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SIMULATION MODEL OF MILITARY AIRCRAFT DEPENDABLE STRUCTURE AND ITS USE IN THE RESEARCH OF AFTER-SALE SERVICE PROCESSES

The paper examines the relevance of the development of a simulation model of aircraft dependability structure for the purpose of analyzing the processes of after-sale service of military aircraft. It also describes the developed simulation model and the results of simulation.

Keywords: *aircraft, after-sale service, simulation model.*

Introduction

Following the decisions of the Government of the Russian Federation and respective orders and regulatory document of the Ministry of Defense, the after-sale service system of military facilities including aircraft is undergoing a reform. As opposed to the strategy of service by organizations of the Ministry of Defense, the new system is to entrust the service process to manufacturers. For that purpose, the manufacturing companies and components suppliers are establishing dedicated structures in order to support the process that includes planning of production, storage and timely delivery of spare parts, routine maintenance and repair of failed equipment. These structures and units are to maintain close cooperation with military units that operate the purchased weapon systems. In this context, the study of after-sale service processes for development of an efficient management system is a relevant research and development task. The related issues are covered in monograph [1] that analyzes the structure of the after-sale service of complex engineering facilities and suggests mathematical tools for its research. The book highlights the use of probabilistic and analytical methods. Those methods have well known limitations in terms of capability to adequately represent the processes occurring in complex organizational and engineering systems including the system of after-sale service. The monograph also highlights the applicability of simulations that do not have any fundamental restrictions in terms of adequate representation of complex processes. The authors attempt to create one of the key parts of the general simulation model (SM) of after-sale service, namely the SM of the dependability structure of a complex engineering facility, i.e. an aircraft, which is submitted to such service. The aircraft dependability structure (ADS) is defined by a set of components (elements, units, subsystems and the aircraft as a whole) the operation of which is considered in terms of fulfilling the aircraft dependability requirements (failure-free operation, scheduled maintenance, occurrence of failures, performance of maintenance activities, use of spare parts, resources, etc.), described by a number of indices determining this dependability (for example, probability of failure-free operation, availability, etc.).

The purposes and tasks of the specified simulation model are defined by the requirements of the upper level simulation model representing the operation process of the whole system of after-sale service. From this point of view SM of ADS should enable, on the one hand, estimation of aircraft dependability indices within the established strategy of operation support by spare parts and repair resources, and on the other hand, contribute to the development of the strategy of accumulation and use of spare parts, accumulation and support of necessary repair resources by providing statistical information on failure-free times of various ADS components, by quantitative estimation of demand for spare parts and repair resources based on the information on failures and restorations of ADS components.

Below is the description of the process of ADS simulation: problem definition, stages of formalization, development of the simulation program, carrying out of simulation.

Problem definition

The problem is defined as the development of an ADS SM to be used as part of the SM process of an aircraft after-sale service.

Purpose of the SM:

- Estimation of aircraft dependability indices within the defined strategy of operation support with spare parts and repair resources;

- Support of strategy development for accumulation and use of spare parts, generation and support of required repair resources by means of statistical information on failure-free times of various ADS components, quantitative estimation of demand for spare parts and repair resources based on the information on maintenance, failures and restoration of ADS components.

Used assumptions.

At the initial stage of SM ADS development we shall assume the availability of unlimited quantities of spare parts and repair resources.

ADS concept and operation process

ADS is represented as multilevel treelike structure, where at the upper level the component corresponding to the whole ADS is placed. At the following lower level, the ADS system splits into components corresponding to aircraft subsystems that perform individual vital and purpose functions (i.e. airframe, engine, flight-control system, weapons control system, etc.). Subsystems in turn split into smaller functional subsystems, then units. Units themselves consist of other units and elements. At the lowest level of any branch, ADS elements are situated.

An element from the point of view of ADS operation process is considered to be indivisible. Laws of failure-free time (FFT) distribution are defined for ADS elements. In their nature, the element failures can be gradual (wear-out) and sudden. Both types of failures can occur in parallel [2, 3]. Various kinds of distribution laws (DL) are used for formalized probabilistic description of FFT. The most commonly used are the exponential, normal, lognormal, Weibull-Gnedenko ones, etc. [4].

An ADS element failure can lead to certain consequences (failure, malfunction or reduction of operational efficiency) affecting the condition of the components of the respective ADS branch (in chain order upwards) to which the element belongs (including the highest level ADS components, i.e. the whole ADS).

To enhance the dependability of individual ADS components, at its various levels certain types of redundancy can be used: loaded (hot), semi-loaded, non-loaded (cold), moving redundancy, etc. Therefore, the failure of certain ADS component does not necessarily lead to the failure higher-level components.

If the failure of an element does not entail the failure of the respective ADS component, the status of this part is defined as faulty [5]: i.e. it carries out all functional tasks (probably, less efficiently), yet contains failed elements. Otherwise the ADS component turns into failure state.

Stress affecting an aircraft in operation influences the FFT of each element. Stress depends on the operating mode: tactical mission, patrol, training, outdoor aircraft storage, aircraft storage in shed, aircraft storage in heated hangar, etc. The operating mode is the list of conditions in which an aircraft operates. Changes in aircraft operating mode normally happen routinely (air alert, tactical mission, maintenance, etc.), but it can also be random (e.g., in case of unforeseen change in ADS condition). Generally, for each mode there is a list of ADS components that ensure its implementation. For ADS elements of those components their own FFT DLs can be defined.

For each ADS element the following statuses can be implemented:

1. On. The element performs all required functions. The initiation of this status the element must be operable (absence of failure) and installed on the aircraft.

2. Off. The element is switched off and does not perform any functions. It is assumed that the element awaits activation under certain conditions. A switched off element is assumed to be operable and installed on the aircraft.

3. Failed. An element is in failure mode. It does not perform any functions and requires urgent recovery. Upon recovery it switches off.

4. Removed from ADS (removed from aircraft). The element is dismounted for maintenance or repair. The element can be both failed and operable.

Similar statuses can also be defined for other ADS components (that are not necessarily elements).

Besides the operating modes, an element's FFT DS generally depends on its operating history, i.e. time of operation in other modes. In addition, dependent failures can occur in some ADS components: failures of certain elements caused by failures of other elements as the result of change of operation conditions.

In terms of dependability analysis, ADS it is a restorable system, i.e. after a failure event of an ADS component, if it does not lead to catastrophic consequences, recovery is performed (repair or replacement). A catastrophic situation is a very low probability event. Therefore, the development of the simulation model considered here does not aim to model such situations.

The process of ADS component recovery consists of two procedures: failure detection and recovery activities (repair or replacement of failed ADS component).

Failure events of some ADS component, generally, may not manifest instantly and if identified, usually cannot be immediately eliminated. This means that failures of ADS components can be accumulated, and this accumulation in certain combinations can lead to more severe consequences than each failure of ADS component individually.

The ADS component failures can be detected in the following ways:

1. In operation with the help of special indicators. Such failures are called “explicit”.

2. During maintenance. Such failures are called “latent”. They are detected with special instruments and monitoring devices.

The detection of an ADS component failure initiates the repair process (if required by technical regulations) or replacement (if spare parts and repair resources are available). Generally, the restoration process is random: events of “latent” failures detection, maintenance time, repair or replacement of failed components can be random. However, when reliable statistical input information regarding the time of recovery activities is not available, respective data given in corresponding engineering manuals can be used [6,7].

Note again that for the purpose of the SM development we assume that the required spare parts and repair resources are unlimited, which allows simplifying the process of formalization at this stage. At further stages of SM developed these assumptions will be removed.

Choice and substantiation of SM class

The ADS operation can be represented by means of SM based on the description of such event-trigger phenomena as failures of elements and related failures of other ADS components, beginning and termination of various types of maintenance operations, detection of failures, beginning and termination of repair and replacement of failed ADS components, etc. In this context, the ADS model can be represented as a discrete SM that functions on the basis of model (time) events method (MEM) [8]. The list of key model events and the diagram of their interaction that reflects the process of parallel event planning at processing is shown in Fig. 1.

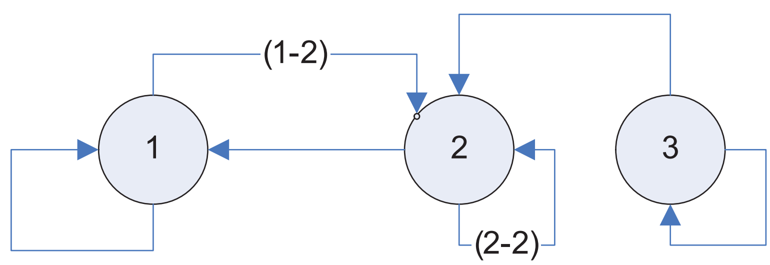

Fig. 1. Flow graph of events interaction

Names and codes of key time events:
1. Element failure;
2. Performance of operation on an ADS component (switching-on, switching-off in operation; termination of installation, removal or adjustment during maintenance);
3. Change of operating mode.

Conditions of event-scheduling:
(1-2) If the failed element has a functioning redundant element;
(2-2) If not all specified operations for an ADS operating mode initiation have been performed.

Indices of evaluation criteria for modeling results:
1. Implementation and statistical characteristics of spare parts and repair resources consumption in repair and recovery operations:
- processing of a set of runs statistics: failure rate of individual ADS components in a single SM run;
- processing of one long run with stationary assumption and ergodic nature of the processes taking place in the SM: evaluation of failure rates for individual ADS components.
2. ADS availability (the ratio of ADS FFT to the SM run time).

SM parameters

Below is the aggregative description without detailed discussion of data structures used for specification and storage.

• ADS parameters reflecting its multilevel treelike structure, types of redundancy used in its individual components, effects of the failure of each individual component (dependence of failures of ADS components, the possibility of recovery operations of individual ADS components by replacement of failed parts or recovery operations have been identified). Types and time characteristics of maintenance and its frequency. For the “latent” failures of elements, the types of maintenance that ensure “latent” failures detection have been identified. For complex latent failures, the probability of detection, the list of maintenance operations and their time characteristics have been defined.

- The list of ADS operating modes.
- ADS components that should operate in each mode.
- Scenario of ADS operation mode change.
- Types and parameters of FFT DS of elements for each mode.

SM status

The key status variables of ADS SM are the ones that define the current status of individual ADS components.

These variables are defined in the list structure of data unambiguously connected to ADS. According to the above description, the list of statuses of ADS components includes: operational or faulty; in service or out of service; included in ADS structure or excluded from it (uninstalled).

For the ADS and individual components, the type of mode is defined for current simulated time. Accordingly, the inclusion of ADS components in the operation is defined.

For each ADS element, the total operating time is identified (taking into consideration the load factors depending on the current operating mode). For each ADS component, the total operational time is accumulated. For each ADS component, failure rates per simulation times are accumulated for each ADS components and the ADS as a whole.

For the above basic time events, the list of information specified in the additional attributes of record for those events is as follows:

Failure of an element event (1):

- Failed element indicator;
- Type of failure.

Operation on ADS component event (2):

- Indicator of the ADS component operated on;
- Name of operation;
- Time required to perform operation;
- Load factor on ADS component during operation;
- ADS status required for performance of operation.

Scheduled change of operating mode event (3):

- Number of mode from the set of possible ADS operating modes.

Initial SM status

Status of all components is operational. Operating mode is the first of the plan. All ADS components are involved in operation according to the specified mode. Operation time for each ADS component is 10% from maximum. Planned failures of all types of all ADS elements are recorded in the statistics database (SDB). Variables for statistics gathering are in zero state.

Simulation of random events

The most important random event in the SM under examination is the random variable of **failure-free time of ADS elements**. The complexity of simulation of this random event is due to the following:

- ADS elements during its functioning operates in different modes that vary according to the specified plan;
- each element in different modes has its own FFT DS parameters;
- failures of elements can be of two types: sudden failures (SF) and wear-out failures (WOF). It is assumed, that the time of SF occurrence depends only on the ADS operating conditions (type of operating mode), while the time of WOF occurrence also depends on the time of operation in certain modes (so-called time to failure);
- there are dependent failures when a failure of some elements causes failures of other elements or accelerates their failure by affecting the parameters of their FFT distribution law.

It is suggested to use different probabilistic descriptions of FFT for the above failure modes and, accordingly, different algorithms for identification of their occurrence time:
- for SF, the exponential law of FFT distribution (ELD) will be used. Its parameters will be defined by the type of the element and the ADS operating mode. In theory, the ELD "has no memory", i.e. at each change of ADS operating mode the parameters of the FFT distribution law in the next mode do not depend on the operation time in previous modes. Using this property of ELD, it is suggested to carry out **simulation of the SF** moment as follows: at each change of mode, an FFT occurs. It is compared to the ADS operation time in this mode at the next stage; the moment of failure is registered if the FFT occurrence time is less than the operation time in the considered mode;
- for DF, the normal law of distribution (NLD) is used. For each mode the concept of "load factor" is used. It is characterized by the ratio of an element wear rate in a mode to its deterioration rate in some conditions for which NLD parameters are defined. Considering the above, it is suggested to perform the **simulation of the DF moment** as follows: based on the NLD, the time to failure occurrence is identified; then, during simulation, the actual times to failure obtained per operating modes are summarized (these times to failure are weighed (multiplied) by the corresponding load factors. The DF moment is defined by the equality of the above values.

Besides the moments of change of ADS operating modes, simulation of elements FFT occurrences is also performed at replacement of failed ADS components during simulation of repair and recovery operations as a consequence of dependent failures.

For simulation of dependent failures, in accordance with the structure of interaction of dependent failures, defined in the SM parameters, when an element fails a number of other elements with possible dependent failures are identified.

If it is SF, then according to the specified probability, failures of these dependent elements are simulated, or parameters of FFS DS are redefined upwards in probabilities for smaller FFT values, and according new FFT occurrences are identified.

If it is DF, then load factors increase for subsequent modes which again leads to a reduction of time to DF occurrence.

Another random event, of which the occurrence **must be simulated is the event of latent failures detection**. The simulation of these events is performed during the processing of model events related to ADS maintenance operations according to the SM-specified probabilities of latent failures detection events.

Algorithms of simulated events processing

During the processing of an Element failure event, the following operations are performed:

1. Recording of the time during which the component with the failed element was in the previous status.

2. Setting of the ADS component in the failure status.

3. Removal of all failure events of the given component from the SDB.

4. Search of the backup component or the switched off redundant component. Activation of the switched off operational redundant component if possible.

5. Change of the FFT parameters of the elements the failures of which depend on the status of the failed element, simulation of their FFT occurrence and updating of the SDB.

6. Activation of the failure indicators of the failed component if those are available.

7. If backup ADS components are not operational and the failure of this component should lead to the failure of a higher level component, then execute the failure procedure of a new component (Recursive performance of this operation upwards along the whole ADS branch).

8. Save statistics on the given component failures.

Operation on an ADS component

An event processing involves the performance of the following sequence of actions:

1. Definition of operation type.

a. For the Activation operation, the component activation procedure is initiated. This procedure activates the component by creating the required failure events and removing the excessive ones.

b. For the Switching-off operation, the component switching-off procedure is initiated. This procedure switches the component off by creating the required failure events and removing the excessive ones. After that, the whole section graph (all components of the unit) of the given element switches off.

c. For the Uninstallation operation, the component status switches to not present in the ADS structure.

d. For the Installation operation, the procedure is initiated that appoint the component as part of the ADS. The procedure nullifies the operation time parameters for the component and switches it off.

e. For the Adjustment operation, the component is switched to the operational state and the components that failed due to the failure of this component are recovered.

2. Activation of the “latent” failures search procedure.

3. Calculation of the execution time of the following operation in the respective sequence.

4. Event planning (K=2).

Change of operating mode event

An event processing involves the performance of the following sequence of actions:

- accumulation of statistics on the operation times of the active ADS components taking into account the completed mode;
- adjustment of the FFT distribution laws of elements wear-out failures, updating of the SDB specific to those failures;
- elements sudden failures FFT occurrence simulation and updating of the SDB subject to the scheduled duration of the new operating mode.

Statistics gathering and calculation of the KORM values

The statistics gathering includes the following functions:

• Gathering statistics on the failure-free times of the ADS and its components;
• Recording of various spare parts use;
• Recording of various repair resources use;

• Calculation of the availability factor of the ADS and its components;

• Statistical processing of the results of spare parts and repair resources use and identification of the statistical characteristics of these processes.

Using the simulation results, the required statistical characteristics are calculated:

• The availability factor of an aircraft is defined as the ratio of the time of operability to the time of simulation;

• Statistical characteristics of spare parts and repair resources use are calculated. For this purpose it is assumed, that by the time of failure detection it is required to have spare parts available, and for the time of recovery it is required to involve necessary repair resources. As a result of the information processing, the processes implementation is defined for required spare parts and repair resources of each kind for the support of the aircraft availability.

General information on the simulation program

The SM software has been developed in the Borland Delphi 7.0 programming environment. The results of the program's operation are displayed in the main window in the form of the current model status and tracing. For correct display of the model status it is recommended to keep the number of the ADS components within 150, and the levels within 10. During the calculation of the simulation results after a number of runs the tracing and graphic information is not displayed, therefore the dimension is not restricted and the output information is saved in files.

Simulation results

This model was performance tested using the example of the DS of the TU-154 air-conditioning and pressure regulation system (fig. 2) [7]. This system consist of a source of air in the form of three motors and auxiliary power-plant (APP), primary cooler unit, two vent lines, two secondary cooler units, flight deck ventilation system, two passenger cabin ventilation systems and various sensors and regulators on the flight engineer's panel and maintenance panels. The system uses cold backup of the air bleed valves, valves in the pipeline, as well as hot backup of air lines, secondary cooling units. The following dependent failures are possible: turbo refrigerating subsystems failure in case of failure of the oil cooling subsystem; auxiliary power-plant failure in case of its cooling system failure.

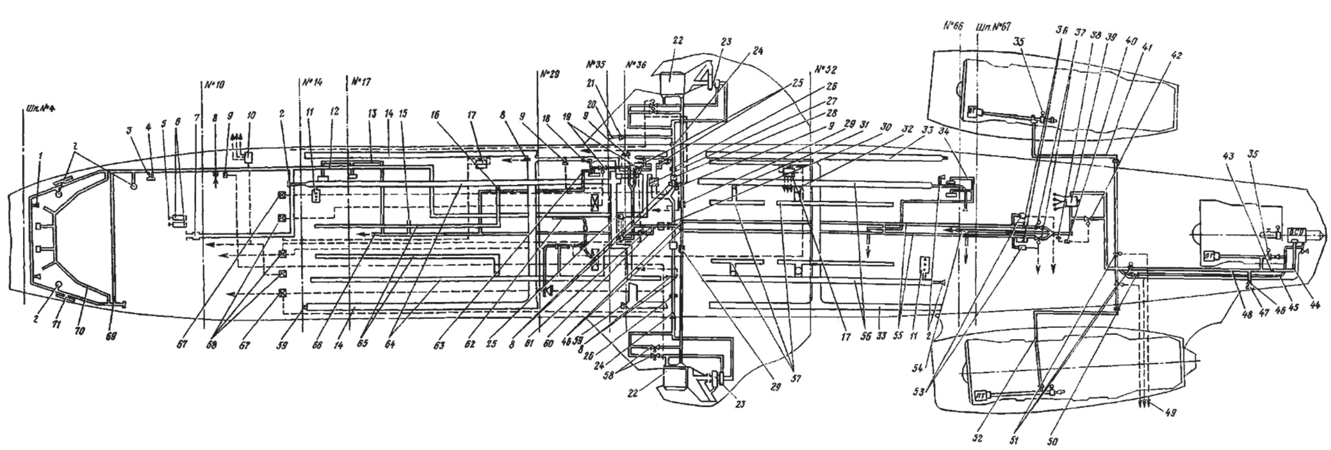

Fig. 2. Structure of the TU-154 air-conditioning and pressure regulation system

The total number of ADS components is 116, the number of elements is 87, the number of ADS levels is 6.

The plan of ADS operating modes includes two modes: operation on the ground, operation in flight. In the Operation on the ground mode only the main air radiator is on, in the Flight mode secondary radiators are also on which defines various loads on the ADS elements.

The following sequence of operations is simulated during ADS maintenance: removal of hatches of engine nacelles, inspection of pipelines, air bleed taps and valves; hatches of the left and right half-wings are taken off for inspection of air inlets, turborefrigerating units with oil system and valves of the left and right secondary cooling units. Three hatches in the luggage compartments are also removed for inspection of other parts of the system.

The flight engineer's panel includes sensors of air bleed subsystem failure for each motor (activates in case of failure of valves or taps of the air bleed subsystems), the sensor of tail compartment overheating (activates in case of failure of the preliminary cooling unit), the temperature sensors for each airline and for each secondary cooling unit and overheating sensors for passenger cabins and flight deck and the air consumption indicator that signals air intake failures. In addition, there is an on-ground check panel with corresponding sensors. It is used for ADS maintenance.

"Latent" failures are also possible in the ADS SM. In case of secondary cooling unit valve failure the backup valve will activate preventing air overheating. Similarly, there are backup mixer taps and ventila-

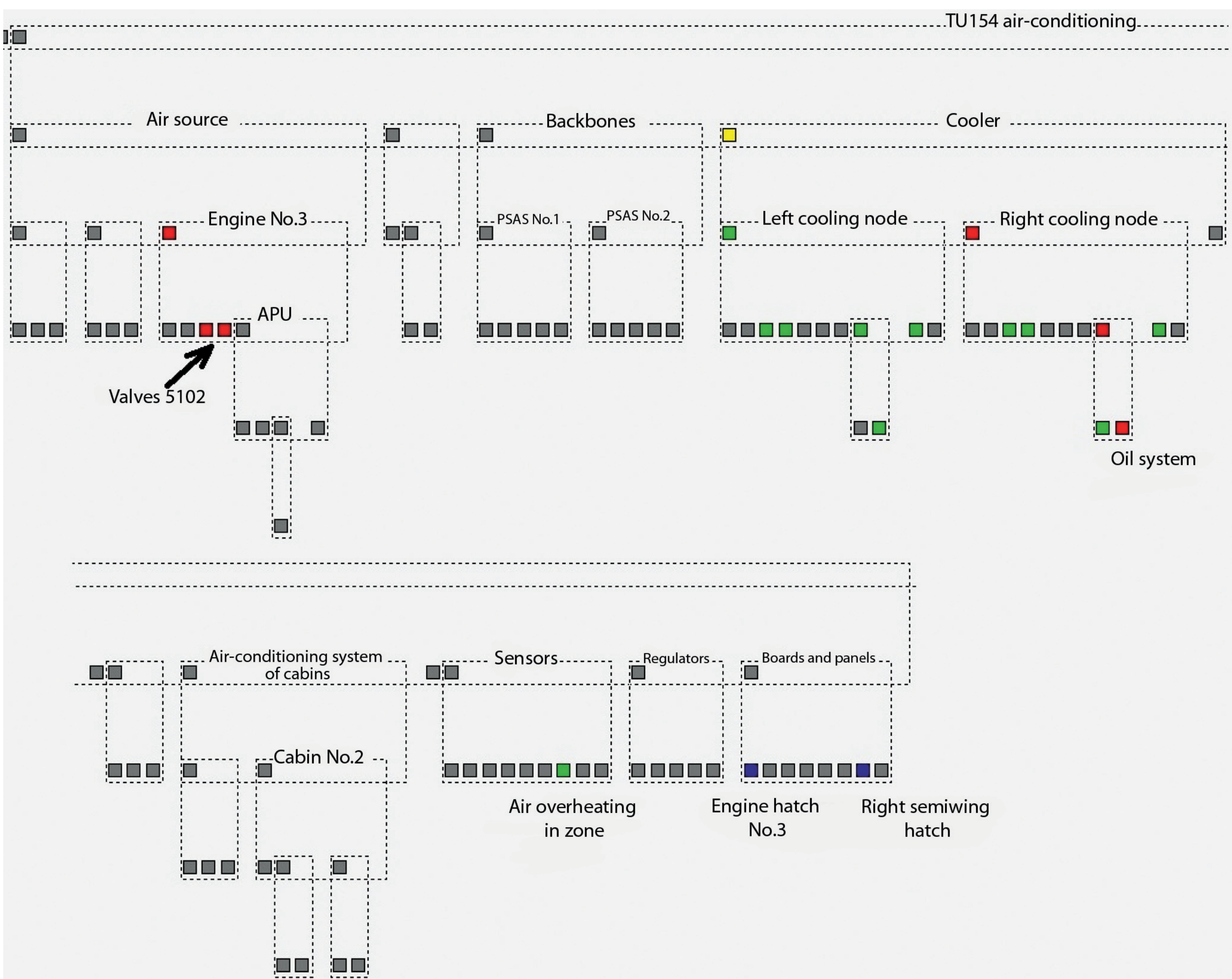

Fig. 3. Graphic representation of SM operation upon failure of valves 5102

tion system distributors for the flight deck and the passenger cabins. Those failures can be detected only by means of maintenance with defined probability.

For the majority of ADS components the activation status is defined. Each element in active state has two types of failures: operation time (normal distribution law) and sudden (exponential distribution law). For the inactive elements, wear-out failures caused by storage are possible.

Elements are replaced by removing the protective cover, uninstalling the failed element, installing the new element and adjustment. Some failed elements are replaced by replacement of the respective units, e.g. in case of oil system failure the whole turbo refrigerating unit is replaced.

Simulations can be performed with a set of independent runs or with one long run in the assumption of coming to stationary ergodic mode of the SM operation.

In the test mode, the SM provides for a visual output of information on the changes of status of any group of components of the simulated DS. In particular, fig. 3 presents the process of maintenance caused by the failure of valves 5102 of the third engine.

The figure uses the following color representation of the ADS components statuses: grey is switched off, green is activated, yellow is malfunction, red is failure, dark blue is excluded from the ADS.

Such information representation enables the logic analysis of the SM operation process and verification of its compliance with the description of the DS operation process.

Below is the graphical representation of the statistical results obtained by a set of runs of the DS operation process from the specified initial state in the form of failure frequencies in time for the whole DS.

The general description of the simulation plan is as follows.

Run time is 2 years. During this time 500 flights and 10 to 15 full maintenances operations are performed. Duration of each flight is 10 hours. All elements in the initial state have operation times of not more than 10 % of the life time. Sample size is 5000 runs.

The results of simulation of the failure frequency of the whole air-conditioning system ADS are shown in fig. 4. 6,5 MB of RAM were required for the implementation of this ADS SM. The simulation took 8 minutes and 46 seconds.

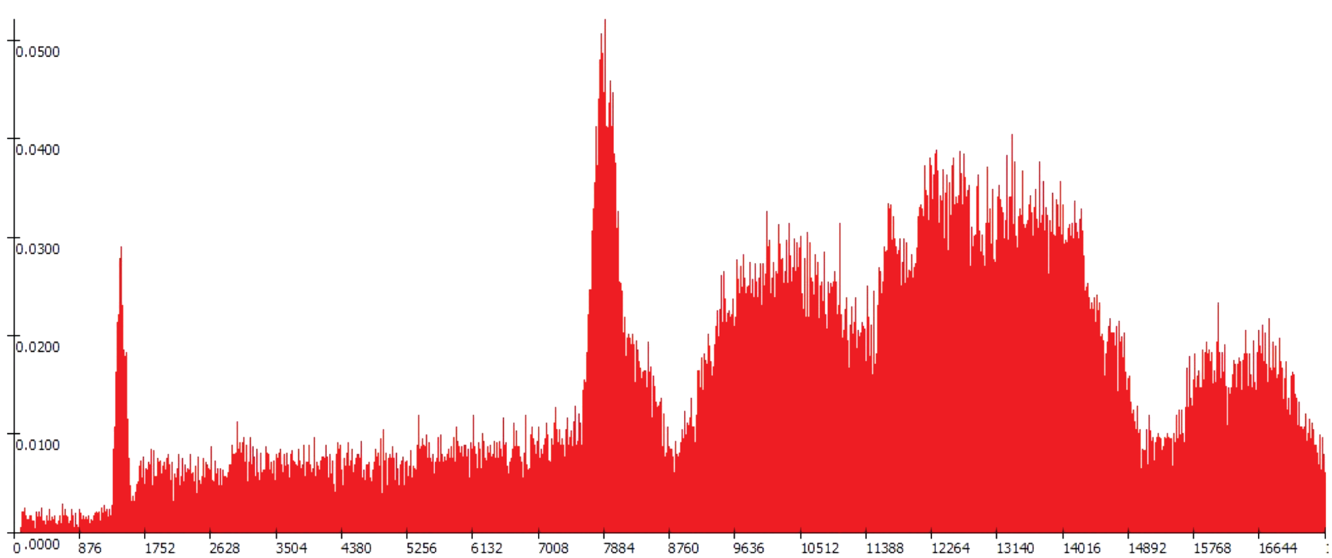

Fig. 4. The diagram of failure frequency of the whole air-conditioning system ADS in time

In fig. 4 we can observe two periods of ADS peak failure and two intervals of increased failure rate. The detailed analysis of ADS status in the specified time intervals has shown, that the first peak was caused by failures of the oil in the cooling system (according simulation results, during the SM run oil fails 5,44 times on the average and up to 12 times maximum). The second peak was caused by the failures of the valves 5102 that ensure air supply from the engine and the auxiliary power plant. The other intervals of increased failure rate were caused by failures of cooling systems: valves, turbo refrigerating units, moisture separators and ventilation systems of passenger cabins and flight deck: mixer taps, distributors and control devices.

In view of the results analysis, changes were made to the maintenance plans: scheduled replacements of oil were increased by five times; some units were to be replaced by new ones even when the replaced units are still in operating condition. These changes ensured significantly lower failure rates of the air-conditioning system ADS. The results of simulations after the specified changes under the similar plan are shown in fig. 5.

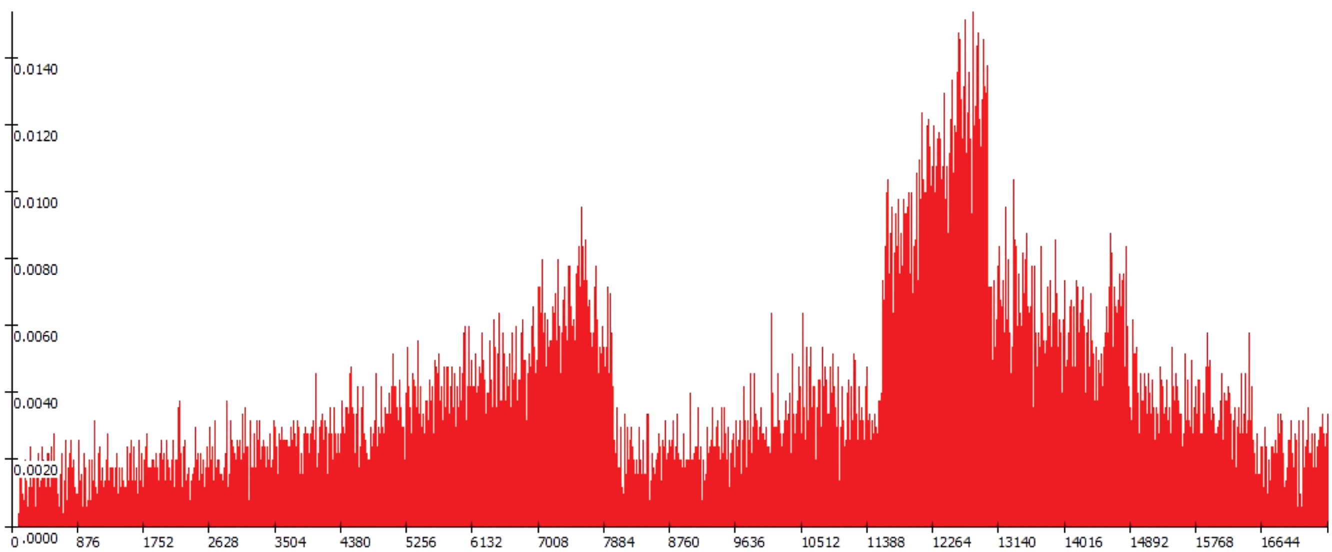

Fig. 5. The diagram of failure frequency of the whole air-conditioning system ADS in time after the changes to the maintenance plan

A comparison of the diagrams in fig. 4 and 5 shows that the changes ensured significantly lower ADS failure rates.

It can also be concluded that the developed SM is of high quality, it is sensitive to variations of parameters, and, hence, it can be used in higher level models for the analysis of aircraft after-sale service.

References

1. **Sinitsyn I.N., Shalamov A.S.** Lectures on the theory of integrated logistical support systems. Moscow. TORUS PRESS, 2012.

2. **Antselovich L.L.** Airplane dependability, safety and survivability: Coursebook for college students in Aircraft design. Moscow. Mashinostroenie, 1985.

3. **Arepiev A.N., Gromov M.S., Shapkin V.S.** Matters of operational survivability of aircraft designs. Moscow. Vozdushny transport, 2002.

4. Technology dependability and efficiency: Reference book: In 10 volumes. Volume 8. Moscow. Mashinostroenie, 1990.

5. GOST 27 002-89. Technology dependability. Basic concepts, terms and definitions.

6. **Biriuzova E.I.** Single guidelines for airframe maintenance. Moscow. DOSAAF Publishing house, 1959.

7. **Voloshin F.A., Kuznetsov A.N.** – Tu-154 aircraft. Design and maintenance. (Book 2), 1975.

8. **Khakhulin G.F.** Basic principles of simulation model design. Moscow. NPK Potok Publishing house. 2002. 224 p.