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Entropy-probabilistic model for controlling the human factor in the system of ensuring the airworthiness of aircraft and their components

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Original article

Abstract

The following issues are addressed in the paper:

1. A mathematical model for controlling human factors in the aircraft maintenance system is proposed, aimed at identifying priority tasks in maintaining airworthiness under conditions of limited resources.
2. The model is developed using factor analysis under uncertainty, employing the entropy ranking method. In this approach, non-conformances in the activities of technical personnel (violations and errors) are represented as a multidimensional random generalized factor that comprises several measurable specific factors. The task of the management system is to determine the entropy of the generalized factor based on these measurable components.
3. A functional diagram of the control system is developed based on a systems approach, considering it as a dynamic system that, at each moment, is described by a set of physical variables (parameters).
4. Based on statistical data on deviations in the activities of airline technical personnel collected over a 10-year period, entropy indicators were obtained for several logically grouped factors—generalized indicators characterizing the main areas of management activities related to the continuing airworthiness of aircraft.
5. The results make it possible to identify the main areas of preventive activities within the airline aimed at reducing the negative impact of human factors during aircraft maintenance, which is particularly important under conditions of limited resources.

Keywords

- airworthiness
- aircraft
- human factor
- non-conformance in activities
- ranking
- procedure management
- entropy

Authors contributions

A – Preparation of the research project
B – Assembly of data for the research undertaken
C – Conducting of statistical analysis
D – Interpretation of results
E – Manuscript preparation
F – Literature review
G – Revising the manuscript

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None declared.

Introduction

Airworthiness is a measure of an aircraft's suitability for safe flight, defined by established requirements and standards and confirmed by the appropriate official documentation [1]. The growing importance of this issue in contemporary civil aviation is driven by several key factors:

- the existence of numerous independent airlines that differ significantly in ownership structure, operational characteristics, aircraft types, transport volumes, and other parameters [2];
- the development and refinement of documents and tools within the system of rules and forms of government regulation in the aviation sector [3];
- the aging of aircraft fleets in many airlines [4];
- the steadily increasing number of adverse events during the intended operation of aircraft caused by human factors within the continuing airworthiness system [5,6].

Ensuring aircraft airworthiness is carried out during the design phase of the aircraft based on the required scope of bench tests, flight tests, certification trials; and during serial production at all stages of aircraft devellopment [7]. Airworthiness is further maintained by aviation companies throughout aircraft operation and maintenance [8]. This area of continuing airworthiness is the most problematic [9]. Therefore, special attention is devoted to this area at all levels of the organisational structure. Maintenance programs for all types of aircraft also necessarily include tasks related to continuing airworthiness [10,11]. These tasks are subject to special oversight by the Aviation Authorities. However, due to its particular importance, this issue requires the continuous improvement of approaches and methods for its resolution. This article examines the influence of human factors as a risk factor in continuing airworthiness. This is one of the main responsibilities of engineers and technicians involved in aircraft maintenance. For these purposes, technical personnel use specialised equipment to assess the condition of the aircraft systems, adjust, regulate, and repair them, as well as perform disassembly and assembly work. However, for various reasons, errors and violations in complying with regulatory technical documentation occur in their activities, posing a threat to continued airworthiness and flight safety [10]. Analysis of such non-conformances in personnel activities indicates their diversity and differences in manifestation, allowing them to be grouped into four main categories 12,13]:

- inaccurate performance of required actions;
- performing of unnecessary actions;
- failure to perform required actions;
- untimely performance of required actions.

The situation is worsened by factors such as the untimely detection and correction of errors by specialists, the presence of permissible measurement inaccuracies that lead to non-compliance, and similar issues. Therefore, in the following sections, the human factor will be represented as "non-conformance" (violations and errors) in the activities of technical personnel. Various approaches exist for studying this problem, among which the most advanced is the SHEL model [14]. The practical foundation for such research consists of statistics on "non-conformance" (violations and errors) in the activities of technical personnel. However, the available literature lacks detailed information on methodological approaches and techniques for the collection, evaluation, classification, and use of such data.

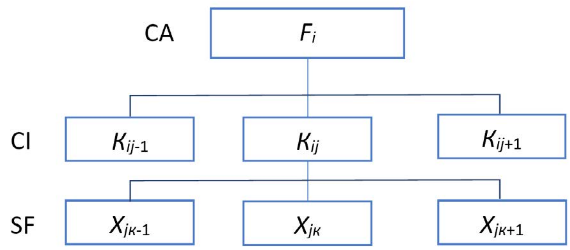
More comprehensive information is available in Maintenance, Repair, and Overhaul (MRO) organizations that possess their own maintenance bases equipped with modern tools and qualified specialists. However, such information is typically confidential and not fully accessible. To obtain the necessary data, the authors used various sources, including the Federal Aviation Agency's Aviation Safety Information Analysis and Sharing (ASIAS) system. This system includes several databases on incidents and accidents, among which are the Aviation Safety Reporting System (ASRS) [15] and the National Transportation Safety Board (NTSB) database [9, 18], covering the period from 1999 to 2020. The ASRS database is based on anonymous reports submitted by employees on a completely voluntary basis. The NTSB database was created by an independent commission based on accident investigations conducted throughout its history.

Issues related to the organization and management of continuing airworthiness have also been discussed in the works of several researchers [13, 17]. Analysis of these sources from different perspectives has shown that interest in the human factor in aircraft maintenance systems has grown significantly over the past 10–20 years, and that the proposed methodologies partially enable solving such tasks. For example, methodological recommendations presented by these and other authors are based on the principles of a systems approach to studying continuing airworthiness and typically involve a sequence of analytical steps. One of the advantages of these methodologies is the authors' proposed schemes for studying the structure, characteristics, and operational features of aircraft, as well as identifying factors that affect airworthiness, using approaches such as mathematical statistics, probability theory, reliability theory, engineering psychology methods, aviation ergonomics methods, and others. However, the application of these methodologies to aircraft airworthiness assurance is more appropriate during the earlier stages of design and manufacturing. At the same time, the reviewed sources lack sufficient methods for quantitatively assessing the level of aircraft airworthiness in operation. There is no unified, effective methodology for managing the human factor [19]. There is also a lack of organized information necessary for studying this risk factor, and information specifically on its influence on airworthiness is almost nonexistent. The analysis also showed that airlines continually face the task of identifying priority issues related, on the one hand, to the need to eliminate or reduce risks affecting airworthiness, and on the other hand, to resource limitations. This creates a need for risk ranking that includes the human factor within the aircraft maintenance system. This article presents a mathematical model for managing the human factor in the aircraft maintenance system using entropy-based evaluation. The model is based on the analysis of non-conformances in the activities of technical personnel during aircraft maintenance. The model enables identification of the main areas of managerial activity. It was tested by analysing statistical data on deviations in the activities of technical personnel of a Latvian airline over a ten-year period. Entropy indicators were obtained for a set of logically grouped, generalized factors that characterize the main areas of managerial activity for the continuing airworthiness of aircraft. The results make it possible to identify the key areas for preventive action by the airline aimed at reducing the negative influence of the human factor in aircraft maintenance, which is especially important under conditions of limited resources.

Entropy-probabilistic model for managing the human factor in the Human Factor Control System (HFCS)

The model is based on the goal of ensuring the targeted development of control actions on the human factor to prevent its negative influence on the aircraft airworthiness, taking into account the available resources. The model is based on the goal of ensuring the targeted development of control actions addressing the human factor to prevent its negative impact on aircraft airworthiness, while taking into account the available resources. Following the systems approach [20], the model being developed is represented as a multidimensional system consisting of a set of subsystems and elements that are functionally interrelated. Their purpose is to collect information on non-conformances (violations and errors) in the activities of aviation technical personnel, as well as to process and analyze this information. The results are then used to develop control actions aimed at reducing the negative influence of these factors. In developing the model, non-conformances are described using indicators adopted in qualimetry for quality assessment [21]. The control actions are represented as generalized indicators F_i, where $\{i = 1, \ldots, n\}$, each of which includes a set of complex indicators K_{ij}, where $\{j = 1, \ldots, m\}$. These are grouped according to logically related causes of the non-conformance occurrence. Thus each F_i has its own unique set of j-th complex indicators. Each of these is quantitatively evaluated as the probability of the occurrence of recurring identical specific non-conformance, which we denote as the elementary (individual) component indicators X_{jk}, where $\{k = 1, \ldots, l\}$. These represent a recorded specific non-conformance (error or violation) in technical personnel activity over a given period of time.

Thus, the structure of the control actions F_i is represented by a three-level model (see Figure 1). The lowest level of specific factors (SF) in the SF system includes recurring individual indicators, the number of which is recorded over a given period. The next level, the level of complex indicators (CI), includes indicators K_{ij}. The top level includes a set of control actions (CA), whose quantitative values represent the goal of this model, as they cannot be measured directly.



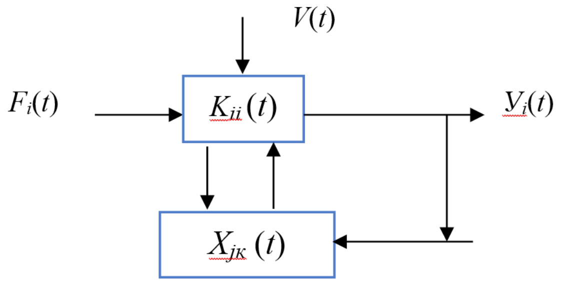
Where:
CA—Control actions level
CI—Complex (probabilistic) indicators level
SF—Recorded Specific Factors of “non-conformance” in staff activity

Figure 1. Three-level model for determining control actions in the SF system

The set of generalized indicators $F_i(t)$ defines the Human Factor Control System (HFCS):

$$\{F_1(t), F_2(t), \ldots F_n(t)\}. \quad (1)$$

The next element of the model is the procedure for ranking control actions in terms of determining priority actions for managing the human factor, based on their level of negative influence on continuing airworthiness and on available resources. Let us consider the functional diagram of the HFCS shown in Figure 2.



Where:

$F_i(t)$—i-th control action

$Y(t)$—effect resulting from the i-th control action

$K_{ij}(t)$—j-th indicator of the probability of recurring non-conformance

$X_{jk}(t)$—k-th indicator of recurring non-conformance in staff actions

$V(t)$—external environmental influence

Figure 2. Functional diagram of the human factor control system (HFCS)

The state of the HFCS as a dynamic system at any given moment t is described by a set of physical variables that represent a set of non-conformances (violations and errors by personnel) recorded at the moment t:

$$\{X_{j1}(t), X_{j2}(t), \ldots X_{jl}(t)\} \quad (2)$$

By changing the control signal $F_i(t)$, the system can be transitioned to a new state with parameters:

$$\{X_{j1}(t_1), X_{j2}(t_1), \ldots X_{jl}(t_1)\} \quad (3)$$

That is, the system can be controlled.

On the other hand, knowing the values of the control signals $F_i(t)$ and the corresponding outputs $Y_i(t)$ over an extended period of time, we can determine the system's initial state:

$$\{X_{j1}(t_0), X_{j2}(t_0), \ldots X_{jl}(t_0)\} \quad (4)$$

or its current state (1), i.e., perform system observation.

The human factor in the aircraft maintenance system, represented as non-conformance (violations and errors) in the activities of technical personnel, is characterized by a high degree of diversity and variation, as well as a wide range of external manifestations. Their complexity, variability, and uncertainty under different circumstances significantly complicate the task of defining standard indicators. In this regard, we introduce the concepts of the controlled state of the system and the observed state of the system.

The controllable state of the system is a state in which, for any moments of time t_0 and t_1 (where $t_1 > t_0$), there exists a control action $F_i(t)$ within the interval $t_0 < t < t_1$ that transfers the system from its state at time t_0 to its state at time t_1.

The observable state of the system is a state in which, based on the measured or observed vectors $F_i(t)$ and $Y_i(t)$ over a finite time interval $t_0 < t < t_1$, it is possible to precisely determine the system's state at time t_0 as well as its current state at time t_1.

Thus, an observable system is understood to have the ability to record, at different points in time, quantitative or qualitative indicators that allow for the assessment of the current overall state of the system. In other words, continuous monitoring is conducted to identify non-conformance (errors and violations) in the activities of technical personnel.

However, the available literature provides limited concrete information on methodological approaches and techniques for collecting, assessing, classifying, and utilizing such data. Therefore, for the purposes of defining the analytical framework, we assume that within the modeled Human Factor Control System (HFCS), four types of possible states may occur at different stages of its operation over the study period:

- SCO — States that are Controllable and Observable;
- SCUO — States that are Controllable but Unobservable;
- SNCO — States that are neither Controllable nor Observable;
- SUCO — States that are Uncontrollable but Observable.

For the HFCS to be effective, it must remain in a Controllable and Observable state (SCO). Any combination of other states (e.g., SCO and SUCO; SCUO and SNCO; SCO and SCUO, etc.) leads to a condition of uncertainty regarding the system's current parameters. This means that if the system is influenced either by control actions or by external environmental factors at random moments in time, its state begins to change. Until a new, stable state is fully established, a certain degree of uncertainty will persist. The level of this uncertainty depends on the combination of control and observation processes. For instance, if the system is monitored during this period (i.e., its parameters are recorded), the degree of uncertainty can be reduced or even eliminated entirely. As is well known, the degree of uncertainty in a system is measured by entropy [22].

The use of entropy is one of the promising approaches in modeling complex stochastic systems, particularly for risk ranking and determining priority measures for risk reduction, which is the goal of this study [23,24]. Based on this, an entropy-based approach is employed to rank risks associated with non-conformance in technical personnel activities, in order to determine priority tasks for maintaining aircraft continuing airworthiness at the established level [25].

To do so, the entropy values of the generalized indicators $H(F_i)$ are used. The mathematical interpretation of the model is given by the following equation [26]:

$$H(F_i) = \sum_{(i=0)}^{j} P(K_{ij}) \log P(K_{ij}) \quad (6)$$

Where:

$P(K_{ij})$—probability of a concrete type of deviation in the personnel's activities, recorded over a certain period (specific factors).

$H(F_i)$—entropy level of the generalized factor, representing the i-th control object in the HFCS.

Results and discussion

Results

The proposed model was tested using data on "non-conformance" in the technical personnel activities from sources containing statistical data for a 10-year period (1995–2005) at Riga Airport, for AVRO-RJ70 aircraft. The total flight time of this fleet during the specified period was T_Σ = 2,684,217 hours [27]. The total number of non-conformance (individual indicators X_{jK}) committed by the personnel amounted to over 100 quantities, which were grouped into 20 complex indicators K_{ij} based on the results of the analysis. The probability of their occurrence was calculated over the study period. Using an automated expert system [26], these were further combined into 5 generalized factors F_i (as shown in Figure 1):

- F_1—Improvement of personnel management organization in aircraft maintenance.
- F_2—Enhancement of management organization within the operational circuit of aircraft maintenance in the airline's network.
- F_3—Improvement of quality control in aircraft maintenance.
- F_4—Enhancement of professional training and discipline of technical personnel.
- F_5—Improvement of technical personnel's efficiency in working with modern diagnostic and control equipment.

The percentage distribution of complex indicators included in each of the generalized factors is presented in Table 1.

Table 1. Percentage distribution of non-conformance in the technical personnel activities

F_1	F_2	F_3	F_4	F_5
21,5%	16,2%	22,9%	25,1%	14,3%

The complex indicators K_{ij} included in each generalized factor F_i are characterized by a common logical feature. For example, the generalized factor F_1 includes five complex indicators K_{ij}, as shown in Table 2:

Table 2. Factors K_{ij} included in the generalized indicator F_1

K_{11}	Violations and erroneous actions during aircraft maintenance procedures
K_{12}	Allowing personnel to work without the necessary training
K_{13}	Use of non-certified tools by personnel
K_{14}	Performing work by personnel without appropriate authorization (not specified in licenses)
K_{15}	Aircraft releasing for operation with malfunctions not listed in the relevant documents (MMEL and MEL)

Their diversity indicates that these violations stem from deficiencies in the overall organization of work within the MRO. This conclusion is based on the fact that all logically related complex indicators listed above manifest systematically, as evidenced by the significant number of violations and errors (21.5% of the individual indicators). Indeed, ineffective organization in maintenance operations within the technical department can lead to situations where personnel work without proper briefing or certification, or use uncertified tools, which in turn provoke violations and errors during maintenance procedures. Similar logical chains connect other individual indicators grouped into complex indicators, which are, in turn, consolidated into generalized factors (F_2, F_3, F_4, F_5).

The next step in applying the model involved calculating the entropy values of the generalized factors F_i, using equation (6), and ranking them according to the quantitative value of each, in terms of their negative influence resulting from personnel violations and errors on aircraft continuing airworthiness. The ranking results are presented in Table 3. The highest entropy value indicates the area requiring the most immediate managerial attention in addressing these issues with personnel.

Table 3. Ranking of control actions

F_i	F_1	F_2	F_3	F_4	F_5
$H(F_i)$	5.16	3.49	2.47	2.32	1.54

As a result, a well-founded sequence of necessary control actions was obtained to prevent the loss of aircraft continuing airworthiness due to violations and errors in the work of technical personnel during the maintenance process. The highest priority was assigned to the factor related to the organization of aircraft maintenance operations within the MRO. The second priority concerned the improvement of management organization within aircraft maintenance across the airline's route network. The third position corresponded to the enhancement of maintenance quality control. The fourth priority involved improving the professional training and discipline of technical personnel. Finally, the fifth priority addressed the improvement of technical personnel's performance when working with modern control and diagnostic equipment. The combination of these factors defines the Human Factor Control System within the MRO, ensuring the required level of aircraft continuing airworthiness.

Discussion of the results

The application of this model requires a well-considered approach to selecting the composition and number of indicators that define the control actions Fi and the probabilistic values K_{ij} of the recurring partial indicators X_{jK} (see Figure 1). This is due to the wide variety of possible "non-conformance," which makes it possible to classify them with varying degrees of detail and categorization — that is, with different levels of generalization. Such classification demands a certain level of expertise in logical analysis. This task can be performed by qualified specialists or through expert surveys, depending on the status and capabilities of the maintenance organization. For these purposes, it is proposed to use an algorithm developed with the participation of the authors of this article (V. Shestakov, J. Tereščenko) for analyzing deviations and violations in the work of maintenance structural units and personnel under conditions of uncertainty, aimed at developing measures to improve flight safety levels [28], as well as in a doctoral dissertation supervised by (V. Shestakov) [16]. The algorithm is designed so that the risk management system related to "deviations" in the technical personal activities evaluates them as either "acceptable" or "unacceptable." If the risk is deemed "unacceptable," appropriate measures are taken, including establishing personal responsibility. The analysis framework enables prompt response to "deviations" in the work of technical personnel. The algorithm is structured with consideration for the limited manager responsibility to make decisions and the possibility of involving a higher-level manager in the analysis and decision-making process. The "involving" of a high-level manager in the analysis scheme is possible at any stage. The algorithm also accounts for the incompetence or indecisiveness of the manager in performing certain stages and allows for the involvement of colleagues, more qualified specialists, or specialists from other departments, etc., to solve specific analysis tasks. The proposed algorithm is implemented in an automated expert system for analysis, used to solve various tasks requiring this type of expertise, and was employed by the authors during the testing of the proposed model [16].

Conclusion

The effectiveness of human factor management in continuing airworthiness is largely determined by the timely identification and elimination of unexpected "deviations" (violations and errors) in the technical personnel acting. Therefore, the main principles of management are:

- Timely identification of "deviations" that may lead to airworthiness decrease in.
- Assessment of their danger level and forecasting trends in their influence on airworthiness.
- Timely development of preventive measures.
- Implementation of operational and long-term measures to prevent or limit "non-conformance";
- Monitoring the effectiveness of management activities in the technical service.

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