Models of Decision-Making by the Pilot in Emergency "Engine Failure During Take-Off"

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Abstract

Timely detection of engine failure at all stages of the flight and prevention of the catastrophic situation due to correct and coordinated collaborative actions of aviation specialists are the relevant tasks. The general technique of decision-making by the aviation operators in emergency and diagrams of causal relationships of the pilot actions in the case of engine failure during take-off is presented. The flowchart of the algorithm of the pilot actions in an emergency "Engine failure during take-off" when the captain decided to reject take-off is developed. The deterministic, stochastic, and non-stochastic models of decision-making by the pilot in emergency "Engine failure during take-off" under certainty, risk, and uncertainty conditions are built. The deterministic models are designed with the help of network planning, stochastic models – on the basis of the expected value criterion with the help of the Bayesian approach as decision tree, non-stochastic models – based on the Wald, Laplace, Hurwitz, Savage criteria with the help of decision matrix. The worked-out models can be used both for the informational support and professional training of the air navigation system operators.

Keywords

Bayesian approach, causal relationships, certainty, decision matrix, decision tree, event tree, flowchart, network graph, risk, uncertainty

1. Introduction

Aviation is the safest mode of transport. This is a generally accepted fact, which is confirmed by statistics. In 2014-2019, there were 107 accidents in the world, during which 3245 people died. Whereas in 2018 alone, airlines around the world carried nearly 4.5 billion passengers on about 45 million flights [1]. 2017 was the safest year in the history of commercial airlines: a total of 10 crashes were registered, of which only half were passenger aircraft (ACFT). In 2018, according to the Aviation Safety Network [2], the number of accidents rose sharply to 18, killing 561 people.

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ACFT crashes are very rare, about 200 times less common than car accidents. Civil aviation statistics over the past six decades show a downward trend in tragic events and increased security. But taking into account the registered accidents in 2019, these indicators are above the average for the last five years [3].

The reasons for aviation accidents are human factors (68%), technical factors (18%), and environmental factors (14%) [4–7].

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

According to a Boeing study [8], 11% of aviation accidents with human casualties occur during a flight at cruising altitude, 2% – during the descent phase, 2% – during the initial approach to landing, 29% – at the stage of the final approach to landing, 24% – during landing. At the beginning of the flight, according to statistics, there are fewer problems: 12% of ACFT crashes occur during take-off and initial climbing (before removing the flaps), 13% – during climbing and another 7% – on the ground during towing, taxiing, loading / unloading, etc. (Figure 1).

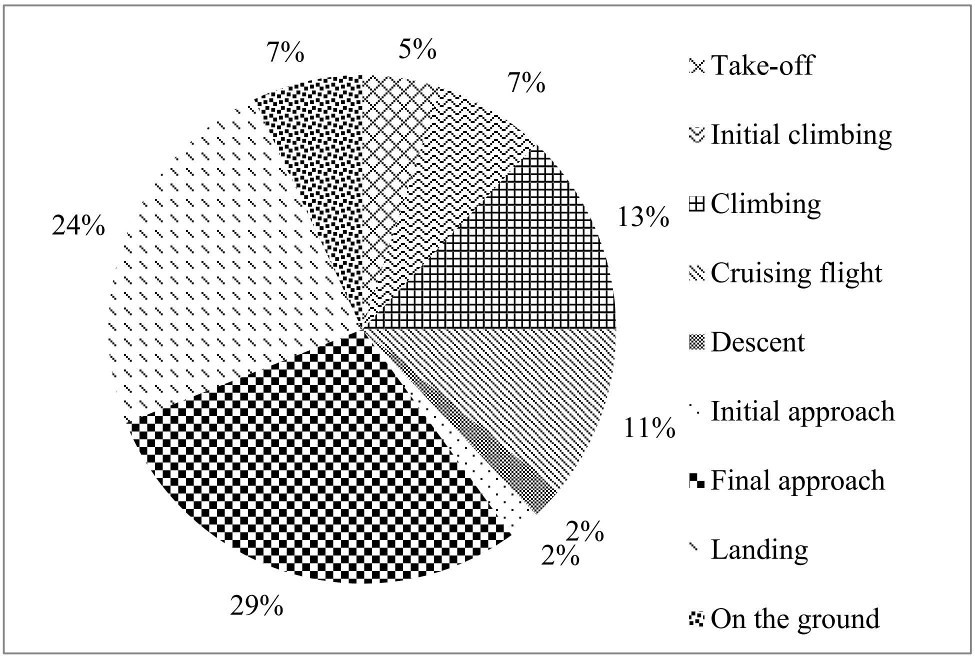

Figure 1: Distribution of the number of ACFT crashes by flight stages

Consider how aircraft incidents are broken down by type using the statistics of the Transport Safety Board of Canada collected from 2007 to 2017 [9] (Table 1, Figure 2).

Table 1
Distribution of incidents by types, %

Year	Incident type					
	Risk of collision / violation of intervals	Announcement of an emergency	Engine failure	Smoke / Fire	Collision	Another type of incident
2007	19	34	15	14	1	16
2008	19	35	14	12	1	19
2009	19	40	14	12	1	14
2010	25	38	11	10	0	15
2011	18	41	14	13	1	14
2012	16	41	14	11	1	17
2013	17	42	12	10	2	17
2014	13	42	14	12	2	17
2015	14	42	14	11	1	18
2016	17	37	13	10	2	20
2017	18	37	10	11	3	21
On the average	18	39	13	11	1	17

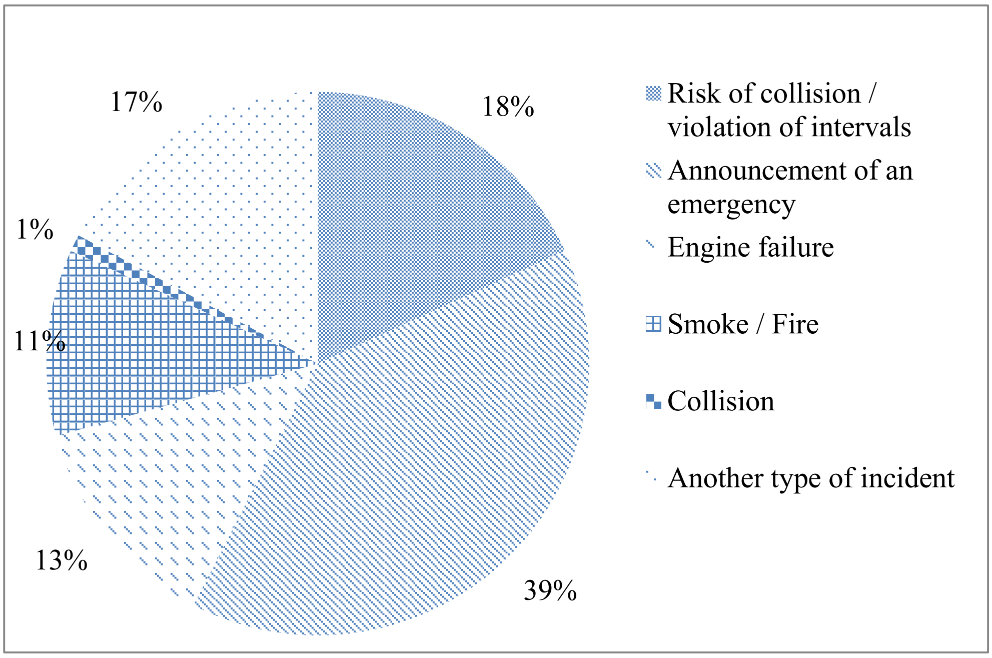

Figure 2: Distribution of incidents by types, %

It can be seen that the most frequent incident is the announcement of an emergency (39%), in the second place – the risk of collision / violation of the intervals between ACFT (18%). A significant share is occupied by engine failure (13%), the smallest share – in collisions between aircraft (1%).

Figure 3 shows the distribution of aviation accidents and incidents that occurred on the territory of Ukraine in the period from 2013 to 2017 with civilian Ukrainian and foreign aircraft by category [10].

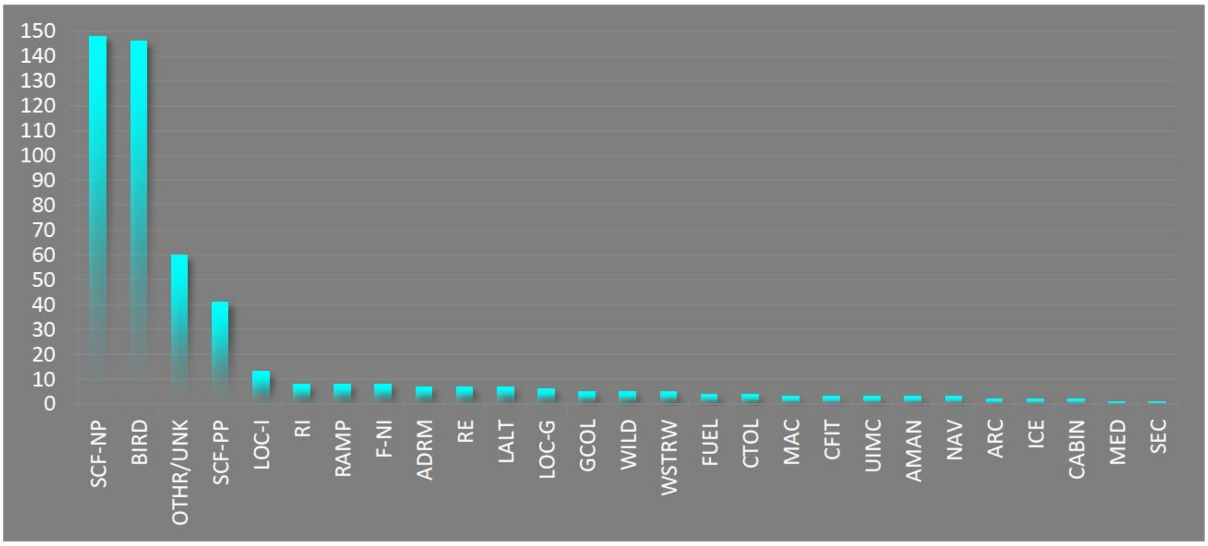

Figure 3: Summary data of aviation accidents and incidents by categories for 2013-2017, units

This diagram indicates that incidents most often occur due to technical failures (SCF-NP), bird collisions (BIRD), and engine failures (SCF-PP), and these trends do not change significantly over the years. The most common causes and consequences of aviation engine failure are shown in Figure 4 [11].

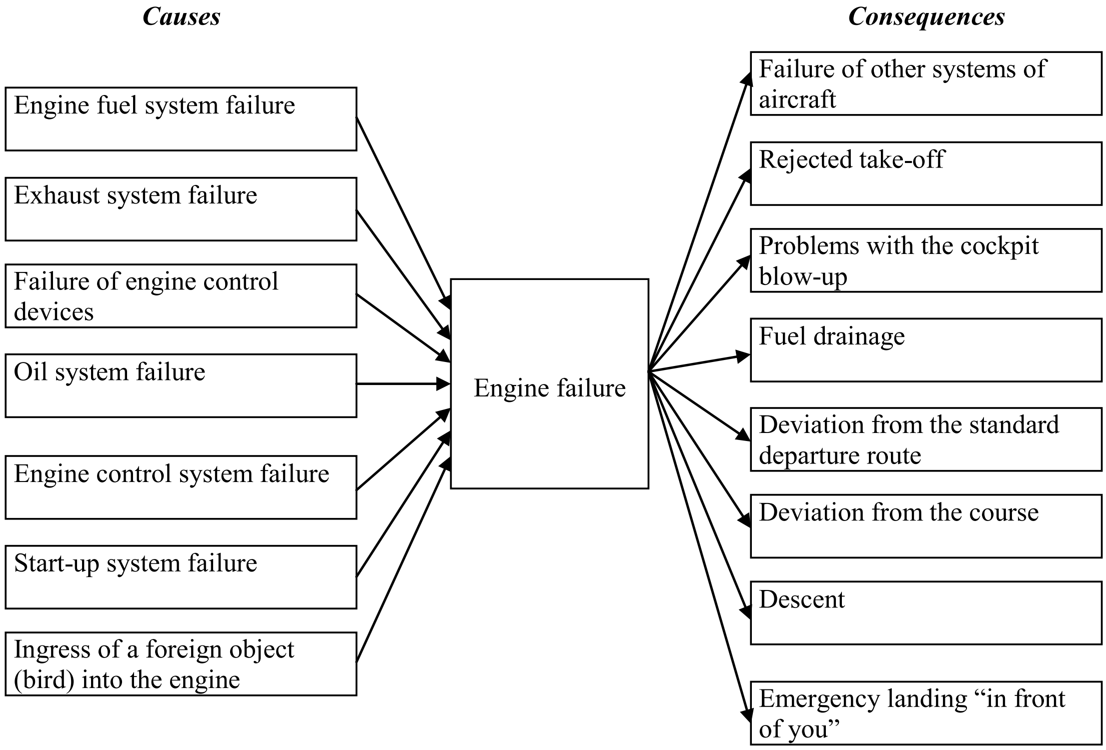

Figure 4: Causes and consequences of aviation engine failure

The most common causes of engine failure are engine fuel system failure and exhaust system failure. Among the consequences are the most often deviation from the standard departure route, deviation from the course, emergency landing "in front of you" [12]. Timely detection of engine failure at all stages of the flight and prevention of the catastrophic situation due to correct and coordinated collaborative actions of aviation specialists are the relevant tasks.

In the works [13; 14] is provided a fragment of the network graph describing the collaborative work of the ACFT crew (pilot-in-command – co-pilot) from the moment of engine failure during take-off to the issuance by the captain to continue or reject take-off. The critical time of actions of the ACFT crew and performance of works by the air traffic controller (ATCO) in case of engine failure during take-off in deterministic and stochastic conditions is obtained.

With the help of network planning the analysis of joint actions of the ACFT crew (Pilot Flying and Pilot Monitoring) in the case of flight emergency (FE) "Power supply problems" is conducted, the time for operational procedures with using the method of expert assessments is determined, structurally-time table and network graph are built, a critical time of work by two pilots (Pilot Flying and Pilot Monitoring) is obtained [14].

Deterministic, stochastic, non-stochastic, and neural network models of the collaborative decision-making (CDM) by ACFT pilot / unmanned aerial vehicle's remote pilot and ATCO in FE for maximum synchronization of operators' technological procedures are developed [15; 16].

The purposes of this work are:

- to build models of decision-making by the pilot in the case of rejected take-off using the example of FE "Engine failure during take-off";
- to develop an algorithm of analysis of situation and synthesis of CDM models by the pilot in the case of rejected take-off in FE "Engine failure during take-off".

3. General technique of decision-making by the operators in the flight emergency

The general technique of decision-making (DM) by the operators in FE is presented in Figure 5.

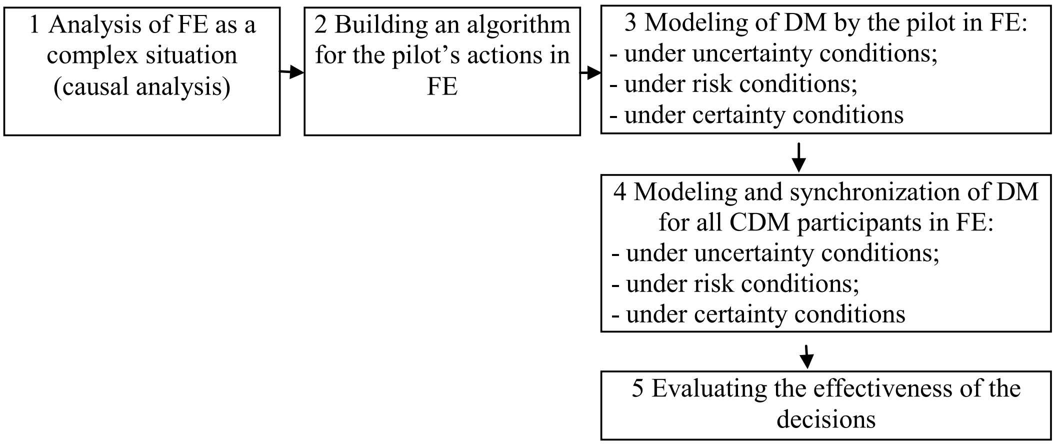

Figure 5: The general technique of DM by the operators in FE

The general technique of DM by the operators in FE is included:

1. Analysis of situation as a complex situation: identification of causal relationships.
2. Building an algorithm for the pilot's actions in FE.
3. Modeling of DM by the pilot in the case of rejected take-off as an emergency:

- models of DM under uncertainty conditions: determination of the alternatives $\{A\}$ and factors $\{F\}$ that influence the choice of the optimal solution (tool – decision matrix) (Table 2);

Table 2
Decision-making matrix in uncertainty

	{A}	Factors influencing decision-making in emergency					
		f_1	f_2	…	f_j	…	f_n
Alternative solutions	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}

- models of DM under risk conditions: evaluation of risk R for different solutions (tool – decision tree). Each stage of DM is characterized by solutions ($A = \{A_1; A_2; \dots, A_n\}$), a time t of situation development on some stage, and additional value β, that depends on the stage of the situation development and DM in time for parry a situation (Figure 6). When solving the problem of minimizing risks at each stage, additional risks arise ($+\beta_k$), the threats are increasing with time t (1):

$$R_k = t_k \sum_{i=1}^{n} p_i u_i \pm \beta_k, \quad (1)$$

where t_i – is a time of stage k;
β_k – is an additional risk on stage k;
p_i – are the probabilities of situation development, $\sum_{i=1}^{n} p_i = 1$;
u_i – are the expected outcomes (losses/profit).

The model of DM under risk is shown in Figure 6. Step-by-step correction of the decision matrix is carried out in risk assessment [17].

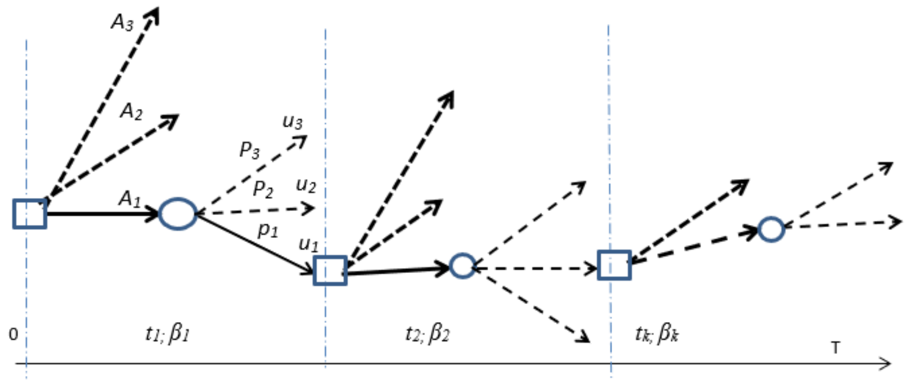

Figure 6: The stages of situation development and DM in the decision tree

- models of DM under certainty conditions: determination of the optimal solution by the criterion of minimizing the critical time of pilot actions in FE T, development of instructions for the pilot actions in the FE (tool – network planning).

4. Modeling and synchronization of DM for all CDM participants in FE (ACFT crew, ATCO, ground handling agents, rescue service, aerodrome service, production and dispatch service, etc.):

- under uncertainty conditions: determination of the alternatives $\{A\}$ and factors $\{F\}$ that influence the choice, determination of the optimal solution by the criterion of minimizing potential loss U (tool – decision matrix);
- under risk conditions: determination of alternatives A and probabilities of influence the factors $P(F)$, determination of the optimal solution by the criterion of minimizing potential risk R (tool – decision tree);
- under certainty conditions: determination of the optimal solution by the criterion of minimizing the critical time of collaborative actions in the FE T, development of instructions for joint actions of the operators in the FE (tool – network planning).

So, for example, stochastic and non-stochastic uncertainty, neural, and dynamic models can be integrated into deterministic models. When analyzing a critical situation in a team decision (A_1, A_2, A_3), each operator determines his actions to solve the problem (S_1, S_2, and S_3). In a deterministic model some actions are ambiguous, multi-alternative (S_1, S_2, and S_3). For ambiguous actions, optimal solutions are found using stochastic DM models under risk or uncertainty conditions (Figure 7).

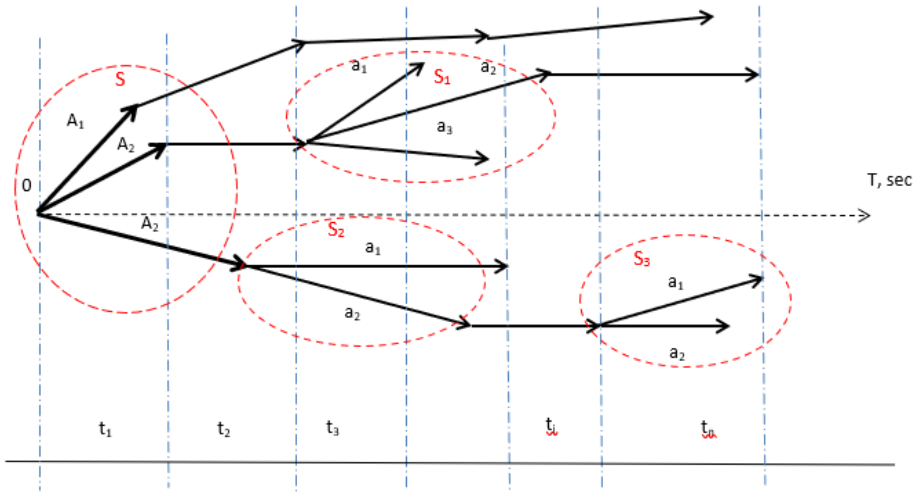

Figure 7: The deterministic models with ambiguous actions *(S_1 and S_2)* of operators (A_1, A_2, A_3)

After determining the minimum risks and maximum safety an integrated simplified model (S_1, S_2, S_3) is an aggregated deterministic model with included stochastic models (Figure 8).

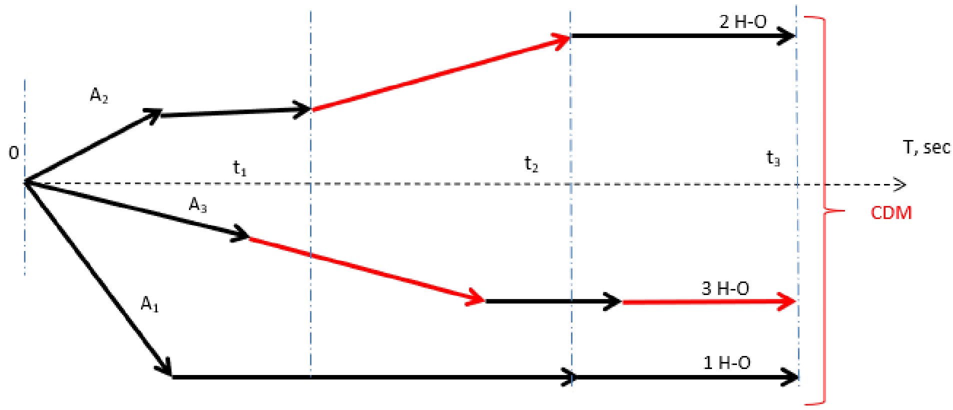

Figure 8: The deterministic models with decisions A_1, A_2, A_3

When analyzing and synthesis of situations emergency by several operators each operator determines his actions to solve problems of ensuring the safety of flights. For example, when need to build the CDM models for the pilot, air traffic controller, flight dispatcher, and technical personal, for choosing optimal actions and synchronization actions of operators in the case of rejected take-off.

5. Evaluating the effectiveness of the decisions.

Currently, the concept of Airport CDM (A-CDM) implements specific solutions 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 DM through more accurate and timely information that provides all partners at the airport a single operational picture of air traffic [18–20]. The A-CDM system is expected to increase situational awareness and reduce the risks of unauthorized ground maneuvering, and economically improve punctuality and reduce operating costs by reducing land delays and thus saving fuel by reducing taxiing time.

4. The diagrams of causal relationships for the flight emergency "engine failure during take-off"

Signs of engine failure during take-off are [11; 12]:

- turning the ACFT in the direction of the failed engine;
- engine pumping (clapping, shaking) and falling speed;
- increase / decrease of gas temperature behind the turbine;
- the lighting of warning devices.

Diagrams of causal relationships in the form of P-type and S-type event trees, each of which is a branched, finite, and connected graph, which has no loops or cycles, have been developed for the FE "Engine failure during take-off".

The semantic model of the P-type event tree (Figure 9) includes one main event – FE, which is combined with specific logical conditions with intermediate (branches) and initial (leaves) prerequisites that led to its occurrence. For example, technical factors are the ingress of a foreign object into the engine (screws, screwdrivers, small stones, birds, etc.), the destruction of the engine shaft bearing or low-pressure turbine disk, breakage of the low-pressure compressor working blade, gearbox failure; human factors – intentional and unintentional actions of technical staff; environmental factors – low quality of fuel and oil, large temperature fluctuations, etc.

The S-type event tree (Figure 10) also always uses FE as the central event, but the branches are scenarios of FE development, and the leaves are possible consequences of its development. Unlike an event tree of type P, an event tree of type S does not have logical nodes <and>, <or>. In essence, such a semantic model is a probability graph constructed in such a way that the sum of the probabilities of each branch is one.

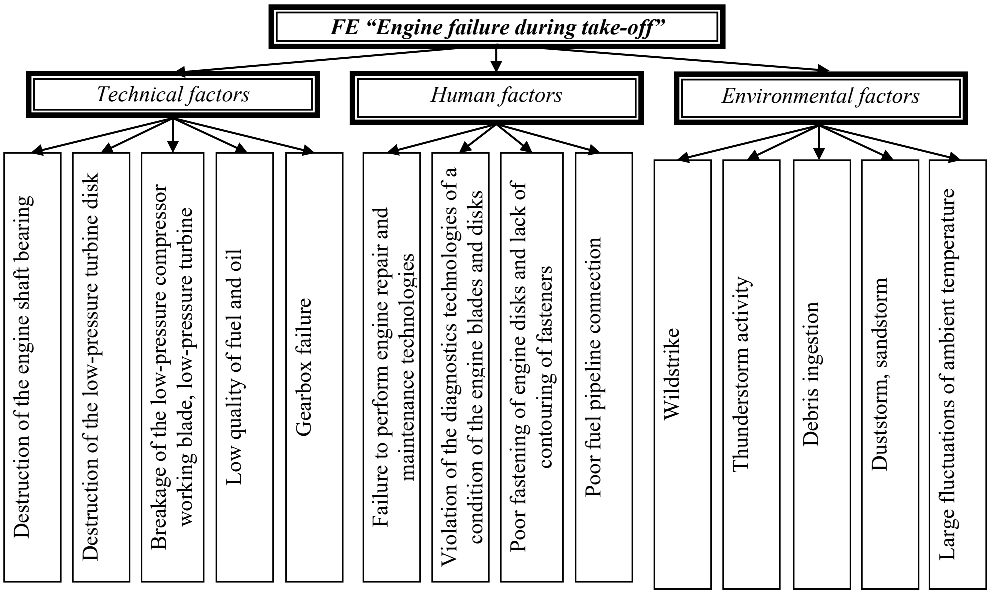

Figure 9: P-type event tree for the FE "Engine failure during take-off"

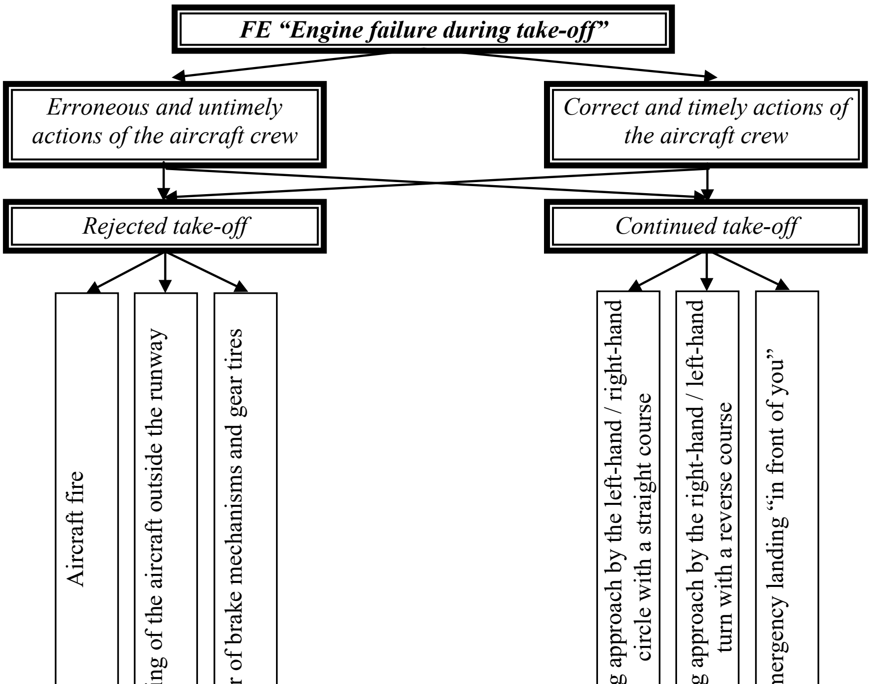

Figure 10: S-type event tree for the FE "Engine failure during take-off"

5. Algorithm of decision-making by the pilot in emergency “engine failure during take-off”

The captain is responsible for DM to reject take-off. He must decide in time to reject take-off before ACFT reaches a DM speed V_1. If a decision is made to reject the take-off, the commander clearly declares “REJECT”, immediately commences the take-off maneuver, and resumes control of the ACFT. If the co-pilot takes-off, he controls the ACFT until the captain positively intervenes and takes control [21; 22].

According to the B737 Quick Reference Handbook (QRH) [22], a flowchart of the algorithm of the pilot actions in the case of engine failure during take-off when the captain decided to reject take-off is built (Figure 11).

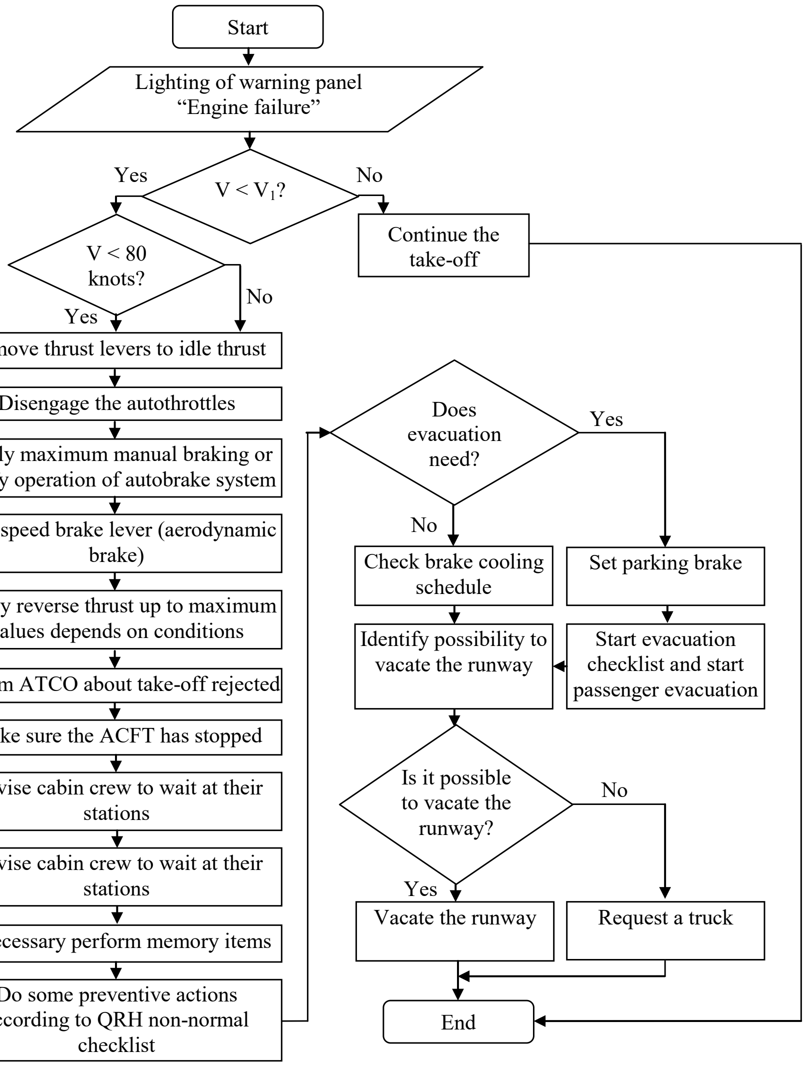

Figure 11: The flowchart of the algorithm of the pilot actions in FE “Engine failure during take-off” when the captain decided to reject take-off

Up to 80 knots, the rejected take-off is carried out in the event of [21; 22]:

- activation of the system failure alarm;
- systems failure;
- unnatural sound or vibration;
- problems with the gears;
- abnormal low acceleration during the take-off run;
- activation of incorrect take-off configuration alarm;
- fire or fire alarm actuation;
- engine failure;
- activation of the windshear warning alarm;
- involuntary opening of side windows;
- if the condition of ACFT is unsafe or impossible to take-off.

After a speed of 80 knots to a speed of V_1, take-off is rejected if [21; 22]:

- fire or fire alarm actuation;
- engine failure;
- activation of the windshear warning alarm;
- if the condition of ACFT is unsafe or impossible to take-off.

During take-off, the crew member who discovers the abnormal situation will voice this as clearly as possible.

The examples of ACFT actions in the case of rejected take-off due to FE are given in SKYbrary [23–25].

6. Models of decision-making by the pilot in emergency "engine failure during take-off" under uncertainty conditions

Factors influencing DM by the pilot in the FE "Engine failure during take-off":

- f_1 – the reasons for engine failure;
- f_2 – ACFT flight-technical characteristics;
- f_3 – ACFT equipment (manual / automatic braking systems, warning panels);
- f_4 – runway tactic-technical characteristics (length, type of coverage);
- f_5 – the condition of the runway surface (coefficient of adhesion);
- f_6 – meteorological conditions at the aerodrome;
- f_7 – category of emergency services;
- f_8 – commercial factors (availability of reserve aircraft, airport fees, contracts with handling services, etc.).

The matrix of possible results of DM by the pilot in the FE "Engine failure during take-off" is given in Table 3.

Table 3
The decision-making matrix by the pilot in FE "Engine failure during take-off" under uncertainty

Alternative solutions		Factors influencing decision-making in FE					
		f_1	f_2	⋯	f_j	…	f_m
A_1	Reject take-off	u_{11}	u_{12}	⋯	u_{1j}	…	u_{1n}
A_2	Continue take-off	u_{21}	u_{22}	⋯	u_{2j}	…	u_{2n}

The optimal solution of DM in the FE "Engine failure during take-off" under uncertainty conditions is determining by the Wald, Laplace, Hurwitz, Savage criteria.

7. Models of decision-making by the pilot in emergency "engine failure during take-off" under risk conditions

Consider an example of risk calculation in the case of lighting of warning panel "Engine failure" during take-off based on the expected value criterion with the help of the Bayesian approach, taking into account a posteriori probabilities.

Risk function for estimating the value of average losses determined in the space of consequences of engine parameters observations $X = |x_1 x_2|$, is set in the form (2):

$$R = \sum_x U(x)(Y; A)P(x/Y)P(Y), \quad (2)$$

where $U = \begin{vmatrix} u_{11} & u_{12} \\ u_{21} & u_{22} \end{vmatrix}$ – is a payment matrix of losses incurred by the pilot as a result of certain actions;

P(x/Y) – is a conditional distribution *X*;

P(Y) – is a priori distribution *Y*.

The structural scheme of the DM process by the pilot in the FE "Engine failure during take-off" in the form of a decision tree is shown in Figure 12.

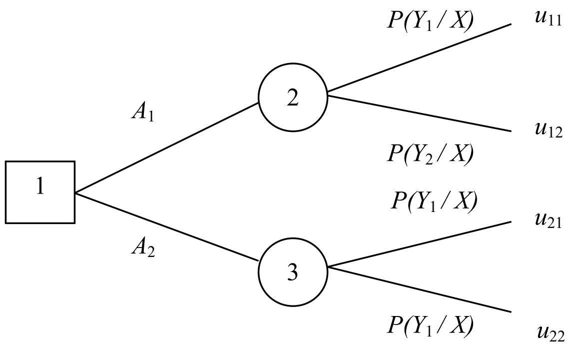

Figure 12: The structural scheme of the DM process by the pilot in the FE "Engine failure during take-off"

Risk in the case of DM by the pilot to reject take-off:

$$R(A_1) = U_{11}\big(P(x_1 / Y_1)P(Y_1) + P(x_2 / Y_1)P(Y_1)\big) + \\ +U_{12}\big(P(x_1 / Y_2)P(Y_2) + P(x_2 / Y_2)P(Y_2)\big).$$

Risk in the case of DM by the pilot to continue take-off:

$$R(A_1) = U_{21}\big(P(x_1 \,/\, Y_1)P(Y_1) + P(x_2 \,/\, Y_1)P(Y_1)\big) +$$
$$+U_{22}\big(P(x_1 \,/\, Y_2)P(Y_2) + P(x_2 \,/\, Y_2)P(Y_2)\big).$$

The optimal solution is an alternative with minimal risk.

The calculation of the risks of DM by the pilot in the case of engine failure during take-off is given in Table 4. If the pilot makes a mistake of the first kind – DM to reject the take-off, although in fact, the lighting of the warning panel has worked false – it will lead to some economically estimated loss (flight delay). If a mistake of the second kind is made – the pilot DM to continue the take-off, although in fact, the lighting of the warning panel has worked true – then a catastrophe can happen. Risk of an incorrect decision, in this case, $R_2 >> R_1$.

8. Models of decision-making by the pilot in emergency "engine failure during take-off" under certainty conditions

Based on a posteriori analysis of stochastic and non-stochastic models of DM, clarified deterministic models are built, which serve to correct existing and develop new instructions for pilot actions. The technology of work performance by the pilot in FE "Engine failure during take-off" when the captain decided to reject take-off following QRH B737 is submitted in Table 5.

Table 4

The calculation of the risks of DM by the pilot in the case of lighting of warning panel "Engine failure"

	Inputs of DM stochastic model		
x_1	Engine parameters are normal (failure hypothesis false)	$P(Y_1)$	Probability of true lighting of warning panel "Engine failure"
x_2	Engine parameters are out of the norm (the hypothesis of failure is true)	$P(Y_2)$	Probability of false lighting of warning panel "Engine failure"
Y_1	True lighting of warning panel "Engine failure"	$P(x_1/Y_1)$	The probability that engine parameters are normal in case of true lighting of warning panel "Engine failure"
Y_2	False lighting of warning panel "Engine failure"	$P(x_2/Y_1)$	The probability that engine parameters are out of the norm in case of true lighting of warning panel "Engine failure"
	The criterion of efficiency is the value of potential losses		
	Losses in case of correct actions		*Losses in case of incorrect actions*
u_{11}	Losses if pilot DM to reject take-off (true lighting of warning panel)	u_{12}	Losses if pilot DM to reject take-off (false lighting of warning panel)
u_{22}	Losses if pilot DM to continue take-off (false lighting of warning panel)	u_{21}	Losses if pilot DM to continue take-off (true lighting of warning panel)

Outputs of DM stochastic model		
R(A₁)	Risk if pilot DM to reject take-off	$R(A_1) = U_{11}\big(P(x_1 / Y_1)P(Y_1) + P(x_2 / Y_1)P(Y_1)\big) + U_{12}\big(P(x_1 / Y_2)P(Y_2) + P(x_2 / Y_2)P(Y_2)\big).$
R(A₂)	Risk if pilot DM to continue take-off	$R(A_1) = U_{21}\big(P(x_1 / Y_1)P(Y_1) + P(x_2 / Y_1)P(Y_1)\big) + U_{22}\big(P(x_1 / Y_2)P(Y_2) + P(x_2 / Y_2)P(Y_2)\big).$

Table 5
The technology of work performance by the pilot in FE “Engine failure during take-off” when the captain decided to reject take-off [22]

№	Operation	Name
1	Remove thrust levers to idle thrust	a_1
2	Disengage the autothrottles	a_2
3	Apply maximum manual braking or verify operation of autobrake system	a_3
4	Rise speed brake lever (aerodynamic brake)	a_4
5	Apply reverse thrust up to maximum values depends on conditions	a_5
6	Inform ATCO about take-off rejected	a_6
7	Make sure the ACFT has stopped	a_7
8	Advise cabin crew to wait at their stations	a_8
9	If necessary perform memory items	a_9
10	Do some preventive actions according to QRH non-normal checklist	a_{10}
	If evacuation need	
11	Set parking brake	a_{11}
12	Start evacuation checklist and start passenger evacuation	a_{12}
	If evacuation does not need	
13	Check brake cooling schedule	a_{13}
14	Identify possibility to vacate the runway	a_{14}
	If possible to vacate the runway	
15	Vacate the runway	a_{15}
	If not possible to vacate the runway	
16	Request a truck	a_{16}

Based on an expert’s opinion the network graph of work performance by the pilot in FE “Engine failure during take-off” when the captain decided to reject take-off is designed (Figure 13).

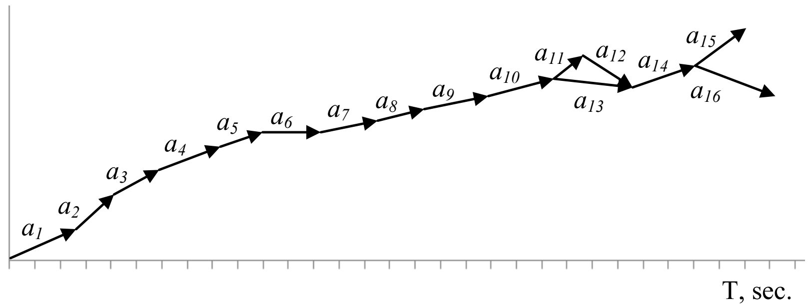

Figure 13: Network graph of work performance by the pilot in FE "Engine failure during take-off" when the captain decided to reject take-off

The critical way is the operations a_1–a_{16}, located one after the other without time gaps and overlapping. Basis on the critical way, the critical time of work performance by the pilot in FE "Engine failure during take-off" when the captain decided to reject take-off can be determined.

9. Results

12% of ACFT crashes occur during take-off, a significant share of aviation accidents is occupied by engine failure (13%). The most common causes of engine failure are engine fuel system failure and exhaust system failure. Among the consequences are the most often deviation from the standard departure route, deviation from the course, emergency landing "in front of you".

The general technique of DM by operators in FE is included: analysis of FE as a complex situation, construction of the algorithm of the pilot actions in FE, modeling of DM by the pilot in FE, modeling and synchronization of DM for all CDM participants in FE, and evaluation of the effectiveness of the decisions.

Diagrams of causal relationships in the form of P-type and S-type event trees, each of which is a branched, finite and connected graph, which has no loops or cycles, have been developed for the FE "Engine failure during take-off". A flowchart of the algorithm of the pilot actions in case of engine failure during take-off when the captain decided to reject take-off is built according to the QRH B737.

Factors influencing DM by the pilot in the FE "Engine failure during take-off" under uncertainty are the reasons for engine failure; ACFT flight-technical characteristics; ACFT equipment; runway tactic-technical characteristics; condition of the runway surface; meteorological conditions at the aerodrome; category of emergency services; commercial factors.

An example of risk calculation in the case of the lighting of warning panel "Engine failure" during take-off based on the expected value criterion with the help of the Bayesian approach, taking into account a posteriori probabilities, is given.

Based on a posteriori analysis of stochastic and non-stochastic models of DM, clarified technology and the network graph of work performance by the pilot in the case of rejected take-off due to engine failure are submitted.

10. Conclusion

Timely detection of engine failure at all stages of the flight and prevention of the catastrophic situation due to correct and coordinated collaborative actions of aviation specialists are the relevant tasks. The general technique of DM by operators in FE and diagrams of causal relationships of the pilot actions in the case of engine failure during take-off are presented. The flowchart of the algorithm of the pilot actions in FE "Engine failure during take-off" when the captain decided to reject take-off is developed. The deterministic, stochastic, and non-stochastic models of DM by the pilot in FE "Engine failure during take-off" under certainty, risk, and uncertainty conditions are built. The deterministic models are designed with the help of network planning, stochastic models – based on the expected value criterion with the help of the Bayesian approach as decision tree, non-stochastic models – on the basis of the Wald, Laplace, Hurwitz, Savage criteria with the help of decision matrix.

Step-by-step correction of the decision matrix with the help of computational systems / information technologies is carried out in risk assessment. After determining the minimum risks and maximum safety an integrated simplified model is an aggregated deterministic model with included stochastic models. The integration of stochastic and non-stochastic models of DM to deterministic models based on a posteriori analysis of FE development will serve to correct existing and develop new instructions for pilot actions. The designed deterministic, stochastic, and non-stochastic models can be used both for the informational support and professional training of the air navigation system operators.

The direction of further research is working out models of DM 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 DM through more accurate and timely information that provides all partners at the airport a single operational picture of air traffic.

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