

Data processing in operation systems of CNS equipment

Oleksandr Solomentsev^{1,†}, Maksym Zaliskyi^{1,2,*,†}, Yuliia Petrova^{1,†}, Alina Osipchuk^{1,†}, Anton Plugoviy^{1,†} and Serhii Halenko^{1,†}

¹National University "Kyiv Aviation Institute", Liubomyra Huzara Ave., 1, Kyiv, 03058, Ukraine

²Interregional Academy of Personnel Management, Frometivska Str., 2, Kyiv, 03039, Ukraine

Abstract

Communication, navigation, and surveillance (CNS) equipment plays an important role in providing air navigation services for flights. Under the influence of degradation processes, the reliability of CNS equipment operation must be maintained and restored. The necessary actions to counteract possible negative impacts are formed and implemented by the CNS equipment operation system (OS). In terms of functional completeness, the OS includes the CNS equipment, personnel, regulatory documentation, processes, cost and information resources, etc. It should be emphasized that the uncertainty of the condition of the OS elements and, first of all, the CNS equipment is associated with possible risks of unnecessary resource consumption, which negatively affects the efficiency and effectiveness of the OS functioning and the quality of air navigation service for flights. Monitoring and further classification of the condition of the OS elements are implemented by observing the trends of parameters that characterize the quality of the OS components. The more components are covered by monitoring, the lower the overall level of uncertainty in the OS and the better its functioning. The trends of the OS component parameters are usually stochastic in nature. At the same time, we have objective non-stationary nature of processes with the presence of the so-called "changepoint" effect. The paper presents proposals for monitoring and control of as many components of the OS as possible using statistical classification algorithms, Internet of Things technologies and artificial intelligence, as well as the use of Local and Central data hubs for storing monitoring data, long-term and comprehensive analysis of the conditions and events in the OS. A calculation is presented that confirms the hypothesis about the feasibility of using statistical processing procedures when monitoring the condition of CNS equipment. The paper presents the synthesis and comparative analysis of monitoring procedures and decision-making on the condition of equipment, characterized by a non-stationary trend of the determining parameter with the changepoint of the initial data.

Keywords

data processing, decision-making, sustainable industry, efficiency, life-cycle assessment, sustainable economic, operation system, CNS equipment, changepoint, prediction

1. Introduction

Radioelectronic equipment are used in many areas of industry and society [1, 2, 3]. In civil aviation, ground-based radio-technical equipment (RTE) for flight support is used for air navigation service of flights [4, 5, 6]. These are ground-based communication, navigation and surveillance means (CNS – in ICAO abbreviations). Of the 4 known stages of the life cycle of RTE – design, manufacture, operation, disposal – operation has the longest duration [7, 8, 9]. This factor has at least two components:

1. It is necessary to apply the required measures for reliable and effective support of aircraft flights.
2. The resource costs in this case far exceed the initial cost of RTE [10, 11, 12].

The efficiency of use (reliability of operation) and the economic component of the operation of RTE are directly related to the operation systems (OS) of these means [13, 14, 15].

WCH'26: Fifth International Workshop on Cyber Hygiene, June 25–26, 2026, Krakow, Poland

*Corresponding author.

[†]These authors contributed equally.

✉ avsolomentsev@ukr.net (O. Solomentsev); maksym.zaliskyi@npp.kai.edu.ua (M. Zaliskyi); panijulia.p@gmail.com (Y. Petrova); alina.osipchuk2012@gmail.com (A. Osipchuk); 1819713@stud.kai.edu.ua (A. Plugoviy); 6169326@stud.kai.edu.ua (S. Halenko)

ORCID 0000-0002-3214-6384 (O. Solomentsev); 0000-0002-1535-4384 (M. Zaliskyi); 0000-0002-3768-7921 (Y. Petrova); 0000-0002-9053-2072 (A. Osipchuk); 0009-0002-9830-9331 (A. Plugoviy); 0009-0002-3365-1494 (S. Halenko)



© 2026 Copyright for this paper by its authors. Use permitted under Creative Commons License Attribution 4.0 International (CC BY 4.0).

The initial design or modernization of the OS of RTE is such a scientific direction that will attract the attention of scientists, specialists of state regulatory bodies, operational personnel, and others [16, 17, 18].

The composition of the OS of RTE can include:

- the RTE themselves,
- operational personnel,
- processes,
- regulatory and administrative documentation,
- consumable resources,
- information resources,
- technological equipment,
- structures,
- personnel workplaces, and others [19, 20].

Thus, the OS of RTE is a rather complex system, therefore the volume of resources from society during the initial design or modernization should also be significant [21, 22, 23].

Current scientific and practical tasks can be considered in at least two aspects:

1. This is the preparation of the OS for effective work after the end of martial law in Ukraine.
2. The introduction of the latest achievements in the field of information technology and statistical data processing in the OS [24, 25].

Recent scientific studies show that it is advisable to carefully collect statistical data on the functioning of all components of the transport infrastructure, process this data, and form preventive and corrective actions based on them [26, 27, 28].

The object of the research in this paper is the process of operating ground RTE. The subject of research in this paper is information technologies in the field of statistical data processing and others that operate on the basis of artificial intelligence for use in the operation systems of ground-based RTE.

The purpose of this research is to reduce the level of uncertainty in the state of components of the operation system and, accordingly, reduce the level of non-target (excessive) costs during the operation of RTE.

2. Problem statement

The purpose of developing information technologies based on AI is to reduce the level of uncertainty in the state of the components of the RTE OS, to form the necessary corrective and preventive actions in order to reduce the level of unnecessary costs during the operation of RTE, provided that the customers of OS services have received the necessary information for the safe and effective operation (aircraft flights) of all subjects and objects of aviation activity within the entire state.

It is advisable to emphasize that with a greater coverage of the elements of the subject area in the part under consideration, a more positive effect can be obtained. This opportunity will be provided by the use of modern information technologies and telecommunications equipment and networks.

It should be emphasized that the structural diagram of the data processing complex in the operation systems of RTE is complex. Therefore, it is proposed to formulate the task statements for the synthesis and analysis of information technologies based on AI for each of the five components of the structural diagram in Figure 1.

Let us consider the five components of the structural diagram in Figure 1:

1. The first component is the OS of a separate enterprise and the Os within country;
2. The second component is the complex of operational management of a separate OS of the enterprise. The content of a particular component may vary depending on the characteristics of a particular enterprise;

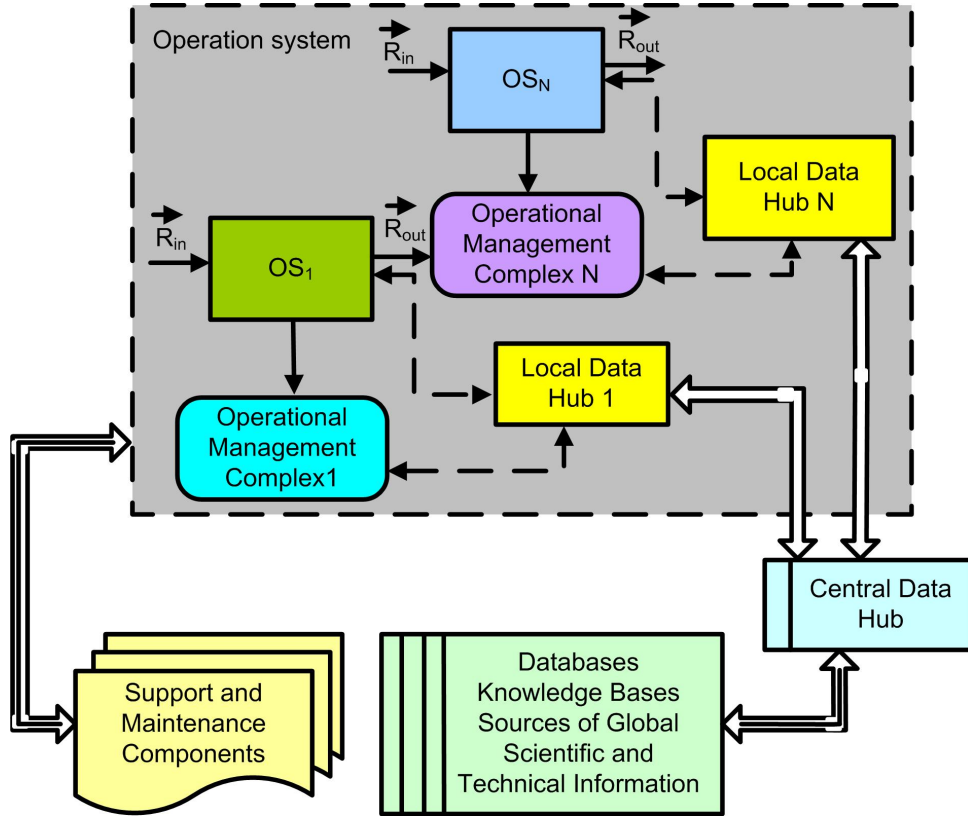


Figure 1: The generalized diagram of the OS.

3. The third component concerns the subjects of providing and supporting the OS of all enterprises;
4. The fourth component is Local Data Hubs for storing, processing, and analyzing data of a separate OS;
5. The fifth component is the Central Data Hub, which unites and reserves the work of Local Data Hubs.

The methodological scheme for forming tasks for the development of information technologies is not necessarily based on AI. We indicate the following elements:

1. The flow of $\vec{R}_{in}$ and $\vec{R}_{out}$, which is the task and result of the activities of a particular component.
2. The content of a particular component.
3. Models that describe the functioning of individual parts of the component.
4. Performance/efficiency indicators.
5. Resources, data processing algorithms.
6. Possible risks.
7. Equipment operating conditions.

Then the description of the subject area for the 1st and 2nd components in the form of generalized functionalities will have the following form from the point of view of assessing the effectiveness and efficiency of the functioning of the i -th operation system OS^i

$$E^{(j)}(Efficiency, Effectiveness) = OS^{(j)}(\vec{R}_{in}(\vec{\gamma}_j), \vec{R}_{out}(\vec{\gamma}_j) / \vec{S}^{(j)}, \vec{A}^{(j)}, \vec{M}^{(j)}, \vec{C}^{(j)}). \quad (1)$$

The operation system $OS^{(j)}$ serves the flow of incoming requests for providing information using ground-based CNS and telecommunication equipment to aircraft and airport units.

The generalized operator $\vec{S}^{(j)}$ characterizes the standard composition of components that are necessary to ensure the functioning of $OS^{(j)}$. These are organizational elements (staff workplaces, office premises, and buildings), documentation, personnel, processes; consumable and information resources. Next, it is appropriate to indicate the set of algorithms for monitoring and controlling the condition of equipment $\vec{A}^{(j)}$.

Models $\vec{M}^j$ are a necessary component in solving synthesis and analysis problems. They are stochastic in nature and describe the change in determining parameters, reliability indicators, features of changepoint, and others.

At the same time, we will assume that risks will not necessarily lead to costs $\vec{C}^{(j)}$, this is a probabilistic category. But, if the events are irreversible, then we will already have costs - decision-making errors, delays in management actions, suboptimal models of events, data, and others.

The generalized formula (1) can be used to formulate individual synthesis/analysis tasks regarding the positions in (1). In the general case, it is necessary to minimize unnecessary costs in the subject area while complying with the requirements for the quality of service provision for customers acting for society during air transportation. When searching for a design solution, one should pay attention to the need to form several alternative options, and then choose the best option within the framework of a particular efficiency criterion. We emphasize once again that all positions of the generalized functional description $OS^{(j)}$ according to formula (1) can be the subjects of the search for optimal design solutions DS

$$DS(\vec{A}^{(j)}) = \vec{A}^{(j)}(Search(AV, EC)/OS^{(j)}), \quad (2)$$

where AV is alternative variants formation, EC is efficiency criteria.

In general, according to (2) during the formation of the project solution, it is necessary to form alternative options, and then use the efficiency criterion to find the most attractive option. Efficiency criteria can be simple (min, max, and others) or there is a multi-criteria option.

3. Methods of data processing in the operation system

The operational control subsystem of a separate $OS^{(j)}$ implements two groups of data processing algorithms. The first group of algorithms performs statistical processing of the determining parameters of the CNS equipment. The second group processes data included in the list of inspection checks of CNS devices by state bodies responsible for the safety of aircraft flights in terms of RTE use. We have two structural schemes for data processing during condition monitoring and decision-making.

The generalized structural scheme for processing data on determining parameters, or reliability indicators, is shown in Figure 2. Data processing is performed using statistical classification algorithms, forecasting the trend of determining parameters for a certain forecast time.

A distinctive feature is processing that can detect the effect of changepoint in the trends of the output data. In addition, processing is advisable to be carried out in a sliding window in order to determine the predicted values in the trends of the output data. In this case, it is advisable to take into account the selected maintenance strategy of the CNS equipment. For example, the condition-based maintenance strategy assumes the presence, in addition to operational tolerances, of preventive tolerances. Then, when finding estimates of parameters that are monitored within the limits of preventive tolerances, regulatory, and other work is not planned to be performed, but it is necessary to take into account the predicted estimates of parameter trends. In general, based on the generalized data processing scheme for the RTE, it is necessary to carry out procedure of the synthesis and analysis of statistical data processing algorithms.

The model of the initial data characterizing the state of the RTE has the following form. This model takes into account the possible non-stationary nature of the trend of the determining parameter (DP), or the reliability indicator, in this case the failure rate $\lambda(t)$. The sliding window is appropriate because a certain amount of data is required to form the estimate $\lambda^*(t)$. In addition, when forming predicted estimates of parameter trends, a training data sample is also required.

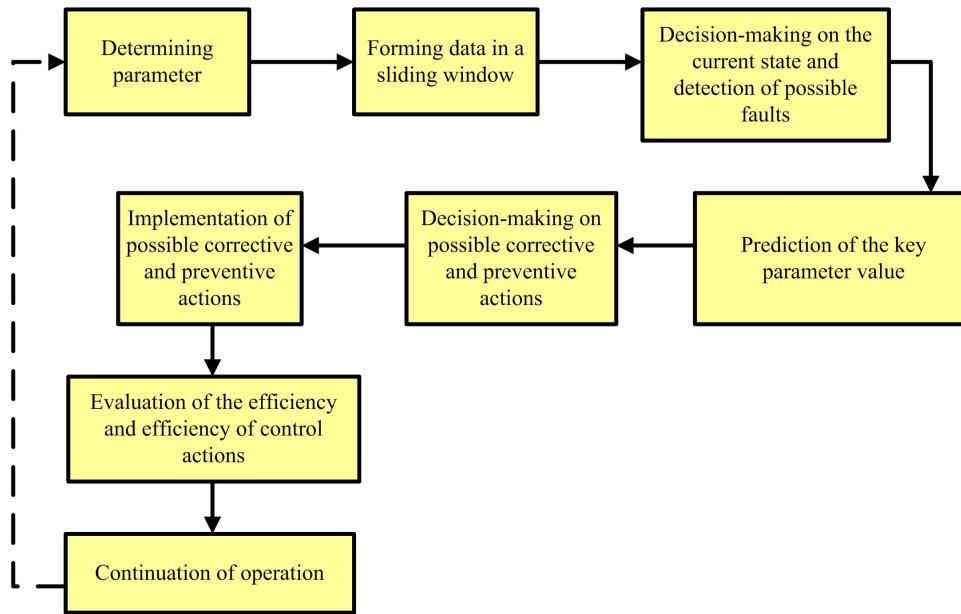


Figure 2: The generalized structural scheme for processing data on determining parameters or reliability indicators.

The trend model has two components: the first component has the number of samples when there is no trend of the changepoint in DP. The duration of the component is random in volume. Next, we will have the second component, which has a linear nature of the change in the DP over time. We will also assume that the forecast - the behavior of the trend of the DP has a ratio to the volume of the training sample as 1:4. The duration of the forecast period is chosen in such a way that during the forecasting period, the personnel of the RTE were able to perform work to return the DP to the nominal value.

The $OS^{(j)}$ has the following main components - RTE, personnel, documentation, processes, consumable resources, and information resources. In addition to the determining parameters and reliability indicators, it is advisable to use statistical processing algorithms for indicators of the effectiveness and efficiency of processes implemented during the RTE operation, the volume of consumable resources, and others. To assess the compliance of all other components of $OS^{(j)}$ for the RTE, it is advisable to use algorithms based on AI information technologies. In general, during RTE inspections, information support for inspections - in terms of collecting initial data from checklists, forming conclusions on the facility's compliance with requirements, comparative analysis with previous inspections, sending data for storage in local and central data hubs, and other technological operations - should be carried out using information technologies based on AI.

We emphasize that, unlike previous studies of RTE operation systems in terms of developing algorithms for statistical processing of data on DP, in this paper we will focus on comprehensive monitoring and analysis of data from all components of this subject area, taking into account Figure 1, in order to systematically and carefully monitor the state of the OS elements within the entire aviation operational industry and then, after data processing, form and implement corrective and preventive actions. The latest information technologies based on the Internet of Things and artificial intelligence will allow achieving a significant improvement in the functioning of the RTE OS, as well as all involved entities that affect the quality of air navigation services provision using ground-based communication, navigation and surveillance equipment.

Regarding the monitoring of information sources and institutions that help resource provision and support of the OS of a separate aviation enterprise and all within the state, it is possible to propose a generalized structural scheme for collecting and processing data using information technologies based on the Internet of Things and AI [29, 30]. The aspect of using these technologies is collecting data from official websites of institutions and enterprises, providing relevant information to decision-makers, forming advice and conclusions for structures responsible for flight safety and the effectiveness of the

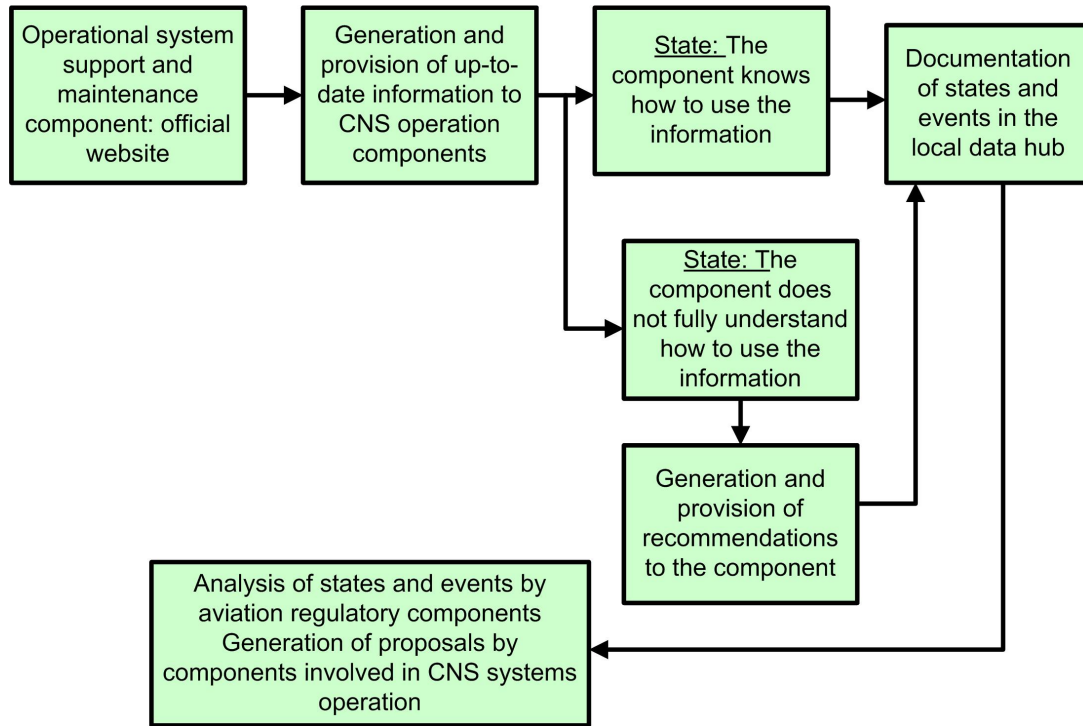


Figure 3: The generalized structural scheme for processing relevant information from the subjects of resource provision of RTE.

RTE operation.

Figure 3 shows a generalized structural scheme for processing relevant information from the subjects of resource provision of RTE.

A model of a phenomenon, state of an object, or process may not necessarily be presented as a trend in time. The model may have a tabular, graphical, mathematical, or other form. It will be assumed that the main thing is that information about the quantitative levels of a particular component will be recorded in the Local and Central data hubs. Then, based on these data, it is possible to perform a comparative analysis of changes in time for a particular model or to perform a comparative analysis of different OS enterprises within the state.

When describing models, we use a certain methodological approach, including the following assumption:

1. Trends in time must have a quantitative dimension.
2. When monitoring and controlling trends, it is advisable to classify them - "norm", "deterioration", "undesirable level or failure".
3. With classification levels, it is advisable to first determine risks, and then possible resource costs, in this sense unnecessary.

Let's start with RTE as the main component of any OS. We will consider the technical condition in two aspects:

1. The defining parameters of RTE is $y(t_i)$. We assume that $y(t_i)$ will characterize the condition of the entire RTE. The function $y(t)$ is continuous in the general case, but we will further consider it at time points t_i .
2. Reliability indicators (primarily failure-free indicators) - T_0^* , $\lambda^*(t)$, and others, determined at moments t_i based on data processing for the period δt in the form of a "sliding window".

Data on the determining parameters $y(t_i)$ and reliability indicators T_0^* , $\lambda^*(t)$ and others are purely stochastic processes and quantities.

If we consider the generalized model for $y(t_i)$, then we have two components: $x(t_i)$ characterizes the objective trend of the determining parameter, and $\chi(t_i)$ characterizes errors and interference that may occur during DP monitoring. In this case, $x(t_i)$ is further divided into two components: $\theta(t_i)$ characterizes the trend tendency and is an unobservable process; $\xi(t_i)$ characterizes the stochastic nature of $x(t_i)$. Then $y(t_i)$ will have the description

$$y(t_i) = x(t_i) + \chi(t_i). \quad (3)$$

$$x(t_i) = \theta(t_i) + \xi(t_i). \quad (4)$$

It is also necessary to emphasize the possible non-stationary nature of $y(t_i)$, if there are events of changepoint in the trends $x(t_i)$ - under the conditions of changes in mathematical expectations, or variance of individual observations $x(t_i)$, both in the part $\xi(t_i)$ and in the part $\theta(t_i)$.

The changepoint effect can be considered adequate to the realities of the RTE operation. In this case, statistical data processing becomes sharply complicated, but this allows a more adequate assessment of the efficiency and effectiveness of $OS^{(j)}$. Possible variants of the component $\theta(t_i)$ is a jump-like function, linear, parabolic, and others. We will assume that the probability distribution of the components $\xi(t_i)$ and $\chi(t_i)$ are usually Gaussian, although there may be other variants. In the conditions of a priori uncertainty of the type of statistical models and their parameters, it is appropriate to use adaptive data processing algorithms, estimation algorithms, statistical parameters of the probability distribution, as well as nonparametric statistical classification algorithms. Data processing with a fixed volume, or within the framework of the Wald approach with a random sample volume.

If we consider the indicators of reliability T_0^* , $\lambda^*(t)$, then we can assume that the above considerations are relevant in this case, but the component $\lambda(t)$ will no longer be, because there will be no measurement errors. Taking into account the changepoint effect will be appropriate. There is a feature associated with the assessment of the indicators T_0^* , $\lambda^*(t)$, it is necessary to specify the term of collection and then data processing, or specify the duration of the sliding window of sample data n , after the accumulation of which we will perform an assessment of reliability indicators.

We will assume that the condition of a portion of the RTE will be characterized by the defining parameters $y(t_i)$, and the other portion by reliability indicators T_0^* , $\lambda^*(t)$. The possible decisions about the state of the RTE after monitoring and control:

1. Two-alternative option: operable or inoperable;
2. Three-alternative classification option: operable, deterioration, inoperable state. There are subtleties, if there are errors in the classification of the technical condition, then we have risks regarding costs, if there are no errors, then it is still necessary to take into account the involvement of procedures for predicting the future state of the RTE.

Let's consider such an aspect, which from the point of view of the model characterizes the processes in order to choose adequate data processing. Several considerations:

1. Resource costs $\vec{C}^{(j)}(\Delta t / Process^{(l)})$ for the implementation of processes for a certain period of time Δt . We distinguish between costs between maintenance, repair, extension of resource and other processes.
2. We will also talk (in accordance with the ISO 9000 Requirements) about the Effectiveness and Efficiency for each process and the value of the Total Effectiveness and Efficiency for OSs of whole country.

We perform the Effectiveness assessment as the ratio (or proportion) of the number of actually completed tasks $ACT^{(j)}(Process^{(l)})$ to the planned number of tasks $PNT^{(j)}(Process^{(l)})$, i.e. for the l -th process and for $OS^{(j)}$ it will be

$$Effectiveness^{(j)}(Process^{(l)}) = \frac{ACT^{(j)}(Process^{(l)})}{PNT^{(j)}(Process^{(l)})}. \quad (5)$$

Efficiency is the proportion of effectiveness to resource expenditures

$$Efficiency^{(j)}(Process^{(l)}) = \frac{Effectiveness^{(j)}(Process^{(l)})}{\overline{C}^{(j)}(\Delta t / Process^{(l)})}. \quad (6)$$

It should be noted that Effectiveness and Efficiency are, in general, random variables; that is, they have a probability density function, or are characterized by moments, at least expected value and variance.

The main approaches and considerations for determining the personnel description model in the OS are:

1. It is possible to determine the total number of personnel for a separate OS and all operation systems in the state. Taking into account the storage of data in the Local and Central Data Hub, it is possible to assess the dynamics of changes in the number of personnel with any periodicity.
2. Data on personnel vacancies in certain specialties.
3. Average age of personnel.
4. Number of possible violations of labor discipline, number of possible cases of injuries.
5. Results of exams during training and internship.
6. Analysis of information on social and public activity, as well as submission of rationalization proposals, assessment of satisfaction with working conditions.
7. Generalized comparative information on which educational institutions employees of the enterprise's facilities for the operation of RTE graduated from, and other useful information about personnel in a professional context.

When analyzing the condition of such an important component as regulatory documentation in the OS, it should be noted that an intensive process of harmonization of regulatory documentation in the Central Administrative Court of Ukraine with international documents of ICAO, Eurocontrol, and other international organizations is currently underway.

Quantitative assessments of this process should also be determined and recorded in Data Hubs, namely:

- the total number of documents and those that are in the process of harmonization;
- the number of possible inconsistencies during the audit by Eurocontrol of state bodies in the field of air navigation services for flights by CNS equipment;
- the number of comments from operational personnel on new documentation;
- the number of resources spent on the development and implementation of new documentation and other data that, in general, should be recorded in Data Hubs.

We emphasize that comprehensive and thorough collection and processing of data on the condition of the OS components, corrective and preventive actions, spent resources and means, and further data and information processing using statistical algorithms, AI, Internet of Things technologies, protection and cybersecurity is the key to a high level of flight safety and efficiency of the OS of ground-based CNS and telecommunication equipment.

4. Results and discussions

We perform calculations to estimate the costs of maintenance and repair of the RTE under the condition that data processing and decision-making occur at time t_i . We will consider two options.

The first option is a scheduled maintenance (SM) and repair system. Conditional maintenance costs - $C_M = 20$ c.u., conditional repair costs - $C_r = 100$ c.u.

Let's assume that the RTE can objectively be in two states: operational with probability $P = 0.95$; inoperative with probability $Q = 0.05$.

The second option is the use of an automated control system (ACS), which also performs computational operations. This system is characterized by the probabilities of erroneous decisions α and β . Additional resources are spent during erroneous decisions. Costs for the ACS system - $C_{ACS} = 1$ c.u.

The mathematical expectation of costs for the scheduled maintenance and repair system is defined as follows:

$$m_1(C/SM) = PC_M + QC_r = 24c.u. \quad (7)$$

The mathematical expectation of the costs of the maintenance and repair system with data processing is determined as follows for $\alpha = \beta = 0.01$

$$m_1(C/CBM) = P((1 - \alpha)C_{ACS} + \alpha(C_M + C_{ACS})) + Q(C_r + C_{ACS} + C_M\beta) = 6.2c.u. \quad (8)$$

Thus, using the condition-based maintenance strategy based on the application of the Autocontrol system is a more advantageous solution, because $6.2 < 24$.

Consider the simulation procedure. Let us make a number of limitations. Suppose that we are comparing two data processing and decision-making procedures. During the inspections, one DP is available. An operational threshold is set for this DP. If it is crossed, a failure is observed.

Monitoring is performed at discrete points in time. In this case, the level of sampling is such that a delay of 5 discretizes is required to perform maintenance.

Data processing is performed in a sliding window. The width of the sliding window can vary. The cost of one processing procedure is $C_{ACS} = 0.01$ USD. Within the sliding window, the first processing procedure performs a linear approximation of the DP trend (linear model). The second processing procedure uses a linear two-segmented regression with a switching point in the middle of the window (segmented model). The ordinary least squares method was used to find the parameters of the models in both cases.

Forecasting of the DP trend is performed 5 counts ahead. If the predicted value exceeds the operational threshold, then maintenance is performed. In the case when the actual value of the DP exceeded the operational threshold, and the forecast did not exceed it, then repairs are performed. Repairs are also performed if within 5 forecasting counts the actual value of the DP exceeded the operational threshold. Let's assume that the costs of maintenance and repair are $C_M = 20$ USD and $C_r = 100$ USD.

The effect of the changepoint was modeled as follows. The model of technical condition deterioration is linear. The moment of occurrence of the changepoint is a random variable and in this study was described by a uniform distribution law. The slope angle of the deterioration trend is also a random variable and was described by the uniform distribution law. The moment of occurrence of the changepoint was taken in the range from 70 to 130 of the monitoring sample point. The slope angle was varied from 30 to 60 degrees.

The supply voltage was chosen as the determining parameter. The nominal value of the supply voltage was 220 V. The operating threshold was set at 270 V. The noise component of the supply voltage was described by a normal distribution with a zero expected value and a standard deviation of 3 V.

Figure 4 shows features of sliding window processing for linear model. The abscissa axis shows the monitoring moments (sample numbers), and the ordinate axis shows the supply voltage value. The red curve shows the actual voltage change over time, which begins to gradually increase after approximately the 75th sample. A sliding window of 50 samples is used to form the predictive model. Figure 4 shows three positions of the sliding window, the middles of which correspond to the 65th, 75th, and 85th samples. Each subsequent window is shifted along the time axis, which allows taking into account the most current monitoring results and promptly updating the model parameters. The dotted lines show the results of calculating the linear model obtained for different positions of the sliding window. By shifting the window to the right, the model more accurately reflects the trend of increasing supply voltage, since it uses more recent observation data. The horizontal dashed line corresponds to the set threshold value of the supply voltage, and the intersection points of the predicted trajectories with this threshold are used to estimate the moment of maintenance.

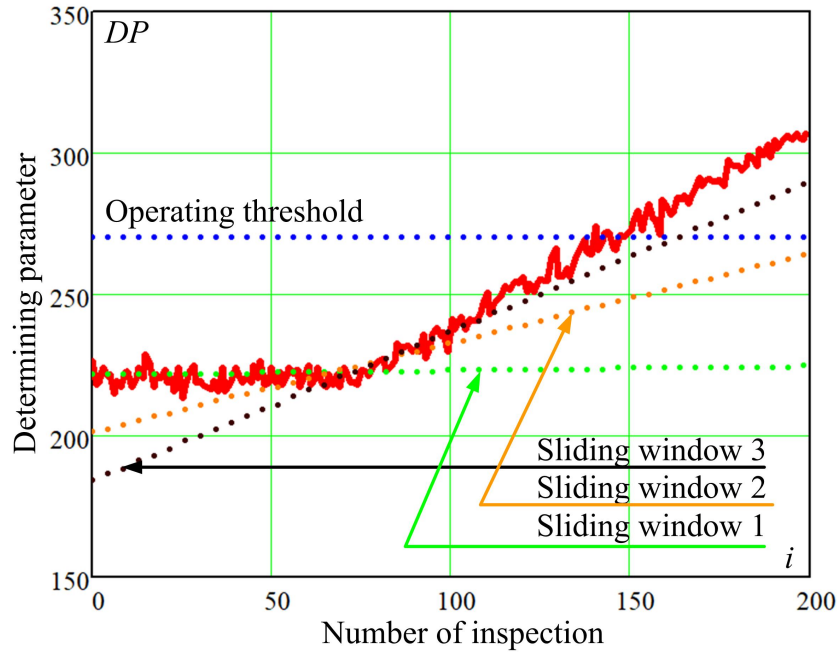


Figure 4: Sliding window processing for linear model.

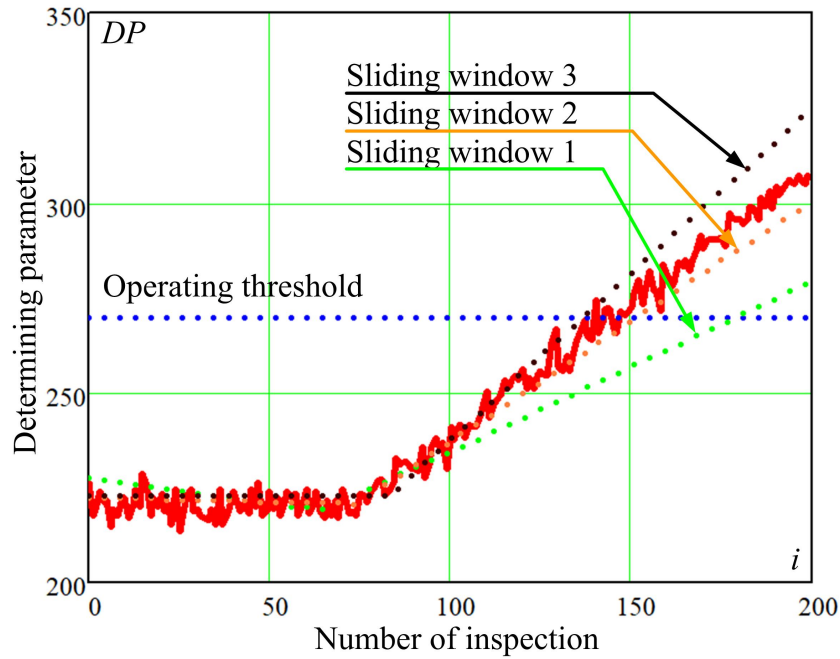


Figure 5: Sliding window processing for segmented regression model.

Figure 5 shows the similar features of sliding window processing for segmented regression model. Comparison of forecast trajectories shows that by shifting the sliding window to the right and including newer data in the analysis, the forecast better reflects the real trend of supply voltage growth. The model built in the second sliding window most accurately agrees with the subsequent behavior of the DP since it takes into account the most current information about the moment of occurrence of the changepoint.

A comparison of the operating costs for the two data processing models is shown in Figure 6. The graphs were constructed for 1000 simulation runs. This graph shows the dependence of average costs (C) on the sliding window size (k) in the range from 50 to 100 for two different mathematical mod-

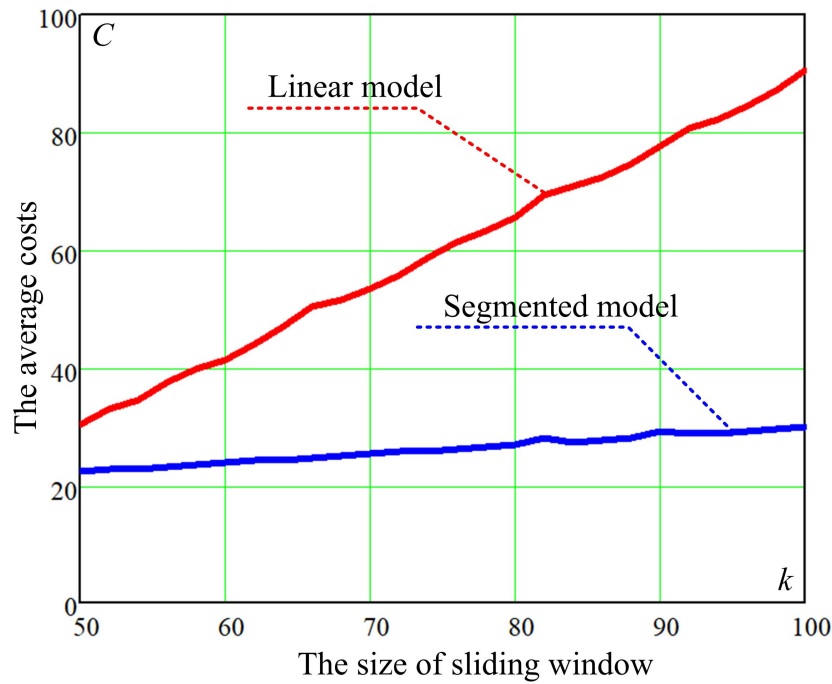


Figure 6: Cost comparison for linear and segmented regression models.

els. The upper red line reflects the linear model processing, which demonstrates a rapid and practically proportional increase in costs from 30 to almost 90 USD with the expansion of the window. In contrast, the lower blue line corresponds to the segmented model processing, which behaves much more stably. Throughout the entire studied interval, the indicators of this model undergo only minor fluctuations, smoothly rising from 22 to approximately 30 USD. Thus, the presented visualization clearly demonstrates the significant economic advantage of the segmented model, which allows keeping costs low even with the maximum window size.

5. Conclusions

The more components and elements in the system and the higher the level of uncertainty in their accounting, the greater the likelihood of risks and unnecessary costs. In the operation system of RTE means, all components organically interact with each other, therefore, monitoring their condition is an important scientific and technical task.

Recent studies emphasize the need to carefully collect statistical data on the functioning of all components, process them, and form corrective and preventive actions to ensure the safety of transport infrastructure and its efficiency.

Trends in parameters that characterize the condition of OS elements are usually stochastic with the presence of changepoint effect. Non-stationarity of sample sets is an objective reality.

To take into account the possible effect of non-stationarity, when processing data on trends of determining parameters, this paper proposes to use the changepoint detection procedure and further form forecasts for assessing the trends of DP in each data window and using piecewise linear approximation.

That is, the task of synthesizing an algorithm for processing a non-stationary process of the trend of the DP has the following features. The analysis of the effectiveness of such a complex algorithm was performed in two versions - without trend forecasting and with trend forecasting for the period during which personnel can perform corrective actions to return the trend to a normal state. Comparative analysis showed that forecasting is a more effective procedure for maintenance and repair of the RTE.

It is proposed to solve the task of updating information about the state of the component structure of the resource support of the CNS using AI, IoT, blockchain, and other technologies. These technologies

are also relevant when conducting inspection checks of the condition of the operation system of a separate enterprise and all OSs within the country.

The possibility of the latest information technologies and the statistical data processing algorithms proposed in the paper during the analysis of the Data Hubs allows solving the problems of:

- storing useful information in the OS;
- comparative analysis of trends of indicators characterizing the activities in the OS;
- to more effectively and efficiently form scientific and technical proposals by state regulatory bodies in the field of civil aviation in general and in the operation of ground-based RTE devices in particular.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

References

- [1] J. Duda, A. Gasior, *Industry 4.0*, Routledge, 2023.
- [2] M. Zaliskyi, V. Ivannikova, O. Solomentsev, I. Ostroumov, N. Kuzmenko, The approach to optimization of the structure of the repair process of aviation radio equipment, *Transport* 40 (2025) 50–63. doi:10.3846/transport.2025.24012.
- [3] F. Yanovsky, *Millimeter-wave radar: Principles and applications*, volume 1st Edition of *Millimeter Wave Technology in Wireless PAN, LAN, and MAN*, Taylor and Francis, Cham, 2008, pp. 305–375.
- [4] O. Sushchenko, et al., Algorithm of determining errors of gimballed inertial navigation system, in: O. Gervasi, et al. (Eds.), *Computational Science and Its Applications – ICCSA 2024 Workshops*, volume 14816 of *Lecture Notes in Computer Science*, Springer Nature, Cham, 2024, pp. 206–218. doi:10.1007/978-3-031-65223-3_14.
- [5] I. Ostroumov, V. Ivannikova, N. Kuzmenko, M. Zaliskyi, Impact analysis of Russian-Ukrainian war on airspace, *Journal of Air Transport Management* 124 (2025) 1–14. doi:10.1016/j.jairtraman.2025.102742.
- [6] O. Holubnychyi, O. Lavrynenko, D. Bakhtiarov, Well-adapted to bounded norms predictive model for aviation sensor systems, volume 736 of *Lecture Notes in Networks and Systems*, Springer Nature, Cham, 2023, pp. 179–193. doi:10.1007/978-3-031-38082-2_14.
- [7] D. Galar, P. Sandborn, U. Kumar, *Maintenance Costs and Life Cycle Cost Analysis*, CRC Press, Boca Raton, 2017.
- [8] B. S. Dhillon, *Maintainability, Maintenance, and Reliability for Engineers*, Taylor and Francis Group, New York, 2006.
- [9] M. Modarres, K. Groth, *Reliability and risk analysis*, CRC Press, Boca Raton, 2023.
- [10] O. Arefieva, Z. Poberezhna, S. Petrovska, S. Arefiev, Y. Kopcha, Devising approaches to modeling enterprise business processes under conditions of modern digital technologies, *Eastern-European Journal of Enterprise Technologies* 1 (2024) 69–79. doi:10.15587/1729-4061.2024.298143.
- [11] M. Zaliskyi, O. Solomentsev, Z. Poberezhna, O. C. Okoro, B. Chumachenko, S. Chumachenko, Information technologies of data processing for linear deterioration process during aviation equipment operation, in: *CEUR Workshop Proceedings*, volume 3732, 2024, pp. 32–44. URL: <https://ceur-ws.org/Vol-3732/paper03.pdf>.
- [12] O. Y. Lavrynenko, D. I. Bakhtiarov, B. S. Chumachenko, O. G. Holubnychyi, G. F. Konakhovych, V. V. Antonov, Application of Daubechies wavelet analysis in problems of acoustic detection of UAVs, in: *CEUR Workshop Proceedings*, volume 3662, 2024, pp. 125–143.
- [13] V. Ivannikova, M. Zaliskyi, O. Solomentsev, I. Ostroumov, N. Kuzmenko, Statistical data processing technologies for sustainable aviation: A case study of Ukraine, *Sustainability* 17 (2025) 5781. doi:10.3390/su17135781.

- [14] O. M. Tachinina, O. I. Lysenko, I. V. Alekseeva, Path constructing method of unmanned aerial vehicle, in: 2017 IEEE 4th International Conference Actual Problems of Unmanned Aerial Vehicles Developments (APUAVD), Kiev, Ukraine, 2017, pp. 254–258. doi:10.1109/APUAVD.2017.8308823.
- [15] O. Solomentsev, M. Zaliskyi, O. Zuiev, Estimation of quality parameters in the radio flight support operational system, *Aviation* 20(3) (2016) 123–128. doi:10.3846/16487788.2016.1227541.
- [16] I. U. Hassan, K. Panduru, J. Walsh, Review of data processing methods used in predictive maintenance for next generation heavy machinery, *Data* 9 (2024). doi:10.3390/data9050069.
- [17] I. Najeh, D. Daucher, M. Redondin, L. Bouillaut, Feedback data processing for maintenance optimization and grouping—an application to road markings, *Future Transportation* 3 (2023) 768–790. doi:10.3390/futuretransp3020044.
- [18] O. Solomentsev, M. Zaliskyi, O. Kozhokhina, T. Herasymenko, Efficiency of data processing for uav operation system, in: 2017 IEEE 4th International Conference Actual Problems of Unmanned Aerial Vehicles Developments (APUAVD), 2017, pp. 27–31. doi:10.1109/APUAVD.2017.8308769.
- [19] T. Nikitina, et al., Algorithm of robust control for multi-stand rolling mill strip based on stochastic multi-swarm multi-agent optimization, in: S. Shukla, H. Sayama, J. V. Kureethara, D. K. Mishra (Eds.), *Data Science and Security*, volume 922 of *Lecture Notes in Networks and Systems*, Springer Nature Singapore, Singapore, 2024, pp. 247–255. doi:10.1007/978-981-97-0975-5_22.
- [20] M. Nagy, M. Figura, K. Valaskova, G. Lăzăroiu, Predictive maintenance algorithms, artificial intelligence digital twin technologies, and internet of robotic things in big data-driven industry 4.0 manufacturing systems, *Mathematics* 13 (2025). doi:10.3390/math13060981.
- [21] T. Nikitina, et al., Method for design of magnetic field active silencing system based on robust meta model, in: S. Shukla, H. Sayama, J. V. Kureethara, D. K. Mishra (Eds.), *Data Science and Security*, volume 922 of *Lecture Notes in Networks and Systems*, Springer Nature Singapore, Singapore, 2024, pp. 103–111. doi:10.1007/978-981-97-0975-5_9.
- [22] O. M. Tachinina, I. V. Alekseeva, O. I. Lysenko, S. M. Chumachenko, Scenario-based approach for control of multi-object dynamic system motion, in: 2015 IEEE International Conference Actual Problems of Unmanned Aerial Vehicles Developments (APUAVD), Kyiv, Ukraine, 2015, pp. 305–308. doi:10.1109/APUAVD.2015.7346627.
- [23] S. Lysenko, N. Bobro, K. Korsunova, O. Vasylychshyn, Y. Tatarchenko, The role of artificial intelligence in cybersecurity: Automation of protection and detection of threats, *Economic Affairs* 69 (2024) 43–51. doi:10.46852/0424-2513.1.2024.6.
- [24] R. Sala, F. Pirola, G. Pezzotta, S. Cavalieri, Data-driven decision making in maintenance service delivery process: A case study, *Applied Sciences* 12 (2022). doi:10.3390/app12157395.
- [25] Z. El Hammoumi, D. Tebr, Y. Charkaoui, I. Satauri, O. El Beqqali, Predictive maintenance approaches: A systematic literature review, *Engineering Proceedings* 112 (2025). doi:10.3390/engproc2025112070.
- [26] J. Al-Azzeh, et al., A method of accuracy increment using segmented regression, *Algorithms* 15 (2022) 1–24. doi:10.3390/a15100378.
- [27] R. Voliansky, et al., Variable-structure interval-based duffing oscillator, in: 2024 IEEE 42nd International Conference on Electronics and Nanotechnology (ELNANO), 2024, pp. 581–586. doi:10.1109/ELNANO63394.2024.10756860.
- [28] I. Shevchenko, O. Lysak, A. Z. Shyshak, I. Mazur, M. Korotun, V. Nestor, Digital economy in a global context: World experience, *International Journal of Professional Business Review* 8 (2023) 11. doi:10.26668/businessreview/2023.v8i4.1551.
- [29] D. Rasshyvalov, Y. Portnov, T. Sigaieva, O. Alboshchii, O. Rozumnyi, Navigating geopolitical risks: Implications for global supply chain management, *Multidisciplinary Reviews* 7 (2024) 2024spe017. doi:10.31893/multirev.2024spe017.
- [30] T. Bielialov, I. Kalina, V. Goi, O. Kravchenko, N. Shyshpanova, A. Negoda, Global experience of digitalization of economic processes in the context of transformation, *Journal of Law and Sustainable Development* 11 (2023) e814. doi:10.55908/sdgs.v11i3.814.