to tragic consequences. 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 of the aircraft crew actions in the case of depressurization in the form of semantic models are presented. The flowchart of the algorithm of the aircraft crew actions in the case of depressurization if cabin altitude is controllable is designed. The deterministic, stochastic, and non-stochastic operative decision-making models by the crew members in emergency "Depressurization" under certainty, risk, and uncertainty conditions are developed. The deterministic models are built with the help of network planning, stochastic models – based on the expected value criterion with the help of a decision tree, non-stochastic models – based on the Wald, Laplace, Hurwitz, Savage criteria with the help of a decision matrix. 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

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

1. Introduction

In 2021, 44 accidents occurred during commercial passenger and cargo air transportation (Figure 1) [1]. Of that total, 11 fatal accidents led to 123 passenger and crew deaths, and one person died on the ground, according to the Aviation Safety Network. Seven of the 11 fatal

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accidents and 20 total accidents occurred during cargo operations. During non-commercial operations such as research, parachuting, training, and test flights, there were 26 accidents in 2021, nine of which were fatal and 50 people died. Corporate aircraft were involved in 28 accidents in 2021. Nine of them were fatal and resulted in 36 deaths among passengers and crew. The amount of fatal commercial accidents last year was up from eight in 2020, but the amount of fatalities in 2021 is down more than 60% from the 315 passengers and crew who died in 2020 accidents. In 2020, two non-commercial fatal accidents resulted in the deaths of four people.

In 2019, there were 20 fatal accidents during commercial transportation, resulting in the deaths of 285 passengers and crew members, and another six people on the ground. Non-commercial operations have had three fatal accidents and six fatalities this year.

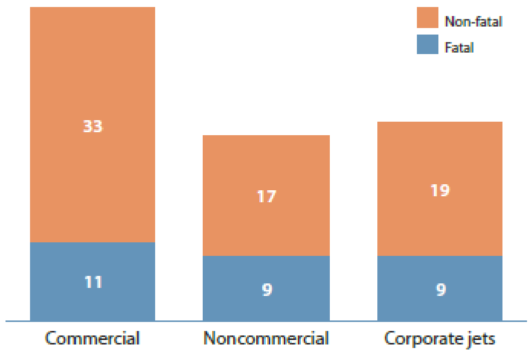

Figure 1: Amount of accidents in 2021 [1]

Over the past two years, COVID-19 has significantly decreased global air traffic. Data from the International Air Transport Association (IATA) shows that total international scheduled passenger transportation during 11 months of 2021 fell by around 60% compared to the same period in 2019 before the pandemic [2]. Regular freight traffic for the same period in 2021, on the other hand, grew by more than 6.5% compared to 2019 [3].

According to the International Civil Aviation Organization (ICAO) [1], the total number of passengers carried worldwide in 2021 was 2.3 billion, down 49% from pre-pandemic 2019 levels, but better than the 60% drop seen in 2020. Since the beginning of the 1990s, the 5-year moving average of ASN fatal accidents has been steadily decreasing [4] (Figure 2).

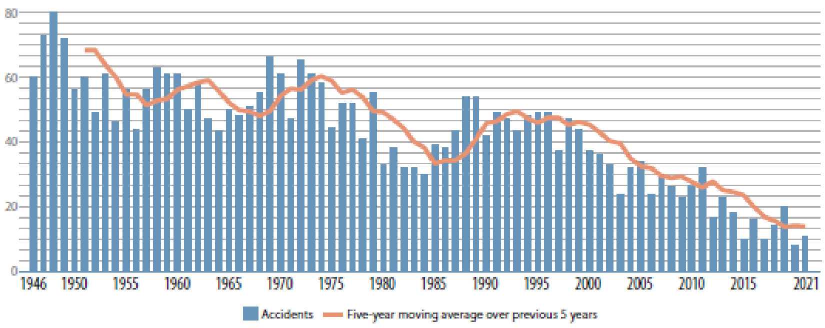

Figure 2: Fatal accidents per year (1946-2021) and 5-year moving average [1]

In the early days of aviation, nearly 80% of accidents were caused by machinery and 20% by human error. Today, on the contrary, approximately 80% of aircraft accidents are related to human error (aircraft crew members, air traffic controllers, flight dispatchers, engineers, etc.), and 20% – to technical malfunctions [5] (Figure 3).

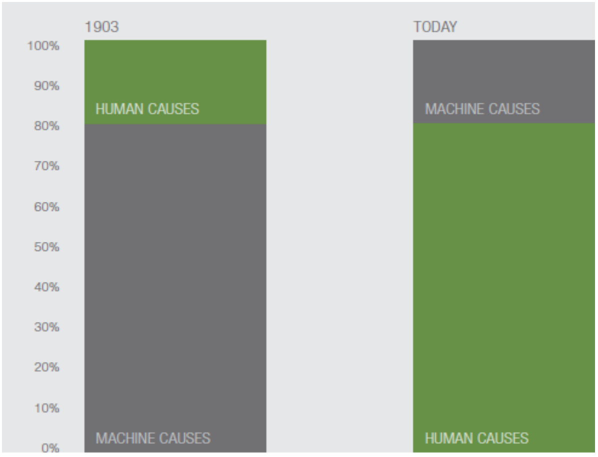

Figure 3: Fatal accidents per year (1946-2021) and 5-year moving average [5]

Therefore, reducing the influence of the human factor on the causality of accidents remains a relevant problem.

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

To increase the level of flight safety, the practical and scientific expediency of studying the problem of interaction of aviation specialists is increasingly being realized. Teamwork research in aviation was first initiated by the USA National Aeronautics and Space Administration (NASA) based on improving the interaction between flight crew members. Over time, this approach was further developed and became one of the most successful tools for preventing human errors [6; 7].

According to the ICAO's modern requirements, for the effectiveness of solutions the use of Collaborative Decision-Making (CDM) models is relevant [8–11].

Nowadays, within the Airport Collaborative Decision-Making (A-CDM) concept, specific solutions are being implemented that can unite the interests of participants (operators of the airport, aircraft, ground handling, air traffic, etc.) in coordinated work. A-CDM concept is based on the principles of transparency and information sharing; it is aimed at enhancement of air traffic and capacity management at airports by decreasing delays, improvement of the predictability of situations, and optimizing the use of resources [8–10].

Moreover, required daily efficiency of operations may be achieved through the mechanism of Flight and Flow Information for a Collaborative Environment (FF-ICE) [11]. FF-ICE concept defines requirements to air navigation information for flight planning, air traffic, flow, and trajectory management; it is a basis of the performance-based Air Navigation System (ANS) [11].

In [12] the issue of synchronizing the technological procedures of the first pilot (named Pilot Flying (PF) – performs the actions of piloting the aircraft) and the second pilot (named Pilot

Monitoring (PM) – performs communication functions) during the cross-monitoring in the flight emergency (FE) – a problem with the power supply – is considered.

In [12–15] the research of deterministic, stochastic, non-stochastic, and neural-network modeling, optimization, and intellectualization of CDM by teams of ANS human-operators (pilot – air traffic controller, UAV operator – air traffic controller, pilot – air traffic controller – flight dispatcher, pilot – air traffic controller – engineer, UAV operator – air traffic controller –pilot, etc.) in various FE.

Nevertheless, the problems of operational interaction between ANS human-operators in real time [16; 17] and weak formalization of the CDM process description, which does not allow applying the performance-based approach for its improvement [18], remain unsolved.

The purpose of this work is to build collective models of operative decision-making by the aircraft crew in the case of flight emergency (for example of *depressurization* if cabin altitude is controllable), which will be used in the Intelligent Decision Support System to improve the efficiency of the collaborative actions of aviation personal.

3. The Diagrams of Cause-and-Effect for the Emergency "Depressurization"

According to the Civil Aviation Authority of UK statistics, 77 occurrences of *aircraft depressurization* were happened during 1990-1999. In accordance with Federal Aviation Authority of USA statistics, 355 occurrences of *aircraft depressurization* happened from 1974 to 1983, an average of about 35 a year. 164 *depressurization* occurrences were reported to the Transportation Safety Board of Canada during 1985-1999, from 1990 to 1999 Australian Bureau of Air Safety Investigation recorded five *depressurization* occurrences [19].

Sudden *depressurization* at a high altitude (more than 24 000 feet) is a very dangerous FE, and with incorrect, and most importantly, untimely actions of the aircraft crew, it leads to tragic consequences. In a matter of seconds, the pressure drops to atmospheric, suffocation sets in, the temperature in the cabin drops to -50 °C, moisture droplets turn into thick fog, visibility in the cabin deteriorates sharply. There are three problems with *depressurization*:

1. Impact effect, in which aircraft crewmembers and passengers can be injured by the impact of an air jet.
2. A sharp drop in pressure causes the expansion of air in the human body.
3. The onset of hypoxia, i.e. suffocation.

A very unpleasant and dangerous phenomenon during depressurization is the expansion of gas inside the body. This is the effect of an open bottle of mineral water. In human life, nitrogen and oxygen are adsorbed by blood and tissues. If the pressure suddenly decreases, gas bubbles can form in various parts of the body. Formed in cavities where there is no exit (stomach, sinuses, tooth socket) causes severe pain. Gas bubbles can also form in tissues and joints, causing pain.

During rapid *depressurization*, the air inside the lungs expands and is forced out through the mouth and nose. People can tolerate sudden *depressurization* without adverse effects as long as the trachea is open. In a calm state, the lung can easily withstand a sudden doubling of its volume. But if the lungs expand too quickly, their lining can rupture, allowing air bubbles to enter the person's blood through damaged blood vessel walls.

Hypoxia is one of the main dangers of cabin depressurization. Consequences for a person: clouding of reason, confusion in thoughts, slowness in assessing the situation and making decisions, dizziness, and, in the extreme case, loss of consciousness. Such symptoms are also noted – rapid breathing, fatigue, headache, sweating, loss of coordination of movements, and blurred vision. The lack of oxygen in the blood causes blue lips and fingers under the nails, as well as tingling, nausea, and a feeling of coldness.

At higher altitudes, the severity of these symptoms increases. If at an altitude of 27 000 feet explosive *depressurization* causes loss of consciousness in one minute, then at an altitude of 36 000 feet – after 18 seconds.

Diagrams of cause-and-effect relationships for the FE "*Depressurization*" 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 4–5).

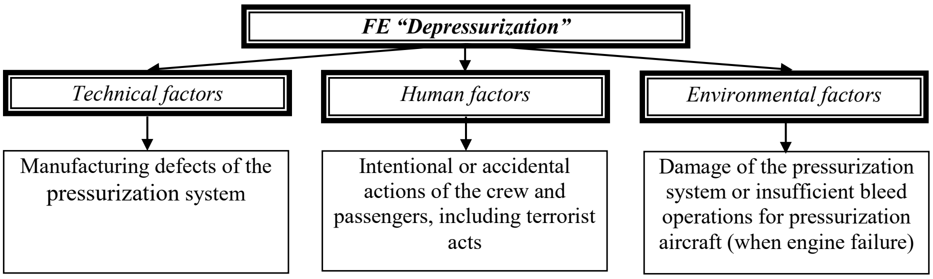

Figure 4: P-type event tree for the FE "Depressurization"

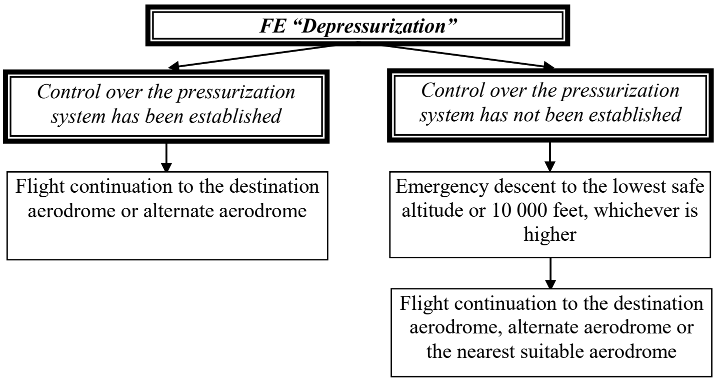

Figure 5: S-type event tree for the FE "Depressurization"

Despite the fact that aircraft cockpit *depressurization* is a rare occurrence, and even if it occurs, the probability of a fatal outcome is high. Flying at high altitudes must exclude even the slightest risk of *depressurization*.

4. Algorithm of Decision-Making by the Aircraft Crew in Emergency "Depressurization"

Explosive *depressurization* is always a random, unexpected phenomenon, but the more monstrous the consequences can be. Therefore, the aircraft crew should always be ready to act in such emergency. Flight safety in this case is ensured by the immediate use of oxygen masks. The emergency descent could be initiated if cabin pressure is out of control at altitudes above 14 000 feet or other operational reasons. Terminated climb and/or preventive normal descent could preclude the necessity of emergency descent.

Following the B737 Quick Reference Handbook (QRH) [20], a flowchart of the algorithm of the crew actions in the case of depressurization if cabin altitude is controllable is built (Figure 6).

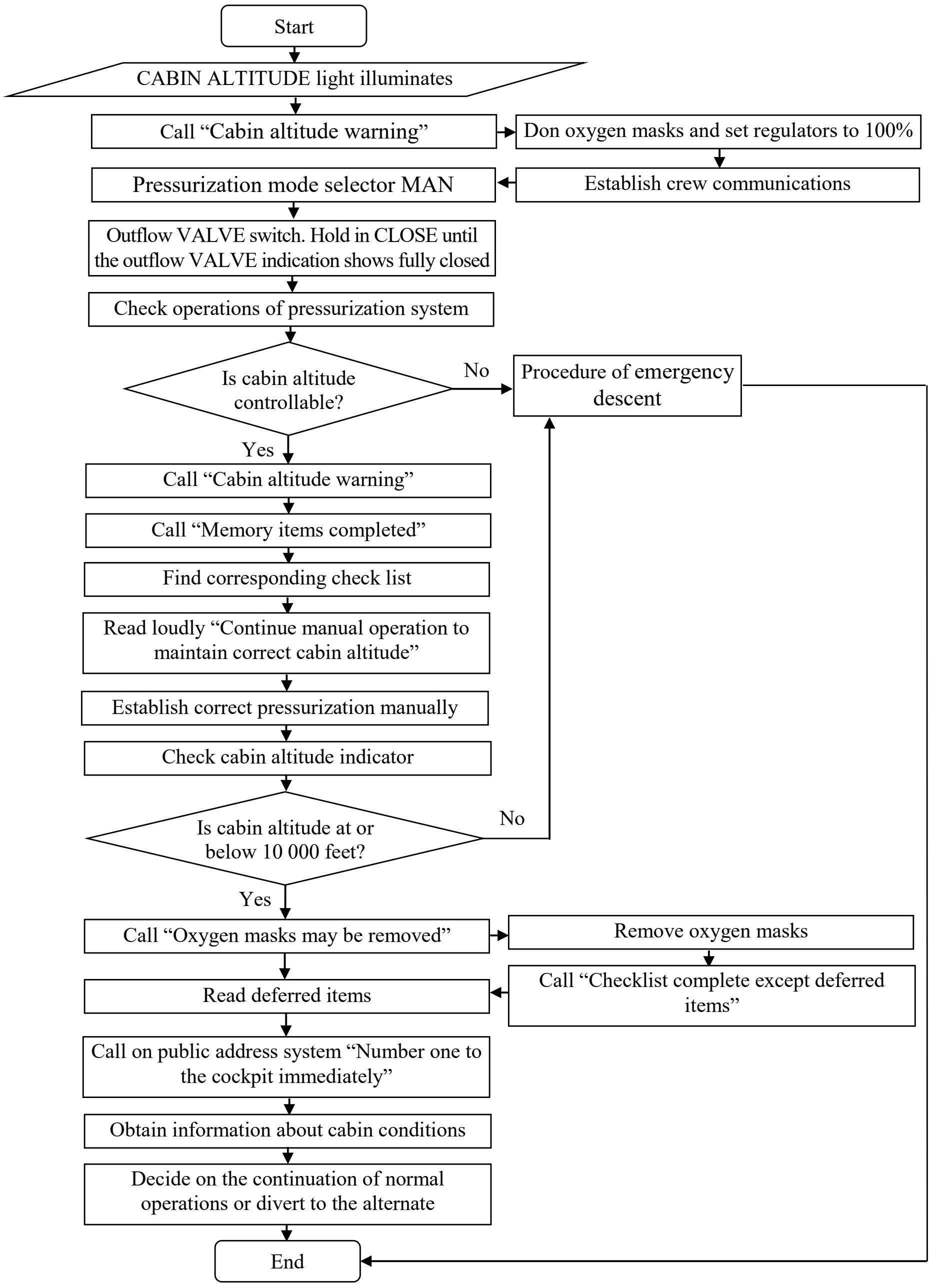

Figure 6: The flowchart of the algorithm of the crew actions in the case of depressurization if cabin altitude is controllable

Examples of crew actions in the case of *depressurization* are given in SKYbrary [21].

5. Deterministic Decision-Making Models by the Aircraft Crew in Emergency "Depressurization"

The concerted technology of work performance by the Pilot Flying (PF) and Pilot Monitoring (PM) in FE "*Depressurization*" if cabin altitude is controllable following QRH B737 is submitted in Table 1.

Table 1

The concerted technology of work performance by the aircraft crew in FE "Depressurization" if cabin altitude is controllable [20]

Operations of PF, a_i,	Name, a_i	Time, t_i, sec.	Operations of PM, b_j	Name, b_j	Time, t_j, sec.
Call "Cabin altitude warning"	a_1	1	Confirm information	b_1	1
Done oxygen masks and set regulators to 100%	a_2	3	Done oxygen masks and set regulators to 100%	b_2	3
Establish crew communications	a_3	3	Establish crew communications	b_3	3
			Pressurization mode selector MAN	b_4	2
			Outflow VALVE switch. Hold in CLOSE until the outflow VALVE indication shows fully closed	b_5	4
			Check operations of the pressurization system	b_6	2
If cabin altitude is controllable					
Call "Cabin altitude warning"	a_4	1	Call "Memory items completed"	b_7	1
			Find the corresponding check list	b_8	4
			Read loudly "Continue manual operation to maintain correct cabin altitude"	b_9	1
			Establish correct pressurization manually	b_{10}	4
			Check the cabin altitude indicator	b_{11}	1
When the cabin altitude is at or below 10 000 feet					
			Call "Oxygen masks may be removed"	b_{12}	1

Remove oxygen masks	a_5	5	Remove oxygen masks	b_{13}	5
			Call "Checklist complete except deferred items"	b_{14}	1
Call on public address system "Number one to the cockpit immediately"	a_6	1	Read deferred items	b_{15}	1
Obtain information about cabin conditions	a_7	10			
Decide on the continuation of normal operations or divert to the alternate	a_8	10			
Total		**34**			**34**

Based on the experts' opinion the deterministic model of work performance by the aircraft crew in emergency "*Depressurization*" if cabin altitude is controllable in the form of the network graph is designed (Figure 7).

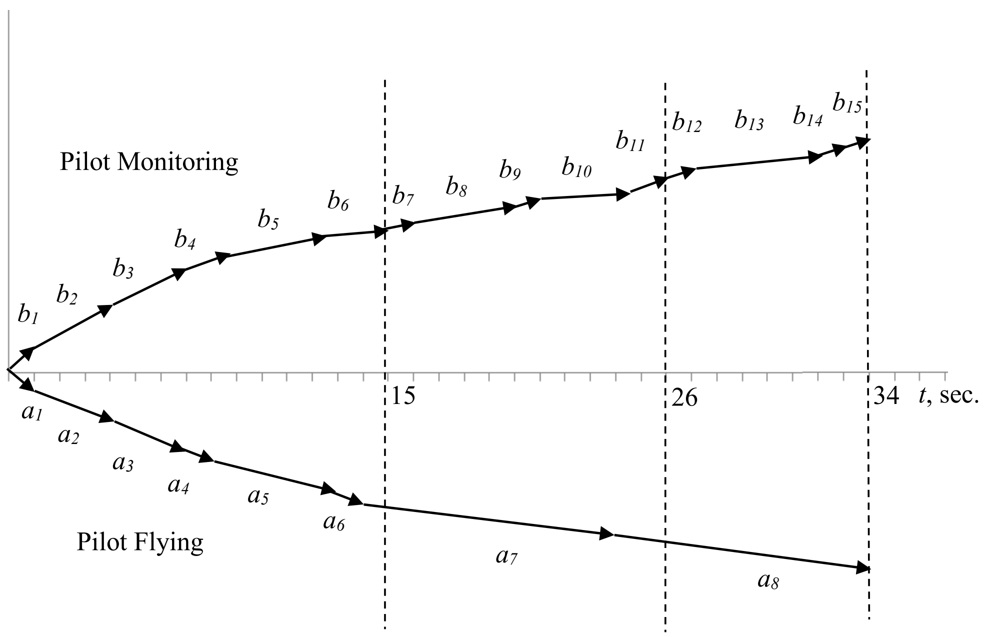

Figure 7: Network graph of work performance by the aircraft crew in emergency "Depressurization" if cabin altitude is controllable

The critical way for PF is the operations a_1–a_8 and for PM is the operations b_1–b_{15} located one after the other without time gaps and overlapping. The critical time t_{cr} of work by the aircraft crew in emergency "Depressurization" if cabin altitude is controllable is 34 sec.

6. Stochastic Decision-Making Models by the Aircraft Crew in Emergency "Depressurization"

Decision-making by the aircraft crew in the FE "*Depressurization*" about the continuation of the normal operations and proceeding to the destination aerodrome or diverting to the alternate aerodrome is included next stages of the solution:

1 – choosing between an alternate or destination aerodrome for emergency landing;

4 – choosing between alternate aerodrome 1 and alternate aerodrome 2 for emergency landing;

7, 8 – choosing between Instrument Flight Rules (IFR) and Visual Flight Rules (VFR).

The probabilities p_j for each outcome U_{ij} were identified: p_1=0.2 – bad weather; p_2=0.8 – good weather conditions.

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

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

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

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 *depressurization* is presented in Figure 8.

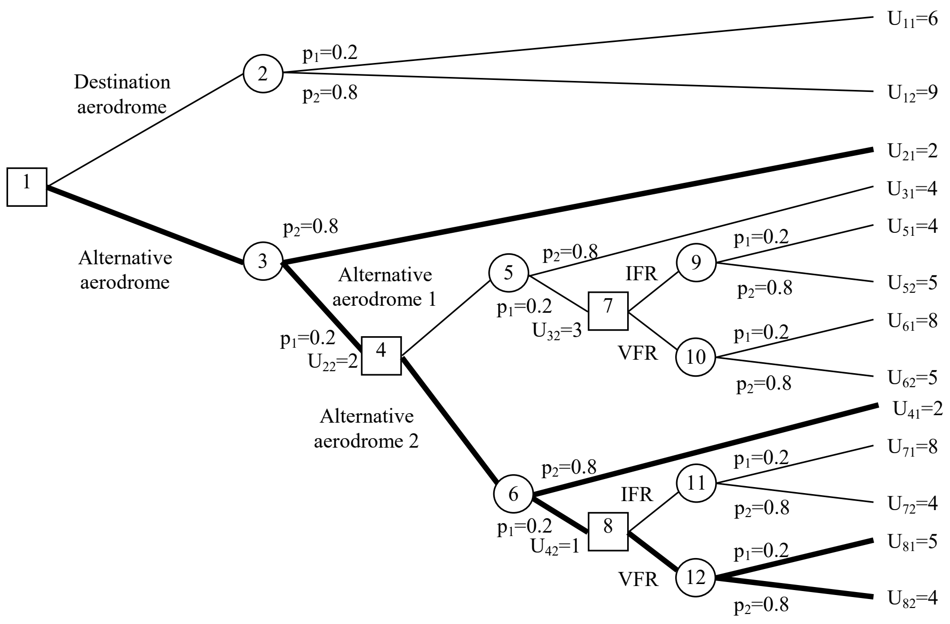

Figure 8: Decision tree of FE "Depressurization"

Risks calculation for the decision tree of FE "*Depressurization*":

$R_{12}=p_1 \cdot U_{81}+p_2 \cdot U_{82}$=0.2·5+0.8·4=4.2 c.u.;

$R_{11}=p_1 \cdot U_{71}+p_2 \cdot U_{72}$=0.2·8+0.8·4=4.8 c.u.

$R_{12}<R_{11}$, so $A_8=R_{12}$=4.2 c.u.

$R_{10}=p_1 \cdot U_{61}+p_2 \cdot U_{62}$=0.2·8+0.8·5=5.6 c.u.;

$R_9=p_1 \cdot U_{51}+p_2 \cdot U_{52}$=0.2·4+0.8·5=4.8 c.u.

$R_{10}>R_9$, so $A_7=R_9$=4.8 c.u.

$R_6=A_8+p_1 \cdot U_{42}+p_2 \cdot U_{41}$=4.2+0.2·1+0.8·2=6 c.u.;

$R_5=A_7+p_1 \cdot U_{32}+p_2 \cdot U_{31}$=4.8+0.2·3+0.8·4=8.6 c.u.

$R_6<R_5$, so $A_4=R_6$=6 c.u.

$R_3=A_4+p_1 \cdot U_{22}+p_2 \cdot U_{21}$=6+0.2·2+0.8·2=8 c.u.;

$R_2=p_1 \cdot U_{11}+p_2 \cdot U_{12}$=0.2·6+0.8·9=8.4 c.u.

$R_3<R_2$, so $A_1=R_3$=8 c.u.

An optimal solution is landing at the alternate aerodrome 2 in VFR, where R_{min}=8 c.u.

7. Non-Stochastic Decision-Making Models by the Aircraft Crew in Emergency "Depressurization"

Static and dynamic factors influencing decision-making by the aircraft crew in the FE "*Depressurization*" about the continuation of the normal operations and proceeding to the destination aerodrome or diverting to the alternate aerodrome are:

1) Internal factors F^i:

- f_1^i – the cause of depressurization;
- f_2^i – flight-technical characteristics of the aircraft;
- f_3^i – equipment of the aircraft;
- f_4^i – time of the FE development;

2) External factors F^e:

- f_5^e – tactic-technical characteristics of the runway;
- f_6^e – the runway surface condition;
- f_7^e – the navigation facility at the aerodrome;
- f_8^e – the lighting system at the aerodrome;
- f_9^e – weather conditions at the aerodrome;
- f_{10}^e – readiness of emergency office at the aerodrome;
- f_{11}^e – factors of the commerce (fees at the airport, ground handling agreements, replacement aircraft, etc.).

The matrix of possible results of the crew actions in the case of *depressurization* if cabin altitude is controllable is given in Table 2.

Table 2

The decision-making matrix of the aircraft crew in FE "Depressurization"

Alternative solutions		Factors influencing decision-making in FE F^i& F^e					
		f_1	f_2	…	f_j	…	f_m
A_1	Destination aerodrome	u_{11}	u_{12}	…	u_{1j}	…	u_{1n}
A_2	Alternate aerodrome	u_{21}	u_{22}	…	u_{2j}	…	u_{2n}

The Wald, Laplace, Hurwitz, Savage criteria will allow finding the optimal solution in FE "*Depressurization*" in uncertainty conditions.

To solve the task of finding a compromise between the time of decision-making by human-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 (ANN) with Machine Learning (ML) and analyzing tools of Big Data (BD). To control Artificial Intelligence (AI) solutions by human-operator it is necessary to introduce Hybrid (Combined) Intelligence (HI) Systems that use both human and machine competence [22; 23].

8. Results

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, have been developed for the FE "*Depressurization*". A flowchart of the algorithm of the crew actions in the case of *depressurization* if cabin altitude is controllable in accordance with the QRH B737 is built.

Concerted technology and the network graph of work performance by the Pilot Flying and Pilot Monitoring in FE "*Depressurization*" if cabin altitude is controllable are submitted. The critical time t_{cr} of work by the aircraft crew in emergency "*Depressurization*" if cabin altitude is controllable is 34 sec.

An example of risk calculation in the case of *aircraft depressurization* based on the expected value criterion with the help of the decision tree is given. An optimal solution is landing at the alternate aerodrome 2 in VFR, where R_{min}=8 c.u.

Internal and external factors influencing decision-making by the aircraft crew in the FE "*Depressurization*" about the continuation of the normal operations and proceeding to the destination aerodrome or diverting to the alternate aerodrome are determined: the cause of depressurization; flight-technical characteristics of the aircraft; equipment of the aircraft; tactic-technical characteristics of the runway; the runway surface condition; the navigation facility at the aerodrome; the lighting system at the aerodrome; weather conditions at the aerodrome; readiness of emergency office at the aerodrome; factors of the commerce (fees at the airport, ground handling agreements, replacement aircraft, etc.).

The compromise between the time of decision-making by human-operators under the influence of various factors in uncertainty conditions and the critical time of FE parry in certainty conditions can be found based on the use Artificial Neural Networks (ANN) with Machine Learning (ML) and analyzing tools of Big Data (BD).

9. Conclusion

According to statistics, an average of about 35 occurrences of aircraft depressurization are happening a year. Sudden *depressurization* at a high altitude (more than 24 000 feet) is a very dangerous FE, and with incorrect, and most importantly, untimely actions of the aircraft crew, it leads to tragic consequences. 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 of the aircraft crew actions in the case of *depressurization* in the form of semantic models of the P-type and S-type event trees are presented. The flowchart of the algorithm of the crew actions in the case of *depressurization* if cabin altitude is controllable following the QRH B737 is designed.

The deterministic, stochastic, and non-stochastic operative decision-making models by the crew members in emergency "*Depressurization*" under certainty, risk, and uncertainty conditions are developed. The deterministic models are built with the help of network planning, stochastic models – based on the expected value criterion with the help of a decision tree, non-stochastic models – based on the Wald, Laplace, Hurwitz, Savage criteria with the help of a decision matrix.

The direction of further research is to design the individual and collective deterministic, stochastic, and non-stochastic operative decision-making models by different aviation personnel in FE that can use in the composition of Intelligent Decision Support System. In the future, to solve the task of finding a compromise between the time of decision-making by human-operators under the influence of various factors in uncertainty conditions and critical time of FE parry in certainty conditions it is proposed to use Artificial Neural Networks (ANN) with Machine Learning (ML) and analyzing tools of Big Data (BD). Next research requires developing a methodology for the cooperation of Human Intelligence and Artificial Intelligence (creation of Hybrid Intelligence) to improve the efficiency of interaction between the Artificial Intelligence Systems and ANS human-operators (aircraft crew, UAV operator, air traffic controller, flight dispatcher, ground operator, engineer, etc.).

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