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The Methods for Aviation Systems' Safety Analysis during Combinations of Dangerous Heterogeneous Events Including Human Factor

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Abstract: This study presents a probabilistic method for assessing the safety and reliability of aviation systems based on modeling transitions between functional and failed elementary states. The analysis includes five core components of the aircraft system: crew, engines, avionics, power supply, and structural elements. Using failure and recovery flow intensities derived from real-world data for various aircraft types in 2022, the authors construct a system of differential equations to calculate dynamic safety indicators. The method applies state-transition graphs and formal mathematical models to describe the system's behavior under different conditions. Particular attention is given to the non-technical elementary state representing crew condition, with a refined classification of critical human factor events such as specific headache types. The study performs calculations in MATLAB and provides comparative safety assessments for multiple aircraft models, such as Airbus (A-319 and A-320), Bombardier CRJ200, Boeing (737, 747 and 777), Sukhoi Superjet 100 (RRJ-95) and An-26B-100.

Keywords: Aviation safety, probabilistic modeling, system reliability, failure intensity, recovery intensity, state-transition graph, human factor, aircraft systems, mathematical modeling, flight risk assessment, headaches.

1. INTRODUCTION

Nowadays, ensuring the safety and reliability of technical systems, particularly in critical areas, such as aviation, represents a complex and multifaceted task. This complexity stems from the necessity of considering numerous factors that may affect system performance. Such factors include the class of the system, its functional purpose, the goals and tasks it must perform, as well as external operating conditions. Safety and reliability of the system must always consider its specific characteristics and requirements. Otherwise, the analysis becomes excessively complicated and redundant, thus complicating both the development and implementation of effective reliability and safety measures [5, 11].

For aviation systems [7, 11, 12], where errors or failures may lead to catastrophic consequences, the approach to evaluating safety and reliability requires particular thoroughness. It is crucial to clearly define the system's objectives and tasks, and then conduct calculations strictly based on these data. This approach allows us to narrow the scope of considered factors, enabling researchers to focus precisely on those that are genuinely influencing system safety and reliability under specific operating conditions.

Mathematical modeling represents one of the key tools for evaluating the safety and reliability of technical systems. Typically, such modeling involves specialized algebra that formalizes the processes occurring within the system and assesses their impact on overall safety. Mathematical models used for these calculations often include elements from various mathematical areas, including differential equations, graph theory, probability theory, and others. These models allow you to not only describe the system's current state but also

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predict its behavior under various conditions, which proves particularly essential for aviation systems operating within a dynamic and changeable environment.

2. PROBLEM STSTEMENT AND MATHEMATICAL MODELS

The problem is formulated as ensuring the maximum safety criterion and determining the probabilities of accidents for a set of failures' intensities in the aviation system'.

In the context of aviation systems, researchers previously developed two mathematical models that enable assessment of probabilistic safety characteristics.

The first model relies on analyzing four elementary states of different aviation system components. These states may include normal operation, partial failure, complete failure, and recovery. A graph constructed from these states represents system behavior, with vertices corresponding to potential system states and arcs reflecting transitions between them. Each system state corresponds to a differential equation that describes how the probability of the system occupying that state changes, considering incoming and outgoing transitions. Solving this system of equations yields dynamic probabilistic safety characteristics for the aviation system.

The second model builds upon the first by incorporating five elementary states, which enables the knowledge of a more detailed description of system behavior and accounts for additional factors that may influence its safety. For instance, this model may include states associated with external influences such as changing weather conditions or human factors [9]. As in the first model, each state corresponds to a differential equation that captures the probability dynamics based on transitions into and out of that state. Solving the resulting system of equations provides a more accurate assessment of the system's probabilistic safety characteristics.

Both models enable researchers to evaluate not only the current state of the system but also to predict its future behavior. This predictive capability proves especially critical for aviation systems, where anticipating potential failures and implementing preventive measures remains essential. However, each model presents specific limitations and applies only under certain conditions. Therefore, selecting an appropriate model requires careful consideration of the system's unique characteristics and the specific objectives of the analysis.

Further, in Figure 2.1, we can see the graph of the second mathematical model for five elementary states of the system. The number of vertices in the graph is equal to 2^n, in our case for $n = 5$ elementary states there are 32 vertices.

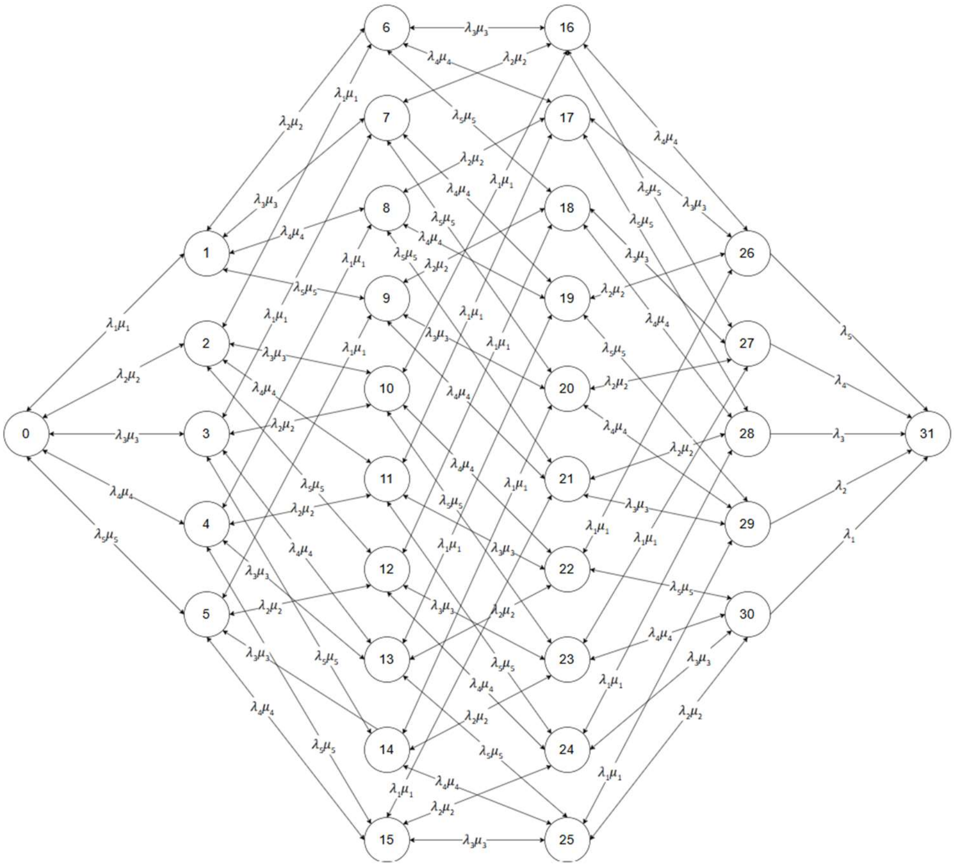

Fig. 2.1. Graph for five elementary states of the aviation system

The following provides a brief overview of how these models operate. As shown in Figure 1, the graph begins and ends with a single vertex. The initial vertex represents the fully functional state in which all of the elementary components operate correctly. This state always starts with a probability value of 1, as the system remains entirely operational. Subsequent vertices represent combinations of 1, 2, 3, and 4 failed elementary states (in the case of a model based on five elementary components). The final vertex corresponds to the state in which all elementary components of the aviation system have failed. This state approaches a critical condition, or may already represent a non-recoverable state, where any attempt to prevent a catastrophic outcome becomes ineffective. The model also introduces λ_i and μ_i for $i = \overline{1,5}$, representing the intensities of the random variables responsible for failure and recovery, respectively.

Based on this graph, we may construct a system of differential equations (2.1), where each equation corresponds to a vertex and describes the interactions between the vertexes for the five elementary states of the aviation system [3].

$$\frac{dP_0(t)}{dt} = -(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5) * P_0(t) + \mu_1 P_1(t) + \mu_2 P_2(t) + \mu_3 P_3(t) + \mu_4 P_4 + \mu_5 P_5(t);$$

$$\frac{dP_1(t)}{dt} = \lambda_1 P_0(t) - (\lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \mu_1) * P_1(t) + \mu_2 P_6(t) + \mu_3 P_7(t) + \mu_4 P_8(t) + \mu_5 P_9(t); \quad (2.1)$$

$$\dots$$

$$\frac{dP_{31}(t)}{dt} = \lambda_5 P_{26}(t) + \lambda_4 P_{27}(t) + \lambda_3 P_{28}(t) + \lambda_2 P_{29}(t) + \lambda_1 P_{30}(t) - (\mu_1 + \mu_2 + \mu_3 + \mu_4 + \mu_5) * P_{31}(t).$$

Here, $\lambda_i, i = \overline{1..5}$, are the failure flow intensities, $\mu_i, i = \overline{1..5}$ are the recovery flow intensities, and $P_i, i = \overline{0..31}$ denotes the probability of the aviation system being in a specific combination of elementary states, as defined in Fig. 2.1.

3. PRACTICAL SCENARIOS

Let us explore how these models and systems could be applied in practical scenarios. The following elementary states represent key components of aviation systems:

1. R_1 is the crew condition;
2. R_2 is the engine condition;
3. R_3 is the avionics condition;
4. R_4 is the power supply condition;
5. R_5 is the condition on structural elements.

The table below represents events associated with technical failures in Class 1-3 aircraft reported in 2022 [2, 4, 6]. The data presented in the table supports the calculation of failure intensity rates λ_i, where $i = \overline{1,5}$. These rates then serve as the basis for computing the probabilistic safety characteristics P_n, where $n = \overline{0,31}$.

Table 3.1. Events Related to Technical Failures in Class 1–3 Aircraft in 2022

Aircraft type / Aircraft system	A-319	A-320	CRJ-200	B-737	B-747	B-777	RRJ-95	An-26B-100	Total
Engine	6	10	1	4	1	2	1		25
Exhaust system (thrust reverser)			1	1			11		13
Fuel system							6		6
Hydraulic system	2	8		1			9		20
Cabin pressurization	3	9	2	4			1		19
Wing mechanization	1	3			2		6		12
Landing gear	3	3					5		11
Air conditioning system							5		5
Instrumentation equipment	1	1	1						3
Radio communication equipment						1	1	1	3
Automatic flight control system (AFCS)				1			2		3
Electrical system	3	1		1					4
Crew	1	3	1	3		3		1	12
Total	20	38	6	15	3	6	47	2	137

The intensity λ_i of the failure flow for each elementary state R_i (where $i = \overline{1,5}$) of the aviation system derives from the corresponding data in the table. The calculation uses the full duration of the year 2022 as the reference period. Thus, the intensity can be calculated as $\lambda_i = \frac{k_i}{1}$, where k_i represents the number of failure-related events associated with each of the elementary system state, and the denominator denotes the conditional time unit (1 year).

Complex technical systems require the use of availability coefficients K_g to enhance their safety and reliability [10]. Given the use of both failure flow intensities λ_i and recovery flow intensities μ_i the availability coefficient follows the expression:

$$K_g = \frac{\mu}{\lambda + \mu} \tag{3.1}$$

Only systems with high availability coefficient – typically close to one – enter operational service. In our case, the model assumes an availability coefficient of $K_g = 0.95$.

Based on the above formula of the availability coefficient, the recovery intensity can be expressed as:

$$\mu_i = \frac{K_g * \lambda_i}{1 - K_g} \tag{3.2}$$

Let's allocate the aircraft systems under each elementary state:

Crew condition R_1:

- Visual acuity of the pilot (ability to perceive instrument data and the external environment);
- Auditory perception of the pilot (ability to hear signals, communication, and warnings);
- Physical capability (ability to operate controls and perform tasks);
- Attention and focus (ability to maintain task concentration and avoid distractions).

Engine condition R_2:

- Engine;
- Exhaust system (including thrust reverser);
- Fuel system.

Avionics condition R_3:

- Instrumentation equipment;
- Radio communication systems;
- Automatic flight control system (AFCS).

Power supply condition R_4:

- Electrical system.

Structural components condition R_5:

- Cabin pressurization;
- Wing mechanization;
- Landing gear;
- Air conditioning system;
- Hydraulic system.

For a more detailed system-level analysis, event trees are used to trace how individual or combined elementary events may trigger events that are more critical. These chains of events can ultimately lead to catastrophic outcomes, especially when the recovery flow intensity becomes insufficient and any crew intervention fails to resolve the situation.

Special attention must focus on the elementary condition R_1 of the crew of the aircraft system, as it represents the only non-technical state. Traditional technical analysis and measurement techniques do not apply here. Therefore, researchers must adopt alternative approaches to assess the safety and reliability of this component.

As an illustrative example, consider various types of headaches as elementary events that may affect the crew's condition and, consequently, flight safety. These events fall under the classification of R_1:

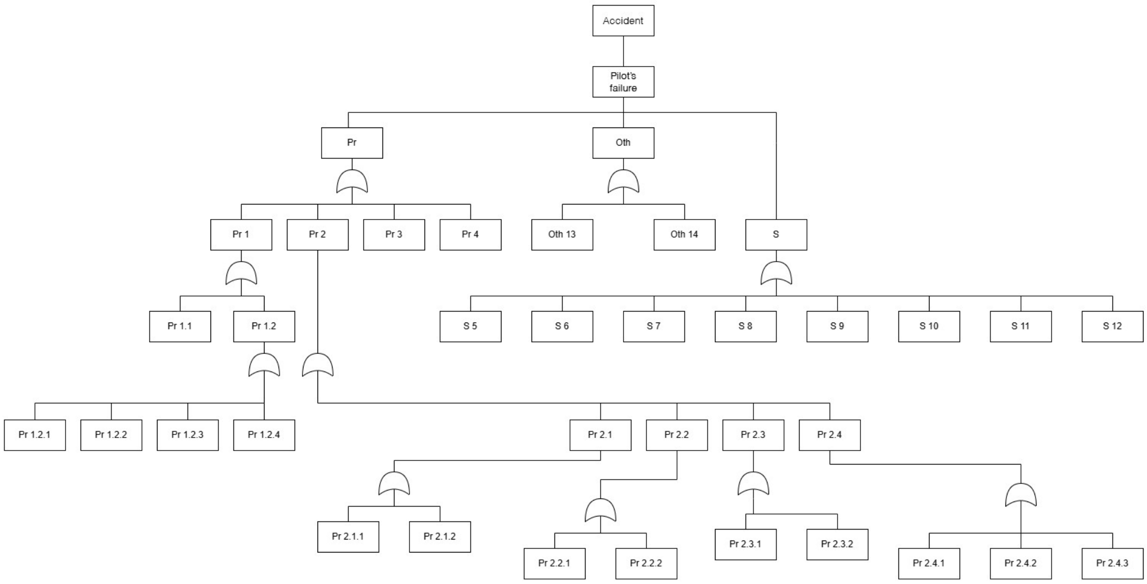

Fig. 3.1. Elementary events for the crew condition R_1 of the aviation system

The study analyzes a risk tree constructed from the previously described elementary events [3]. We expanded the tree to a three-level structure. The third level includes the following key designations [8]:

- Pr 1.2.1 – Migraine with typical aura;
- Pr 1.2.2 – Migraine with brainstem aura;
- Pr 1.2.3 – Hemiplegic migraine;
- Pr 1.2.4 – Retinal migraine;
- Pr 2.1.1 – Infrequent episodic tension-type headache with pericranial tenderness;
- Pr 2.1.2 – Infrequent episodic tension-type headache without pericranial tenderness;
- Pr 2.2.1 – Frequent episodic tension-type headache with pericranial tenderness;
- Pr 2.2.2 – Frequent episodic tension-type headache without pericranial tenderness;
- Pr 2.3.1 – Chronic tension-type headache with pericranial tenderness;
- Pr 2.3.2 – Chronic tension-type headache without pericranial tenderness;
- Pr 2.4.1 – Probable infrequent episodic tension-type headache;
- Pr 2.4.2 – Probable frequent episodic tension-type headache;
- Pr 2.4.3 – Probable chronic tension-type headache.

To assess the probability of an aviation incident influenced by human factors, the study evaluates combinations of critical events within the event tree. These critical combinations represent the minimal set of interconnected events that may trigger an emergency situation.

After identifying the necessary elementary states of the aviation system, systematizing them, assigning failure and recovery intensities, and collecting failure statistics for selected aircraft types in 2022, study proceeds to calculate λ_i and μ_i for several types of aviation systems:

Table 3.2. Intensities of flow and recovery flows for certain aircraft types.

λ_i, μ_i / Aircraft type	λ_1, μ_1	λ_2, μ_2	λ_3, μ_3	λ_4, μ_4	λ_5, μ_5
A-320	3, 57	10, 190	1, 19	1, 19	23, 437
CRJ-200	1, 19	2, 38	1, 19	0, 0	2, 38
B-747	0, 0	1, 19	0, 0	0, 0	2, 38
RRJ-95	0, 0	18, 342	3, 57	0, 0	26, 494

After obtaining the failure (λ_i) and recovery (μ_i) flow intensities for specific aircraft types listed in Table 1, the study proceeds to compute the probabilistic safety metrics using the MATLAB software environment. The differential equation system (2.1) can be implemented using the following program code:

```
dP0 = - (lyambda1 + lyambda2 + lyambda3 + lyambda4 + lyambda5) * P(0) + mu1 * P(1) + mu2 *
P(2) + mu3 * P(3) + mu4 * P(4) + mu5 * P(5);
dP1 = lyambda1 * P(0) - (lyambda2 + lyambda3 + lyambda4 + lyambda5 + mu1) * P(1) + mu2 *
P(6) + mu3 * P(7) + mu4 * P(8) + mu5 * P(9);
…
dP31 = lyambda5  * P(26) + lyambda4 * P(27) + lyambda3 * P(28) + lyambda2 * P(29) + lyambda1
* P(30) - (mu5 + mu4 + mu3 + mu2 + mu1) * P(31);
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4. RESULTS

Perform calculations for each aircraft type based on the obtained failure and recovery flow intensities, along with the previously presented system of differential equations.

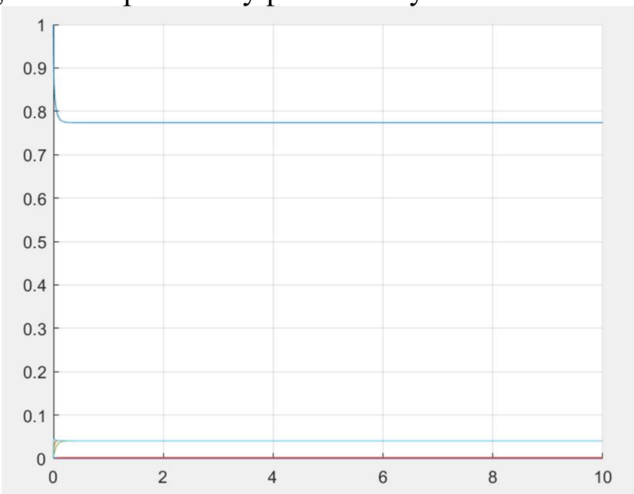

Fig. 4.1. Probabilistic safety characteristics for the A-320

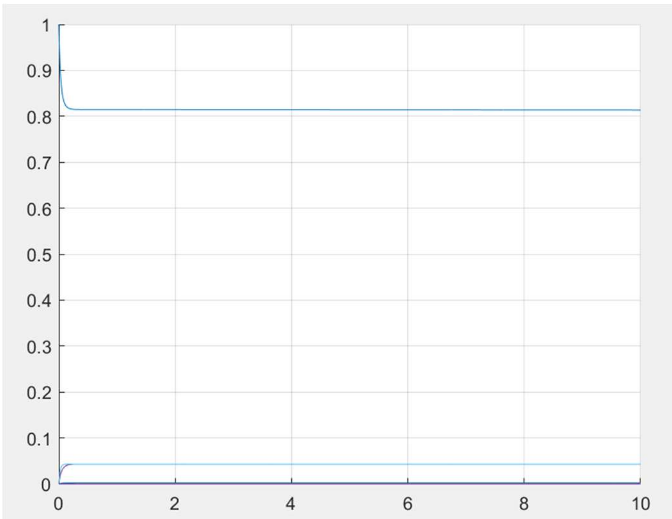

Fig. 4.2. Probabilistic safety characteristics for the CRJ-200

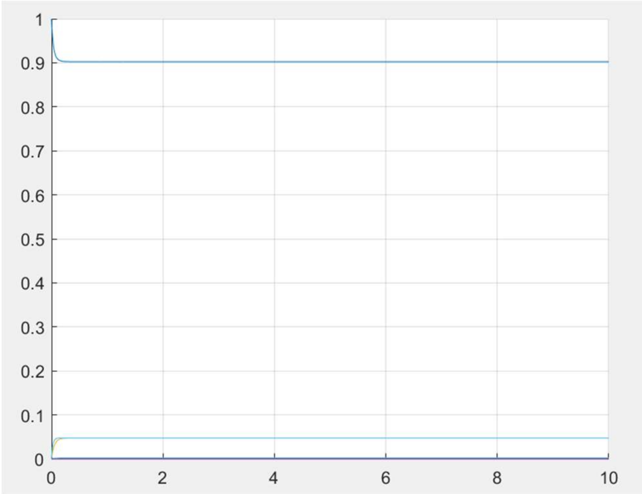

Fig. 4.3. Probabilistic safety characteristics for the B-747

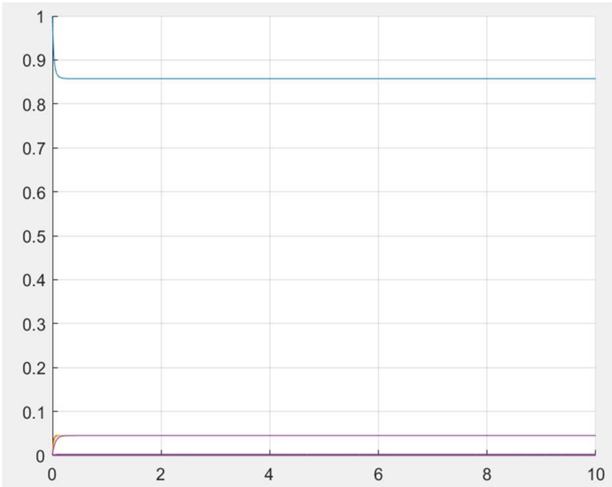

Fig. 4.4. Probabilistic safety characteristics for the RRJ-95

Figures 4.1-4.4 demonstrate that the initial vertex of the graph — representing the state in which all elementary components of the system remain fully operational — serves as the primary indicator for safety evaluation. This probabilistic characteristic remains high, while the values associated with other combinations of functional or failed elementary states R_i appear significantly lower, often approaching zero or remaining around 0.05.

Among the analyzed aircraft types, the B-747 exhibits the highest safety level in 2022, with a probability of $P_0 \approx 0.9$. In contrast, the A-320 shows the lowest safety estimate, with $P_0 \approx 0.78$.

5. CONCLUSION

This study developed and applied a structured probabilistic method for evaluating the safety and reliability of aviation systems based on mathematical modeling of system states and the failure and recovery flow intensities. By combining real-world failure statistics, formal state-transition models, and computational tools such as MATLAB, the methodology provides a quantitative foundation for identifying and mitigating operational risks in aircraft systems.

The analysis of probabilistic safety and reliability characteristics of aviation systems based on the assessment of elementary states and their corresponding failure and recovery flow intensities provides a quantitative evaluation of operational risks [1]. The use of state-transition models enables formalization of transitions between operational and failed system states.

Failure (λ) and recovery (μ) intensities play a central role in these models, as they determine the probability of the system occupying a particular state at any given moment.

Based on these characteristics, engineers and decision-makers implement technical and organizational measures to enhance system reliability and ensure the required level of flight safety. The probabilistic approach offers an objective foundation for designing, evaluating, and optimizing aviation systems throughout their entire life cycle.

In future work, the approach can be expanded by integrating more complex human factor models, environmental variability, and data from more aircrafts to further increase accuracy and applicability. The proposed methodology demonstrates strong potential for supporting data-driven decisions in aviation safety engineering.

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