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USING HEINRICH'S (BIRD'S) PYRAMID OF ADVERSE EVENTS TO ASSESS THE LEVEL OF SAFETY IN AN AIRLINE

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Abstract

One of the key concepts in matters of flight safety is that of special (abnormal) situations, with airworthiness regulation and certification of aviation equipment being based on this concept. At the same time, one is forced to admit that today there is no explicit interpretation of the standardized traits of special situations, nor are they not fully elucidated in the scientific literature. In this article we propose a pyramid-based approach to interpreting special (abnormal) in-flight situations, which allows for risk assessment not using risk matrices, but instead relying only on the probabilistic characteristics of the occurrence of events. Using the presence of a causal relationship between the layers of the pyramid, we propose an algorithm for the transition of varying degrees of danger of special situations. This algorithm can be used to develop an on-board device that informs the pilot about the dynamics of transitions from one situation to another, representing each emergency situation in a certain color.

Keywords: Aviation safety, risks, Heinrich's (Bird) pyramid, special (abnormal) situations.
Type of the work: *Research Article*

INTRODUCTION

It has been known in practice in the production and transport industries for some time that, long before adverse events actually occur, certain precursors may appear. In other words, prior to an incident, latent unsafe conditions have typically already existed. Identifying and eliminating these latent conditions requires objective and in-depth risk analysis. Many studies [1, 2, 9, 14] have shown that the incidence of injuries at enterprises obeys a pattern that resembles a pyramid. Based on this observation, various approaches have been proposed in the literature, establishing a cause-and-effect relationship between the precursors of adverse events and the events themselves. One such method is known as Heinrich's pyramid (or Bird's pyramid), which illustrates the frequency ratios between severe accidents, incidents and hazardous events in the form of 1-10-30-600, thus offering a certain way to manage safety in a given enterprise. The presence of such a link makes it possible to predict the risk of events on the "upper level" by planning to reduce risks on the middle and lower levels.

In this article we propose to use the intensity of events per unit of time as the main indicator. This intensity can be evaluated as a linear combination of the three pyramid-based ratings. The result will be a comprehensive enterprise safety indicator or safety level, K_{SI}:

$$K_{SI} = \frac{1}{3}\lambda_a + \frac{1}{3}\frac{\lambda_I}{K_I} + \frac{1}{3}\frac{\lambda_N}{K_N}, \tag{1}$$

where:

- λ_a – the intensity of accidents at the enterprise;
- λ_I – the intensity of incidents;
- λ_N – the intensity of inconsistencies in the activities of the facility, its services and their personnel;
- K_I and K_N – ratios of the number of incidents or nonconformities to the number of adverse events, respectively, for the studied period of time.

At its core, K_{SI} is an incident risk assessment based on the risk assessment of all events that have occurred in the enterprise over a certain time. The assessment will be the more accurate, the more accurate is the database of inconsistencies in the activities of the organization and its personnel (safety breaches) used in the construction of the pyramid. It is important to note that K_{SI} allows us to set numerical criteria for risk tolerance for "high-level" events and to further expand them across the remaining levels. This safety metric can also be used to plan and evaluate improvements after corrective action plans are implemented. Successful corrective action plans should rule out future incidents and nonconformities, resulting in a proportionate reduction or elimination of incidents (catastrophes and accidents).

However, there are also studies that refute this relationship. Thus, the study [1], where a regression analysis is performed between two variables – incidents and fatalities, shows a completely different relationship, namely that the fewer incidents occurred in a given year, the more fatalities there were. Conversely, the more incidents, the fewer deaths. At the same time, Bird's ratio is widely represented in the scientific and regulatory literature related to transport safety issues, in particular in aviation [2]. In our opinion, at least at the stage of preliminary assessment in matters of transport safety, this ratio can be used as one of the approaches to ensuring safety in transport.

Aviation also makes use of the concept of special (abnormal) in-flight situations, as a threat of varying degrees of danger [3]. These situations are classified according to the degree of danger with quantitative estimates of the frequency of their occurrence. They are widely used in the certification of aviation technology, aircraft accident investigation, as well as in various interpretations in scientific studies.

The purpose of this article is to demonstrate the possibility of assessing the current level of flight safety in an airline using a pyramid approach and interpreting special (emergency) in-flight situations, taking into account that the ideas behind the pyramids are based on the following principles:

- the main classification criterion is the danger of the consequences of a safety breach. This approach makes it possible not to use risk matrices when assessing risks, but rather to rely only on the probabilistic characteristics of the occurrence of events;
- a causal relationship exists between the layers of the pyramid, as a result of which it is possible to analyze the transition conditions of varying degrees of danger of special situations.

We will now take a closer look at each of these questions.

THE DEVELOPMENT OF AN ADVERSE EVENT DURING A FLIGHT

Tracing the sequence of the development of an adverse event during a flight, the following categories of causes can be distinguished: *main, direct* and *related*. A *main* cause is an organizational or constructional reason, which in flight creates a potential for the occurrence of an accident. *Direct* and *related* cases are ones that create real conditions for the transformation of possibility into reality. Thus, a direct cause is one that results in an adverse airborne event (accident or incident). It is usually the result of a root cause. As a result of the impact of direct and related causes, "abnormal" situations arise. They are characterized by a combination of aircraft properties and psychophysiological parameters on the part of the pilots, differing from the normative ones, and of a flight mode differing from the "standard" one. In regulatory documents, these are classified as "special situations" [4, 9]. This is a key concept in addressing safety issues [5, 6], with airworthiness regulation and aircraft certification being based on it.

On the grounds of the above notions, five possible states of an aircraft in flight can be distinguished. Let us represent them by S_i, whereby $i = 0, 1, 2, 3, 4$, and denoting a normal ("regular") flight in the absence of risk factors as S_0; a complication of flight conditions as S_1; a dangerous situation as S_2; an emergency as S_3; a catastrophic situation as S_4. Each of these states, having arisen in flight, can transition into any other state under the influence of new unfavorable factors or control actions on the part of the pilot [6, 7]. These situations may be characterized as follows:

- S_0 – a "normal" situation. The flight takes place under the expected operating conditions in the area of the recommended flight modes.
- S_1 – a complication of flight conditions. An "in-flight aircraft condition" characterized by a slight increase in the psychophysiological burden on the crew or a slight deterioration in the stability, controllability, or flight characteristics of the aircraft.
- S_2 – a dangerous situation. An "in-flight aircraft condition" characterized by a noticeable increase in psychophysiological burden on the crew or a noticeable deterioration in flight performance, stability or controllability, as well as one or several flight parameters outside the operational limits, albeit without reaching the limiting limits and design conditions. Preventing a difficult situation from transitioning into an emergency or catastrophic one can be ensured by timely and correct actions of the crew, including an immediate change in the flight plan, profile and mode.
- S_3 – an emergency situation. An "in-flight aircraft condition" characterized by a significant increase in psychophysiological burden on the crew, deterioration in flight performance, stability or controllability and leading to the limit values and design conditions being reached (or exceeded). Preventing an emergency situation from transitioning into a catastrophic one requires great professional skill on the part of the crew members.
- S_4 – a catastrophic situation. An "in-flight aircraft condition" for which it is assumed that preventing the loss of human life is practically impossible.

Using these concepts, the developmental process of an adverse in-flight event can be represented in the form shown in Fig. 1.

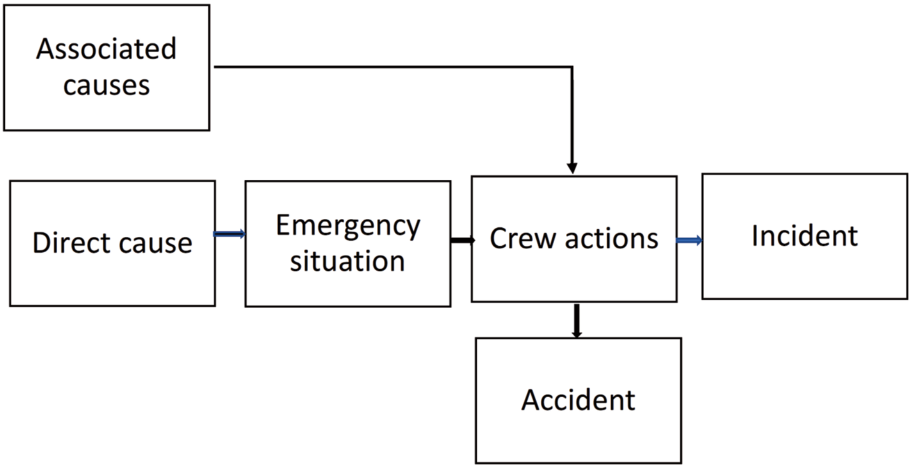

Fig. 1. The development process of an adverse in-flight event.

Abnormal in-flight situations due to the influence of additional unfavorable factors or due to interference in the pilot's control process, passing from one to another, from less dangerous to more dangerous or vice-versa, are depicted in Fig. 2.

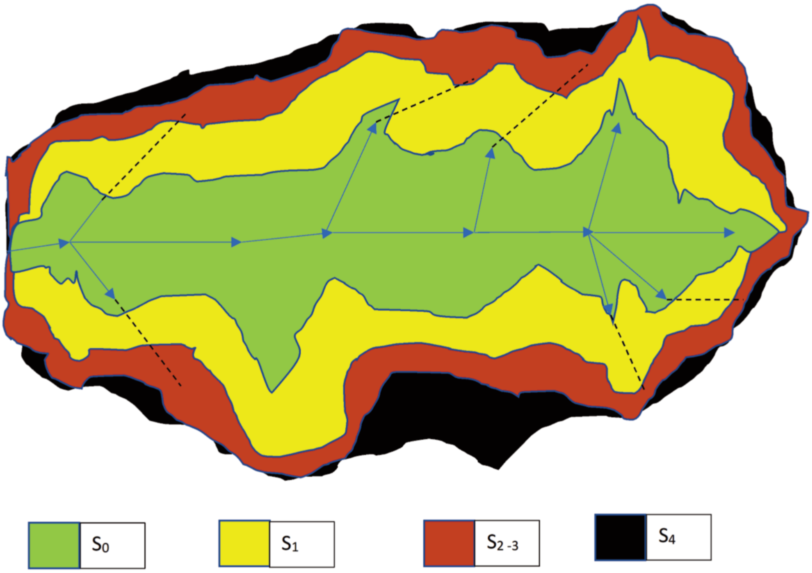

Fig. 2. Transition tree of in-flight situations when an aircraft is exposed to unfavorable factors.

At the same time, there is a large volume of precursors of emergency situations [7,12]. In this regard, we will supplement the above classification of emergency situations with one more category, designating it **as a situation without complications in flight conditions** or precursors of special in-flight situations. Investigation of such events is not provided for by international or national regulations. For an individual airline, however, they provide an indispensable base for improving the efficiency of flight safety. Thus, we have the following levels of the pyramid of events for an aviation enterprise (airline):

- number of catastrophic situations;
- number of emergency situations;
    - number of dangerous situations;
    - number of situations involving complicated flight conditions;
    - number of situations without complicated flight conditions.

Of these, the four emergency situations are basic, whereas one, added by us, is relevant for a single airline.

ESTABLISHING THE FREQUENCY OF SPECIAL IN-FLIGHT SITUATIONS

Based on the above, the frequency of basic situations available in regulatory documents is presented in this form:

- frequently $<10^{-3}$:
- moderately possible – from 10^{-3} to 10^{-5};
- unlikely – from 10^{-5} to 10^{-7};
- very unlikely – from 10^{-7} to 10^{-9};
- practically impossible – $<10^{-9}$.

The given frequencies represent the maximum permissible limits of special situations that can occur when taking into account the in-flight impact on the aircraft of the entire complex of unfavorable factors, which in practice are usually divided into three categories: equipment failures, human factor, and adverse environmental impact [8].

Uniting emergency situations with the presented ranges of their occurrence probabilities, we obtain the following diagram, representing the connection between emergency in-flight situations with the frequency of their manifestation [9], in Fig. 3.

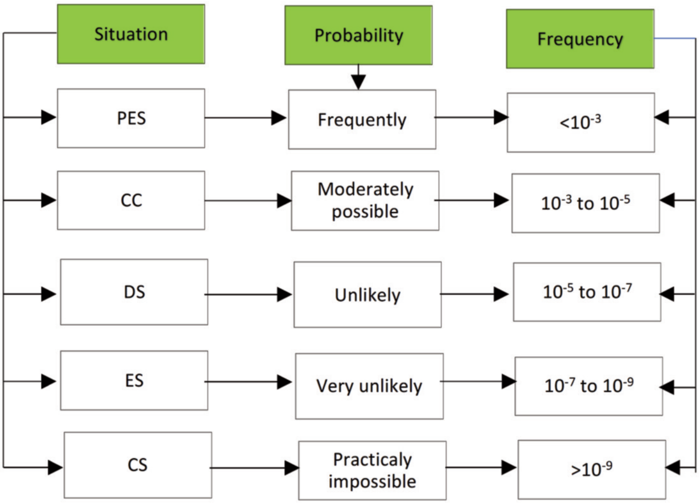

Fig. 3. The relation between emergency situations in flight and the frequency of their manifestation.

According to this figure, a complication of flight conditions is possible once in the range of 10^{-3}–10^{-5} flights, a dangerous situation is possible once in the range of 10^{-5}–10^{-7} flights, an emergency situation once in the range of 10^{-7}–10^{-9} flights. This means that a significant portion of the precursors of emergency situations occurring in flight, in the form of inconsistencies in the activities of the airline's services and personnel, do not in any way affect flight safety, provided that no accompanying reasons arise. As mentioned above in this figure, the ranges of emergency situations are indicated when taking into account all types of unfavorable factors (equipment failures, human, environmental factors). The solution to this problem is associated with uncertainty in identifying these factors and their practical use.

At the same time, the Airworthiness Standards establish upper limits on the probability of special situations when taking into account the in-flight occurrence of only aircraft failures per flight hour or per flight [8, 9]:

- for a catastrophic situation – $Q_{CS} < 10^{-7}$;
- for an emergency – $Q_{ES} < 10^{-6}$;
- for a dangerous situation – $Q_{DS} < 10^{-5}$;
- to complicate flight conditions – $Q_{CC} < 10^{-4}$;
- for precursors to emergency situations occurring in flight – $Q_{PES} < 10^{-3}$.

Therefore, we will consider this particular case in more detail, since each airline carries out a detailed analysis of these risk factors and their analysis. Based on this conditional classification of events, we can develop a statistical-probabilistic model for determining the level (aggregate criterion) of flight safety in an airline and test it in relation to the available statistics on aviation equipment failures in the airline's database.

FREQUENCY RATES OF ACCEPTED TYPES OF EVENTS IN THE AIRLINE

When determining the recurrence of the accepted types of events, we will use the methodology for assessing the aggregate criterion of flight safety, as an indicator showing the number of catastrophic situations (*CS*) per one flight hour or one flight. We denote it as $Q_i = q_i\, r_i$. Then, if we take the hazard indicator of a catastrophic situation r_C as a unit (as the admissible probability of this event occurring at 10^7 flight hours, then the hazard indicators of other types of events can be determined by the formulas [9].

$$r_{ES} = \frac{Q_{CS}}{Q_{ES}} = 0.1;\ r_{DS} = \frac{Q_{CS}}{Q_{DS}} = 0.001;\ r_{CC} = \frac{Q_{CS}}{Q_{CC}} = 0.0001;\ r_{PES} = \frac{Q_{C}}{Q_{PES}} = 0.00001. \qquad (2)$$

All the events we have accepted (emergency in-flight situations), their frequency of occurrence and hazard indicators can be summarized on the pyramid of events, Fig. 4.

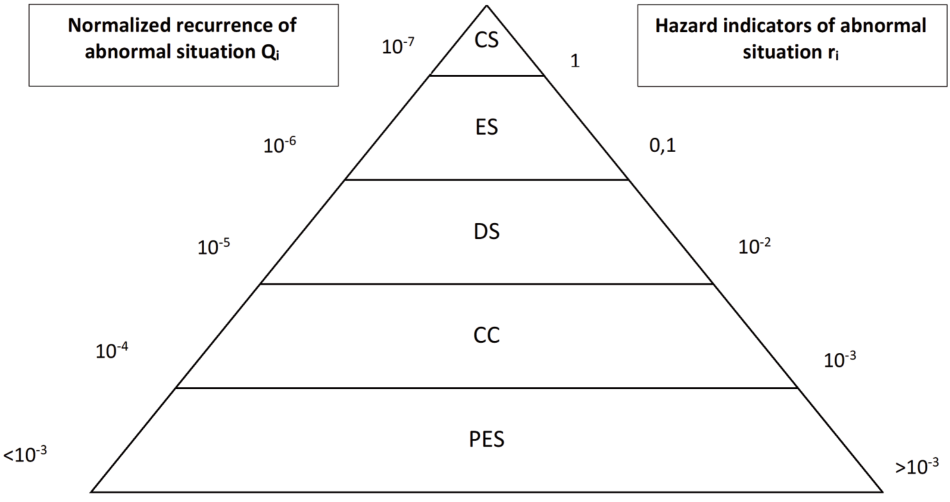

Fig. 4. Pyramid of possible emergency in-flight situations, taking into account precursors to in-flight emergency situations, their frequency and hazard indicators.

The ratio of hazard indicators of emergency situations can be written as:

$$n_{CS} : n_{ES} : n_{DS} : n_{CC} : n_{PES} = 1:10:10^2:10^3:\left(>10^3\right), \qquad (3)$$

where:

- n_{CS} – the number of catastrophic situations;
- n_{ES} – the number of emergencies situations;
- n_{DS} – the number of dangerous situations;
- n_{CC} – is the number of complications in flight conditions;
- n_{PES} – the number of precursors to emergency situations (situations without complicating the flight conditions).

In order to assess the level of risk, all specific situations must be analyzed.

The risk level R will then be the sum of the special situation risks that may arise as a result of the special situations included in Figure 4, using the weight coefficient λ_i. Then a comprehensive indicator of flight safety at the enterprise or the level of flight safety, K_{SI}.

$$K_{SI} = \left(N_{CS}\lambda_{CS} + N_{ES}\lambda_{ES} + N_{DS}\lambda_{DS} + N_{CC}\lambda_{CC} + N_{PES}\lambda_{PES} \right) = \sum \left(N_i \lambda_i \right). \tag{4}$$

Where:
- N_{CS} – the number of catastrophic situations;
- N_{ES} – the number of emergency situations;
- N_{DS} – the number of dangerous situations;
- N_{CC} – the number of events with complicated flight conditions;
- N_{PES} – the number of events without emergency flight conditions;
- λ_{CS} – weight coefficient for a catastrophic situation;
- λ_{ES} – weight coefficient for an emergency;
- λ_{DS} – weight coefficient for a dangerous situation;
- λ_{CC} – weight coefficient for events with complicated flight conditions;
- λ_{PES} – weight coefficient for events without emergency flight conditions.

Information on specific situations to assess the risks in the airline allows us to create a kind of risk scale. However, such a risk scale requires periodic reclassification, as the actual λ values are determined by the level of flight safety achieved, which changes over time. In addition, for different hazards, λ can vary significantly. This fact must also be taken into account in formula (4) when calculating R and dividing the risk factors into three categories [9,10,13]:
- Human factor (*HF*);
- Technical factor (*TF*);
- Adverse environmental factors (*EF*).

In this case, formula (4) will be as follows:

$$\begin{aligned} K_{SI} = \big[& \left(N_{CS}HF \cdot \lambda_{CS}HF + N_{CS}TF \cdot \lambda_{CS}TF + N_{CS}EF \cdot \lambda_{CS}EF \right) + \\ & \ldots + \left(N_{PES}HF \cdot \lambda_{PES}HF + N_{PES}TF \cdot \lambda_{PES}TF + N_{PES}EF \cdot \lambda_{PES}EF \right), \end{aligned} \tag{5}$$

where:
- HF – "human factor";
- TF – "technical factor";
- EF – "environmental factor";
- $N_{CS}HF$ – number of catastrophic situations due to the human factor;
- $N_{CS}TF$ – number of catastrophic situation due to the technical factor;
- $N_{CS}EF$ – number of catastrophic situation due to the environmental factor;
- $\lambda_{CS}HF$ – weight coefficient for the human factor in a catastrophic situation;
- $\lambda_{CS}TF$ – weight coefficient for the technical factor in a catastrophic situation;
- $\lambda_{CS}EF$ – weight coefficient for the environmental factor in a catastrophic situation;
- $N_{PES}HF$ – number of events without complicated flight conditions due to the human factor;
- $N_{PES}TF$ – number of events without complicated flight conditions due to the technical factor;
- $N_{PES}EF$ – number of events without complicated flight conditions due to the environmental factor;
- $\lambda_{PES}HF$ – events without complex flight conditions due to human factor, weight coefficient;
- $\lambda_{PES}TF$ – events without complicated flight conditions due to the technical factor, weight coefficient;
- $\lambda_{PES}EF$ – events without complicated flight conditions due to the environmental factor, weight coefficient.

When creating the risk scale, it is assumed that all its possible values of K_{SI} are in the range from “0” to “1”, which means the lower and upper limit. Such a scale can be used to assess the risk of specific situations. The numerical values of λ_i can be determined using systems of differential equations. However, the most appropriate way to quantify the weight coefficient is through statistical estimation. This is done by determining the frequency of transition from emergency to complex situations and complex flight conditions to catastrophic situations [10]. To achieve this, it is necessary to take the absolute values of the number of different types of special situations that have occurred in the specified period, as well as the number of components that lead to dangerous situations. This is a very complex process and it is therefore useful to develop a method for assessing flight risk [11]. For an airline with small and medium-sized air operations, the relative flight safety indicator can be calculated with sufficient accuracy using the following formula:

$$K = \frac{N_{NE}}{A}, \tag{6}$$

where:

- N_{NE} – the total number of negative (undesirable) events classified in regulatory documents, as well as existing non-conformities and violations of standard (specified) parameters, equipment failures and other events that are not included in the pyramid events shown in Figure 5, such as passengers, flights, landings, etc.;
- A – flight (hours) of the airline’s aircraft during the calculation period.

A condition on coefficient K is $K < 1$.

In order to increase the relative level of flight safety, we introduce a criterion scale factor: $M = 10^5$. N_{NG} is calculated according to the following formula:

$$N_{NE} = K_1 N_{CS} + K_2 N_{ES} + K_3 N_{DS} + K_4 N_{CC} + K_5 N_{PES} = \sum N_i K_i, \tag{7}$$

where K_1, K_2, K_3, K_4, K_5 – weight coefficients of negative events.

In essence, the negative event weight coefficients (K_1, K_2, K_3, K_4, K_5) correspond to the following coefficients λ_i:

- N_{CS} – number of catastrophic situations in the calculation period;
- N_{ES} – number of emergency situations in the calculation period;
- N_{DS} – number of dangerous situations in the calculation period;
- N_{CC} – number of complex flight conditions during the calculation period;
- N_{PES} – number of events without complicated flight conditions during the calculation period.

Adverse events differ not only in the degree of risk of the results of their consequences, but also in the frequency of their occurrence, therefore, using the expert method, the coefficients of event indices are determined [11]:

$$K_1 = 0.5; K_2 = 0.3; K_3 = 0.1; K_4 = 0.05; K_5 = 0.005. \tag{8}$$

Following from the previous equations we obtain:

$$K = \frac{\left(0.5 N_{CS} + 0.3 N_{ES} + 0.1 N_{DS} + 0.005 N_{CC}\right)}{A} \cdot 10^5. \tag{9}$$

The relative flight safety index in the analyzed period is determined by the formula:

$$K = \frac{1 - N_{NE}}{A} \cdot 100\%. \tag{10}$$

This relative flight safety index K over a given period of time is simple and easy to understand. This index takes into account the workload of the airline, all adverse events of the airline and reflects the level of flight safety. In order to compare risk factors, the method of expert assessment is used.

CONCLUSION

1. In practice, before an undesirable event occurs in transport operations, certain precursors appear. Therefore, investigating undesirable events involving deaths and property damage is not the most effective way to identify safety deficits. Rather, timely identification and elimination of such precursors requires an objective and in-depth risk analysis.
2. One of the effective methods of safety management involves the use of Heinrich's (Bird's) triangle. A stable causal relationship is assumed between the levels of such a pyramid, as a result of which it can be assumed that inconsistencies in the activities of services and personnel lead to incidents, and incidents lead to accidents and catastrophes. The presence of such a link makes it possible to predict the risk of events on the "upper level" by planning to reduce risks on the middle and lower levels. Thus, the pyramid shows a way how to manage safety.
3. When a transport unit in normal operating conditions is exposed to one or more adverse factors, "abnormal" situations may arise. Therefore, they have a pronounced random character due to the randomness of the impact of unsafe factors across time and space.
4. By combining emergency situations with the presented ranges of their probability, we obtain a diagram that represents the link between emergency in-flight situations and the frequency of their occurrence.
5. Using the presence of a causal relationship between the layers of the pyramid, herein we have proposed an algorithm for the transition of varying degrees of danger of special situations. This algorithm can be used to develop an on-board device that informs the pilot about the dynamics of transitions from one situation to another, representing each emergency situation in a certain color.

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WYKORZYSTANIE PIRAMIDY ZDARZEŃ NIEPOŻĄDANYCH HEINRICHA (BIRDA) DO OCENY POZIOMU BEZPIECZEŃSTWA W LINII LOTNICZEJ

Abstrakt

Jednym z kluczowych pojęć w obszarze bezpieczeństwa lotów, na którym opierają się przepisy zdatności do lotu i certyfikacja wyposażenia lotniczego, jest pojęcie sytuacji specjalnych (anormalnych). Z drugiej jednak strony obecnie nie ma jednoznacznej interpretacji standardowych cech sytuacji specjalnych, ani nie są one w pełni wyjaśnione w literaturze naukowej. W niniejszym artykule proponowano piramidalne podejście do interpretacji sytuacji specjalnych (anormalnych) w locie, które pozwala na ocenę ryzyka bez użycia macierzy ryzyka, a jedynie w oparciu o probabilistyczną charakterystykę występowania zdarzeń. Wykorzystując fakt, że zachodzi związek przyczynowo-skutkowy pomiędzy warstwami piramidy, proponujemy algorytm identyfikujący przejścia z jednego stopnia zagrożenia sytuacją specjalną do innego stopnia takiego zagrożenia. Algorytm ten może być wykorzystany do opracowania urządzenia pokładowego, które ma za zadanie informować pilota o dynamice przejść z jednej sytuacji do drugiej i sygnalizować każdą sytuację awaryjną określonym kolorem.

Słowa kluczowe: bezpieczeństwo lotnicze, zagrożenia, piramida Heinricha (Birda), sytuacje specjalne (anormalne).