Deterministic and Non-Deterministic Decision-Making Modeling in Flight Emergencies “Gear problems”

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Abstract. Decision-making (DM) modeling by aviation specialists (pilots, controllers, engineers) in abnormality situations is necessary to predict the development of flight emergencies. For DM modeling in the conditions of certainty, the deterministic models are used. These DM models are created based on the instructions – the rules of actions for aviation specialists: for pilots, this is a manual for the flight operation of aircraft, for controllers – the technology of their operations during flight emergencies ASSIST, for ground-based personnel, engineers – are the instructions and relevant rules. Network models of the DM by operators are building, the critical time for the parry of the flight emergencies and the critical path for the optimal solution are determining. For modeling and forecasting the development of flight emergencies, the non-deterministic models of DM in conditions of risk and uncertainty are used. The optimal strategies of the operators' actions with minimal risk are determining, the optimal alternative solutions under the influence of external factors on the DM are selecting. The use of DM methods for constructing deterministic and non-deterministic models is considered on an example of the flight emergency “Landing gear problems”.

1. Introduction

Since the middle of the 1970s air traffic is expanding two-fold once every 15 years [1]. So, the purpose of the Global Air Navigation Plan is to increase the capacity and efficiency of international air transport while enhancing or at least maintaining the current level of flight safety [1].

Despite the high-profile crash of the Boeing-737 MAX, 2019 has become one of the safest years in commercial aviation [2]. However, although the death toll has decreased, the number of fatal accidents has increased to a level higher than the five-year average. During 2019, Aviation Safety Network recorded a total of 20 fatalities (14 crashes with passenger flights, six with cargo), resulting in 283 dead [2]. This makes 2019 the seventh safest year in terms of catastrophes and the third safest year in deaths. Considering the worldwide air traffic of about 39 000 000 flights a year, the accident rate for 2019 is one disaster for about 2 000 000 flights. During 2018, a total of 15 aircraft crashes were recorded (12 crashes with

passenger planes, three with cargo), resulting in the death of 556 people [3]. However, the flight safety indicators for 2018-2019 were worse than the average in five years (14 aircraft crashes and 480 lives lost) and the safest in aviation history in 2017 with 10 crashes and 44 fatalities [3]. Since 1997, there has been a steady decrease in the average number of aircraft crashes due to the constant efforts of international aviation organizations aimed at improving flight safety [3].

Every year aircraft (ACFT) are becoming more reliable and secure. But whatever efforts are being made by aviation professionals to improve ACFT construction's safety, it is not possible to completely eliminate the human factor, which is one of the most common causes of accidents. According to the Interstate Aviation Committee, among the reasons of the accidents for 2018, 80% are deviations in the actions of aviation personnel in the operation and organization of flights and only 20% – are the refusals of aviation equipment [4]. Every year during 2010-2019, more than 70% of all general aviation accidents are the consequences of incorrect decision-making by the pilot (Figure 1) [5]. World statistics also show that the primary cause of airborne tragedies is the human factor (crew or air traffic controller (ATCO) error) [6–7].

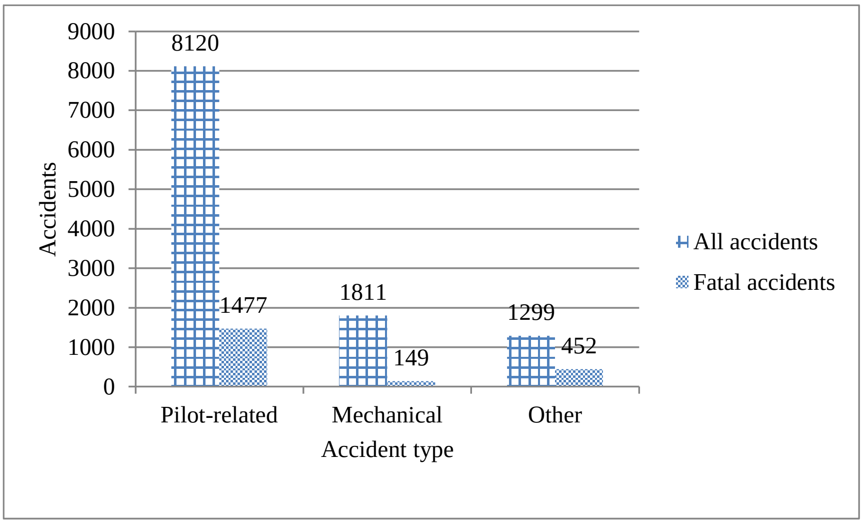


Figure 1. Statistic of general aviation accidents during 2010-2019 [5].

Effective interaction "ACFT crew – ATCO" is a prerequisite for ensuring flight safety in standard conditions and emergencies. Of particular importance is the coherence of the crew and the controller in situations that arise in flight due to the influence of dangerous factors – flight emergencies (FE) [8, 9], the main characteristics of which are an acute shortage of time for decision-making, incompleteness and lack of information, significant psychophysiological load on the ACFT crew.

The variety of circumstances for each FE does not allow for a precise detailed procedure for action to be followed. When operating in an emergency, ATCO bodies carry out complete and comprehensive coordination of actions, and staff is guided by common sense. The interaction between the ACFT crew and ATCO is as follows [8, 9]: the flight crew is guided in their actions by the requirements of the flight manual and the documents regulating the flight operation; ATCO personnel in their actions are guided by technologies of work at specific workplaces taking into account local conditions and peculiarities of air traffic servicing. During 1950-2000 due to the problems in cooperation pilot-ATCO (language barrier, communicating problems, ATCO's intervention in the flight crew work, wrong ATCO instructions/commands, etc.) in aviation accidents have died about two thousand people [10].

The problem of ATCO in FE is the incompleteness and inaccuracy of data on the flight process of ACFT. The problem of the ACFT crew in FE is the incompleteness and inaccuracy of the airspace data. Therefore, the goal of the work is to increase the effectiveness of Air Navigation System operators' actions in FE by developing decision-making (DM) models by operators under conditions of certainty, risk, and uncertainty on an example of FE "Landing gear problems" (an example from the scientific

work of the bachelor of the National Aviation University Maryna Marchenko, fourth year of study, specialty “Aviation Transport” qualification “Air Traffic Services”, discipline “Informatics of Decision-Making”).

The authors have developed collaborative decision-making models in emergency situations for ACFT crew and ATCO [11].

2. Emergency “Landing Gear Problems”

On the known site “SKYbrary” [12] is a lot of useful information about proceedings for aviation specialists in emergencies. The site “SKYbrary” is an electronic repository of safety knowledge related to flight operations, air traffic management, and aviation safety. For example, pieces of information about landing gear are used by students for created mathematical models for the decision-making of ACFT crew and ATCO in an emergency.

Algorithm for making decisions of an aviation specialist in an emergency:

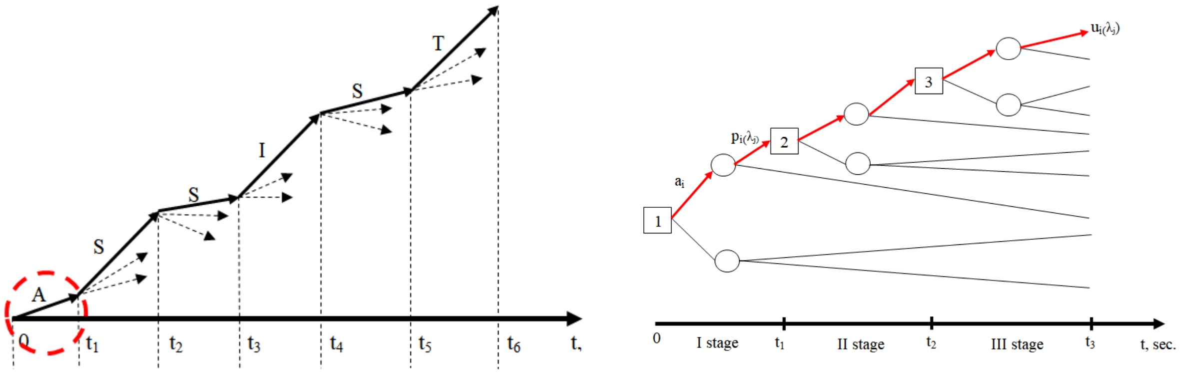
- emergency description;
- emergency procedures for aviation professionals (ACFT crew and ATCO);
- building a deterministic model using network planning methods;
- identification of areas with ambiguous solutions in Network graph;
- building stochastic models (DM under risk and DM under uncertainty);
- determination of optimal solutions for decision making by aviation specialists.

Emergency description. The site “SKYbrary” [12] gives the following reference material. The most modern aircraft are equipped with hydraulic drives for landing gear retraction and extension. Before this, pneumatic and electrical systems were used. The main part of the system is the hydraulic cylinders, which are attached to the strut and the aircraft body. To fix the position, special locks and spacers are used. To fix the rack in the retracted position, a hook-type lock is used, which snaps the shackle placed on the aircraft rack. Each aircraft is equipped with a landing gear position signaling system, with a down position a green lamp is on. Lamps are available for each of the legs. When retracting the racks, the red lamp comes on or the green one just goes out. The release process is one of the main ones, therefore the ACFT are equipped with additional and emergency release systems. In extreme cases, some aircraft have a mechanical opening system. But statistics [13] show that 24% of fatal accidents occur during landing, including due to the problems with landing gear. Therefore, ATCO should always be ready to assist the crew in this situation, expected ACFT’s go around, low pass of Tower for gear inspection by specialist of engineering personnel and manual gear extension [12].

Next, the actions of the ACFT crew in an emergency are considered. The ACFT crew actions are presented in the Flight Manual, in accordance with the type of aircraft.

Suggested controller's actions presented in the ASSIST principle and could be followed: (A - Acknowledge; S - Separate, S - Silence; I - Inform, S - Support, T - Time). The actions of the dispatcher (ATCO) presented in ASSIST are the basis for constructing a deterministic DM model.

Deterministic DM models are built to consolidate decision making for ACFT crew and ATCO. After the identification of areas with ambiguous solutions in the network graph are building stochastic models (DM under risk and DM under uncertainty). Deterministic and stochastic models for ATCO are presented in Fig. 2, where $\{A\}$ – the set of operations (alternative decisions) which are carried out by the controller in accordance with ASSIST in FE; $\{T\}$ – is the time of decision making for each operation; $\{P\}$ – is the set of the probabilities of j-factor influence during i-alternative solution choice; $\{U\}$ – is the set of the losses associated with choosing i-alternative solution during j-factor influence; $\{R\}$ – is the set of the risks associated with choosing i-alternative solution during j-factor influence; $\{\lambda\}$ – is the set of the factors influencing DM.



a) *b)*

Figure 2. Models of DM: a) deterministic model; b) stochastic model

Deterministic models in the case of landing gear failure are created based on the instructions – the rules of actions for aviation specialists: for pilots, this is a manual for the flight operation of aircraft, for controllers – the technology of their operations in FE ASSIST, for ground-based personnel, engineers – are the instructions and relevant rules. The technology of work performance by ATCO following ASSIST "Gear problems" is submitted in Table 1.

Table 1. The technology of work performance by ATCO by ASSIST "Gear problems".

№	Operation	Name
1	Obtain information about landing gear failure	a_1
2	Provide low pass for visual inspection	a_2
3	Acknowledge no gear	a_3
4	Give clearance to go around	a_4
5	Ask about manual gear extension	a_5
6	Clear runway when ACFT 50 track kilometers from touchdown	a_6
7	Towing equipment on stand-by as appropriate	a_7
8	Provide an emergency landing	a_8
9	Safe landing	a_9

An opinion of ten experts was obtained, experts` group opinion for each operation was calculated, and on the base of the structural-timing table (Table 2), the network graph was built (Fig. 3).

Table 2. Structural-hourly table of the technology of work "Gear problems"

№	Contents of the work	Designation of the work	Support on the work	Time of the performing the work
1	Obtain information about landing gear failure	a_1	–	4.2
2	Provide low pass for visual inspection	a_2	a_1	10.7
3	Acknowledge no gear	a_3	a_2	6.6
4	Give clearance to go around	a_4	a_2	8.0
5	Ask about manual gear extension	a_5	a_2	8.3
6	Clear runway when ACFT 50 track kilometers from touchdown	a_6	a_5	3.6
7	Towing equipment on stand-by as appropriate	a_7	a_5	16.9
8	Provide an emergency landing	a_8	a_5	22.0

9	Safe landing	a_9	a_2	23.3

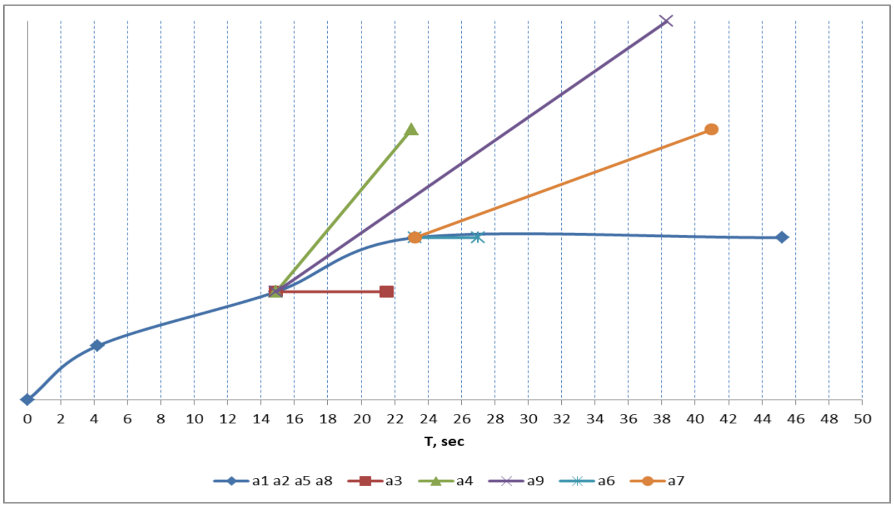


Figure 3. Network graph of technology of work performance by ATCO by ASSIST "Gear problems".

The critical time of work performance by ATCO in the case of landing gear failure is 45 sec. The critical way is the operations a_1, a_2, a_5, a_8, located one after the other without time gaps and overlapping. For the analysis of emergent risks (at each stage of DM) used non-deterministic models, such as DM models under risk and uncertainty.

If the law of the probability distribution of the random variable is known – there is decision making under risk, if unknown – the task of decision making in uncertainty [11].

Non-deterministic (stochastic) DM models under risk. The structural analysis of the FE "Landing gear problems" for stage №9 "Safe landing" in the network graph was performed (Table 2). The stages of solution were defined: $\boxed{1}$ – choosing between alternative or destination aerodrome for emergency landing; $\boxed{4}$ – choosing between alternative aerodrome 1 (Kharkiv) and alternative aerodrome 2 (Dnipro) for emergency landing; $\boxed{7}$, $\boxed{8}$ – 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 (Fig.4).

The optimal solution would be that corresponding to the condition (1):

$$A_{opt} = min\{A_{ij}\}, \tag{1}$$

where $A_{ij} = \sum_{j=1}^{m} p_{ij} \cdot U_{ij},\ i = \overline{1,n};\ j = \overline{1,m}.$

The decision tree in the case of landing gear failure is presented in Figure 3.

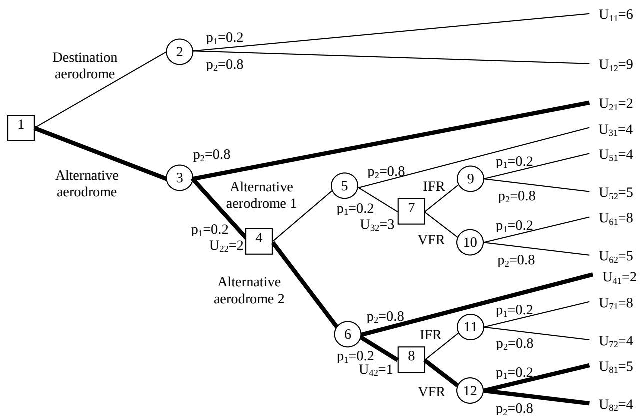


Figure 4. Decision tree for DM in FE "Landing gear problems" for stage №9 "Safe landing".

An optimal solution is landing at the alternative aerodrome 2 (Dnipro) in VFR. To take into account the factors affecting the DM (remoteness and amount of fuel; weather conditions; runway conditions, approach, lighting and navigation systems on landing aerodrome; emergency service, etc.), the DM method in uncertainty is used.

Decision-making modeling under uncertainty. For example, during the ACFT flight from Ivano-Frankivsk aerodrome on the approach at Zhuliany aerodrome the landing gear is the failure to retract and there is a cumulonimbus cloud above Zhytomyr aerodrome (Fig. 5).

Algorithm of the solution:

1. The payoff matrix.
2. Alternative actions $A = \{A_1, A_2, \ldots, A_i, \ldots, A_m\}$.
3. Factors $\lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_j, \ldots, \lambda_n\}$.
4. Outcomes of payoff matrix u_{ij}: $i = \overline{1,n}; j = \overline{1,m}$.
5. Conditions of decision making under uncertainty.
6. To choice the methods (criteria for analyzing the decision problem) of decision making under uncertainty: the criterion of Wald (maxmin); Laplace; Hurwicz; Savage.

Alternative actions $A = \{A_1, A_2, \ldots, A_i, \ldots, A_m\}$ (Fig. 5):

A_1 – Landing at Zhuliany aerodrome.
A_2 – Landing at Ivano-Frankivsk aerodrome.
A_3 – Landing at Ternopil aerodrome.
A_4 – Landing at Zhytomyr aerodrome.
A_5 – Landing at Borispil aerodrome.
A_6 – Landing at Khmelnitsky aerodrome.

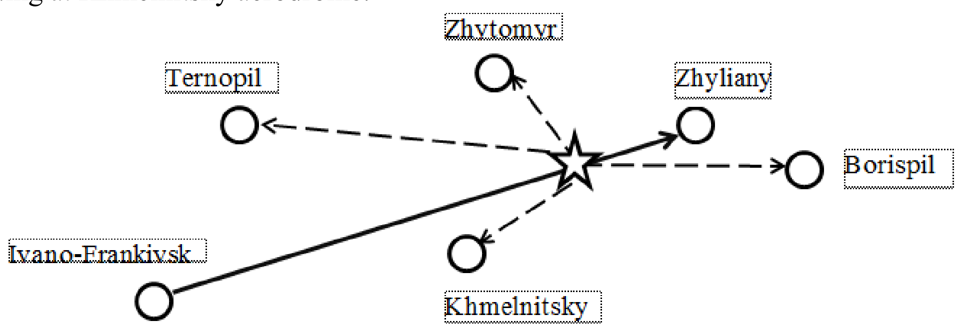


Figure 5. Scheme of the route in FE “Landing gear problems”.

It is necessary to choose the optimum-landing aerodrome using decision criteria: Wald, Laplace, Hurwicz, Savage. The results matrix of DM for choosing optimum-landing aerodrome for a route of ACFT from Ivano-Frankivsk aerodrome to Zhuliany aerodrome with possible alternate destinations at Ternopil, Zhytomyr, Boryspil, and Khmelnytskyi are in Table 3.

Table 3. The results matrix of DM for choosing optimum-landing aerodrome.

	Alternative decisions	Factors that influence DM								Solutions			
A_i	Aerodromes	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8	W	L	H	S
A_1	Zhuliany (destination)	9	7	8	9	8	8	9	10	7	7.5	8.5	3
A_2	Ivano-Frankivsk (departure)	2	8	8	8	7	7	5	4	2	5.4	5	6
A_3	Ternopil	3	5	7	7	6	5	6	3	3	4.6	5	4
A_4	Zhytomyr	7	1	9	2	3	8	4	2	1	4	5	8
A_5	Boryspil	9	7	7	8	8	7	9	8	7	7	8	2
A_6	Khmelnytskyi	3	8	6	5	6	7	6	8	3	5.4	5.5	5

The factors that influence the alternative decision are defined based on the flight rules and air traffic control procedures [8, 9]: λ_1 – remoteness; λ_2 – weather; λ_3 – amount of fuel; λ_4 – runway conditions; λ_5 – the lighting system approach; λ_6 – approach system; λ_7 – the navigation aids; λ_8 – emergency services. Possible results in a matrix are determined with the Expert Judgment Method by rating scales.

Wald criterion (maximin) (2):

$$A^* = \max_{A_i} \left\{ \min_{\lambda_j} u_{ij}(A_i, \lambda_j) \right\}. \quad (2)$$

Laplace criterion (3):

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

Hurwitz criterion (4):

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

where α – is an optimism index ($0 \le \alpha \le 1$), α =0.5.

Savage criterion (minimax regret criterion) (5):

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

where $r_{ij}(A_i, \lambda_j) = \underset{A_i}{\Delta} = \max_{\lambda_k} u_{ij}(A_i, \lambda_j) - u_{ij}(A_i, \lambda_j)$.

As we can see, according to Wald, Laplace, Hurwicz criterion the optimal aerodrome for landing in FE “Landing gear problems” is Zhuliany. As to Savage criterion – Boryspil. But for the more realistic decisions, need to search this problem more detail, especially from the side of the flight deck (pilots), to make a more accurate model to determine the most appropriate and safe decision using the criteria above.

Nowadays ICAO defined new approaches such as the application of artificial intelligence (AI) models the organization of Collaborative Decision Making (CDM) by all aviation operators using CDM models (CDMM) based on general information on the flight process and features of the emergency [14–17].

In the process of analysis and synthesis of DM models in FE effectively to simplify complex models and solutions. For example, stochastic and non-stochastic uncertainty, neural, the Markov, and GERT (Graphical Evaluation and Review Technique) models, reflexion models, dynamic models may be integrated into deterministic models [18]. The models for decision and predicting the emergency situation are using CDMM.

Conclusion

Deterministic, stochastic, and non-stochastic models of DM by pilot and ATCO in FE are presented. The methodological basis for DM modeling in conditions of certainty is network planning, in conditions of stochastic uncertainty – is a decision tree, in conditions of non-stochastic uncertainty – is a matrix of decisions. Examples of DM models in FE “Landing gear problems” are given. The proposed approach was applied to modeling FE “Aircraft decompression”, “Low oil pressure”, “Engine failure”, “Engine on fire”, “Forced landing”, “Communication failure”, etc. as a part of the discipline “Decision-Making” that study by the bachelors, masters and post-graduate students of the National Aviation University.

The direction of further research is the integration of stochastic and non-stochastic DM models by Air Navigation System operators to adjust models based on a posteriori data about FE development. The designed deterministic, stochastic, and non-stochastic models allow supplementing the base of scenarios of flight situations development in the Decision Support System and can be used in the future during the collaborative training of operators.

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