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# SIMULATION MODELING OF MEAN TIME BETWEEN UNSCHEDULED REMOVALS OF RADIO-ELECTRONIC SYSTEMS

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*The simulation modeling algorithm is developed for evaluation of mean time between unscheduled removals (MTBUR) of periodically checked radio electronic systems. The general formulas are proposed for statistical evaluation of MTBUR. A comparison is conducted between the analytical and simulation modeling of MTBUR. A good agreement between the analytical and simulation results is observed.*

**Keywords:** line replaceable unit, maintenance, simulation modeling, unconfirmed failure, unscheduled removal, built-in test equipment

**Introduction.** The continuous growth in modern avionics systems complexity on the one hand allows extending the functionality of flight control and navigation systems, and on the other hand, leads to an increase in operating expenses. The costs of avionics maintenance have now reached 30–40 % of the total aircraft maintenance costs [1]. Therefore, the actual problem is the increasing efficiency of the avionics maintenance due to lower operational costs while maintaining the airworthiness and competitiveness of aircraft fleet.

Modern civil aircraft are equipped with digital flight control and navigation systems of the new generation in which all systems have built-in test equipment (BITE) and structurally consist of a series of modular components that are designed to be replaced quickly at an operating location. Such modular components are called line replaceable units (LRUs). Aircraft safety is ensured by advanced redundancy of avionics systems, while the regularity of flight – by creating a sufficient number of spare LRUs in the exchange fund of the base airport.

The high integration of flight control and navigation systems and high intensity of aircraft operation leads to the fact that by the results of maintenance actions, some LRUs are mistakenly considered inoperable, dismantled and sent to the recovery resulting in substantial costs. This raises the question of the so-called unconfirmed failures (No Fault Found – NFF). Aviation data suggest that there are in excess of 400000 of NFF cases per year, where a false alarm is given and no fault is found after the investigation [2]. The number represents 23 % of all (1,76 million) component removals. The only quotable estimate, provided by Airbus, was published by the Air Transport Association, which estimated annual NFF costs for an airline operating 200 aircraft at $20 million, or $100000 per aircraft per year [2; 3]. A large number of unconfirmed failures can entail unnecessary increase of spare LRUs in the exchange fund to maintain flight regularity, resulting in significant capital costs.

Thus, it is necessary to assess the impact of unconfirmed failures on the maintenance effectiveness and to develop the appropriate models for MTBUR calculation.

**Analysis of existing research results and purpose of work.** There are many references where is proposed as a measure that evaluates the impact of unconfirmed failures to use the MTBUR. For the first time, this measure was cited in the standard MIL–338 [4]. Thus, in the standard it is proposed to evaluate this measure only using statistical information gathered during the operation of aircraft. To assess the effectiveness of the maintenance system at the step of designing new avionics systems or in the early years of their operation the analytical or simulation tools are required to develop. Such tools must take into account the dependence of MTBUR on the reliability and testability properties of avionics systems. Analytical expressions for the MTBUR on a finite and an infinite interval of maintenance planning were first presented in [5; 6 and 7]. However, the MTBUR can be evaluated as well, and by simulation modeling using, for example, the Monte Carlo method. The advantage of simulation modeling of the LRUs maintenance process is the fact that it can describe the maintenance process with a greater degree of adequacy than the analytical modeling. In addition, the simulation modeling allows checking on the adequacy of the analytical model to the real maintenance process. Thus, the purpose of this article is to develop a simulation algorithm for obtaining the statistical estimate of MTBUR and analysis of the adequacy of the known analytical expressions for MTBUR calculation to the simulation results.

**The development of the simulation model.** NFF is a problem primarily associated with intermittent failures of LRUs and false failures of BITE. As shown in [5; 6], at high rate of test checking and high reliability of LRU the MTBUR is largely determined by the trustworthiness of BITE. That is why the simulation is carried out on the example of the MTBUR evaluation with taking into account the BITE trustworthiness. For a periodically tested LRU, the MTBUR can be calculated from the following analytical formula for an infinite interval of maintenance planning [5; 6 and 7]:

$$MTBUR = \frac{1-e^{-\lambda\tau}}{\lambda\left[1-(1-\alpha)e^{-\lambda\tau}\right]}, \qquad (1)$$

where $\tau$ is the average duration between the LRU operability checking; $\alpha$ is the conditional probability of a false failure at the operability checking of the LRU with BITE; $\lambda$ is the LRU failure rate.

For statistical evaluation of the MTBUR on an infinite interval of maintenance planning the following general expression can be used:

$$MTBUR^* = \sum_{i=1}^{N_{FR}+N_{PR}} T_i \Big/ \left(N_{FR}+N_{PR}\right), \qquad (2)$$

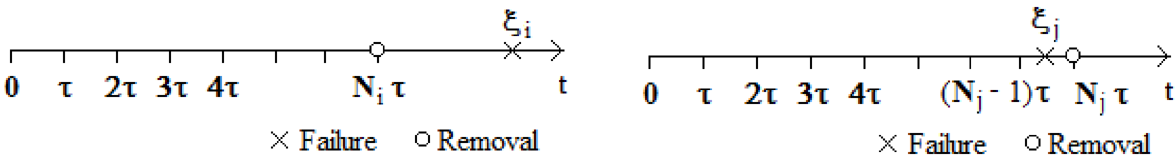
where $T_i$ is the operating time of $i$-th LRU before removal from the board of an aircraft; $N_{FR}$ is the number of LRUs falsely removed from $N_A$ aircraft by the results of checking with help of BITE (false removal); $N_{PR}$ is the number of LRUs properly removed from $N_A$ aircraft by the results of checking with help of BITE (proper removal); $N_A$ is the number of aircraft in operation.

However, for an ease of simulation Equation (2) can be reduced to the following form:

$$MTBUR^* = \sum_{i=1}^{M} N_i\tau \Big/ M, \qquad (3)$$

where $M$ is the number of simulated realizations of the LRU maintenance process; $N_i$ is the number of LRU checks, preceding its rejection; $\tau$ is, like in equation (2), the periodicity of operability checking.

The time diagrams explaining the maintenance process of an LRU are shown in Fig. 1.




*a* *b*

Fig. 1. Maintenance process of LRU with BITE: *a* – false removal of LRU by the results of checking at moment $N_i\tau$; *b* – proper removal of LRU by the results of checking at moment $N_j\tau$

As seen from Fig. 1 (*a*), the LRU, which is in operable state, can be removed from the board of an aircraft at instant $N_i\tau$ if a false failure will occur. In this case the LRU uptime is equal to $N_i\tau$ . On the other hand, if during the LRU lifetime there has not been any false failure, than with high degree of probability the LRU failure will be detected at the next checking time after the failure as shown in Fig. 1 (*b*). In this case the LRU uptime is $\xi_j$ . Since the periodicity of LRU checking by means of BITE is usually small then the uptime can be set to $N_j\tau$ .

Here we assume that the prescheduled removal of an LRU can happen only due to error monitoring by means of BITE. Under this condition, the following relationship is obvious

$$\lim_{\alpha\to 0} MTBUR^*(\alpha) = MTBF^*,$$

where *MTBF* is the mean time between LRU failures.

The generalized algorithm of simulation modeling is shown in Fig. 1.

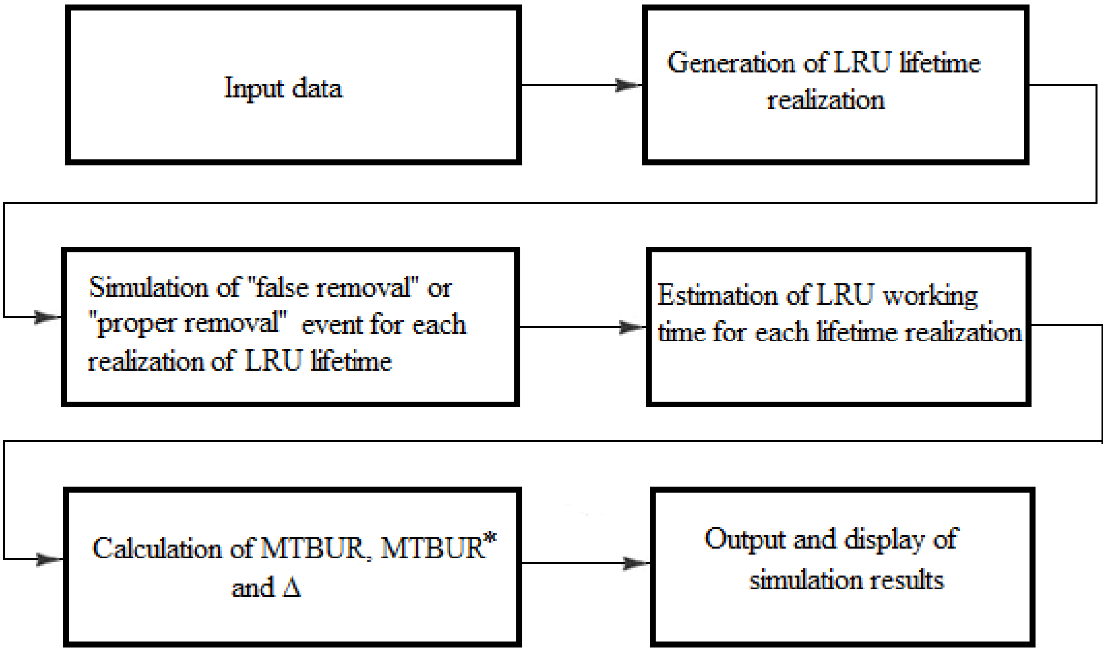



Fig. 1. Generalized algorithm of simulation modeling

For simulating, the original data are set to the following in block 1: *M* is the number of realizations of a random maintenance process which is played out; $\lambda$ is the LRU failure rate; $\alpha$ is the value of the conditional probability of a false failure; $\tau$ is the periodicity of LRU checking by means of BITE. Next, in block 2 the LRU lifetime realization is generated according to the exponential distribution law of time to failure. In block 3 the process of the LRU checking with BITE is modeled. The events of the type "false removal" and "proper removal" of the LRU from the board of an aircraft are modeled according to the calculated probabilities. This step takes into account the properties of reusable checks, discussed in [8], and the conditional probability of a false removal at moment $\nu\tau$ is determined by the expression

$$P_{FR}\left(\overline{\tau,(\nu-1)\tau},\nu\tau\,\middle|\,\xi\right) = \alpha(1-\alpha)^{\nu-1} \quad ,\nu = \overline{1,k},$$

where *k* is the number of the LRU checking; $\xi$ is the LRU time to failure, $\xi > k\tau$ .

In block 4, the maintenance process is modeled and the duration of the working time till removal from the aircraft board is estimated for each realization. In block 5, the results of simulation are processed, the values of $MTBUR$ and $MTBUR^*$ are, respectively, calculated by Equations (1) and (3).

In the same block, the relative difference between the assessed value $MTBUR^*$ and theoretical value $MTBUR$ is calculated. The output of calculation results is performed in tabular and graphical form. The algorithm is implemented in Delphi 2007.

Simulation results are shown in Fig. 2. Here, modeled estimates are plotted as a function of the number of realizations of the maintenance stochastic process and, also, the value of *MTBUR*, calculated from equation (1), is marked. As can be seen, the simulation results show good agreement with the theoretical value of MTBUR, predicted by Equation (1), when the number of realizations exceeds 2500.

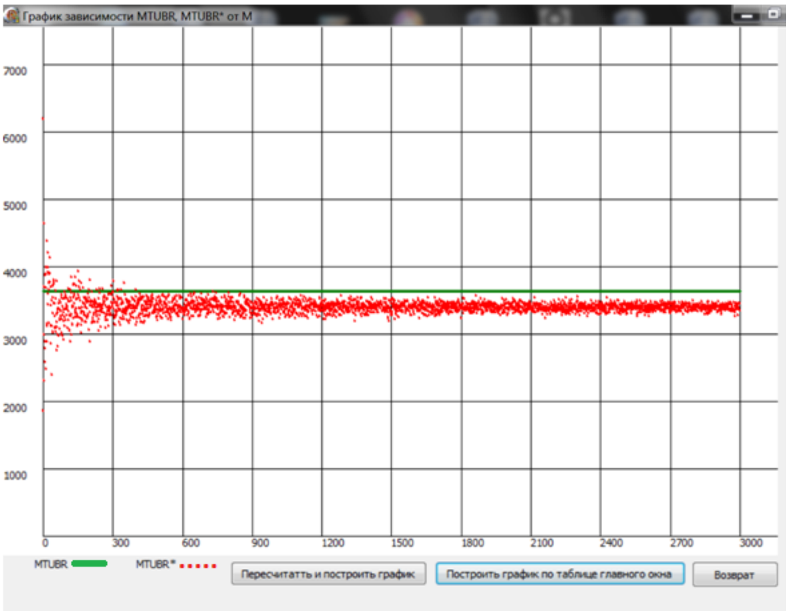



Fig. 2. The dependence of the MTBUR estimate from the number of realizations of the maintenance random process (*M*) for an infinite time of maintenance planning

The chart in Fig. 2 is based on the following input data: $M$ = 3000; $\lambda$= 1/5000 $h^{-1}$; $\alpha = 0{,}0003$; $\tau = 4\,h$. As seen from Fig. (2), the relative deviation of the estimate $MTBUR^*$ from the calculated value $MTBUR = 3636h$ does not exceed 5 %, when the number of realizations $M \geq 2500$, i. e.

$$\Delta = \frac{\left|MTBUR^* - MTBUR\right|}{MTBUR^*} \cdot 100\% < 5\%\,.$$

Further increase of realizations ($M$ > 2500) leads to a decrease of relative deviation $\Delta$, which proves the adequacy of the analytical Equation (1) to the actual maintenance processes of avionics LRUs.

Similarly, the simulation algorithm has been developed to obtain an estimate of MTBUR on a finite interval of maintenance planning. It is designated as $MTBUR_W^*$. The algorithm is different in that it defines a finite number of operability checks on the given warranty interval *T*. The number of checks is calculated from equation $N = \dfrac{T}{\tau} - 1$.

The theoretical value of MTBUR on a finite interval of maintenance planning, designated as $MTBUR_W$, is determined by a formula obtained in [9]:

$$MTBUR_W = \frac{\tau}{\alpha}\left[1-(1-\alpha)^N e^{-(N+1)\lambda\tau}\right]+\left[(1-e^{-\lambda\tau})\left(\frac{1}{\lambda}-\frac{\tau}{\alpha}\right)-\tau e^{-\lambda\tau}\right]\times$$
$$\times\frac{1-(1-\alpha)^{N+1}e^{-(N+1)\lambda\tau}}{1-(1-\alpha)e^{-\lambda\tau}}+\tau(1-\alpha)^N e^{-(N+1)\lambda\tau}. \qquad (4)$$

For statistical evaluation of the MTBUR on a finite planning interval, the following general expression can be used:

$$MTBUR_W^* = \frac{\sum_{i=1}^{N_{FR}+N_{PR}} T_i}{N_{FR}+N_{PR}} + T\left(1-\frac{N_{FR}+N_{PR}}{mN_A}\right), \qquad (5)$$

where $m$ is the number of similar LRUs installed on the board of one aircraft.

Again, for an ease of simulation Equation (5) can be reduced to

$$MTBUR_W^* = \frac{\sum_{i=1}^{N_{FR}+N_{PR}} N_i\tau}{N_{FR}+N_{PR}} + T\left(1-\frac{N_{FR}+N_{PR}}{M}\right).$$

The time diagrams explaining the maintenance process of an LRU with BITE on a finite planning interval are shown in Fig. 3.

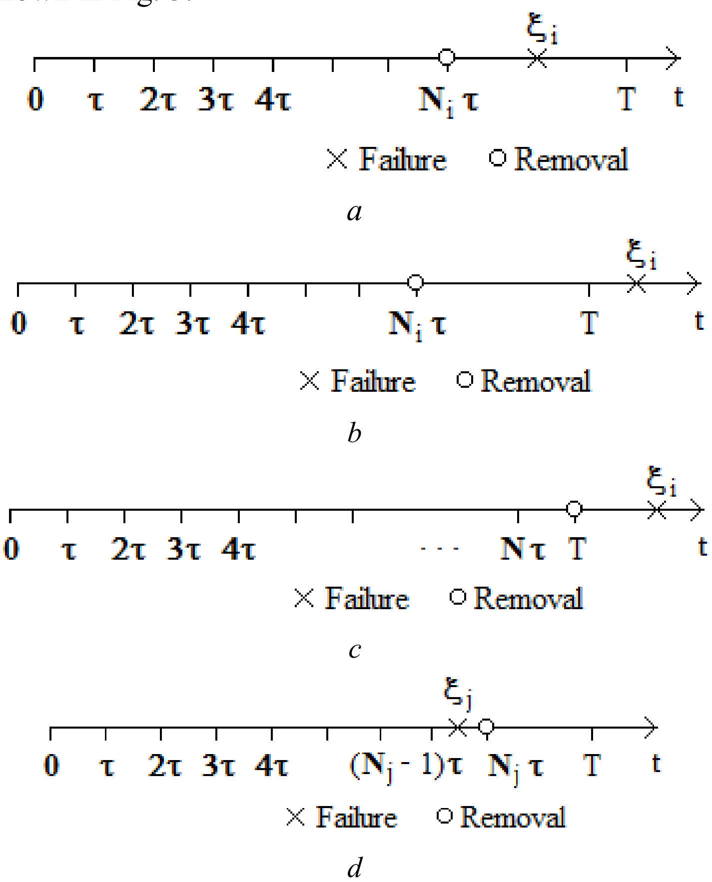



Fig. 3. Maintenance process of LRU with BITE on the finite time of maintenance planning: *a* – false removal of LRU by the results of checking at moment $N_i\tau$ when $\xi_i < T$; *b* – false removal of LRU by the results of checking at moment $N_i\tau$ when $\xi_i > T$; *c* – proper removal of LRU at the end of planning period $T$; *d* – proper removal of LRU by the results of checking at moment $N_j\tau < T$

The simulation results are shown in Fig. 4. The chart in Fig. 4 is based on the following input data: service life warranty $T = 3000h$; $M = 3000$; $\lambda = 1/5000\ h^{-1}$; $\alpha = 0{,}0003$; $N = 749$.

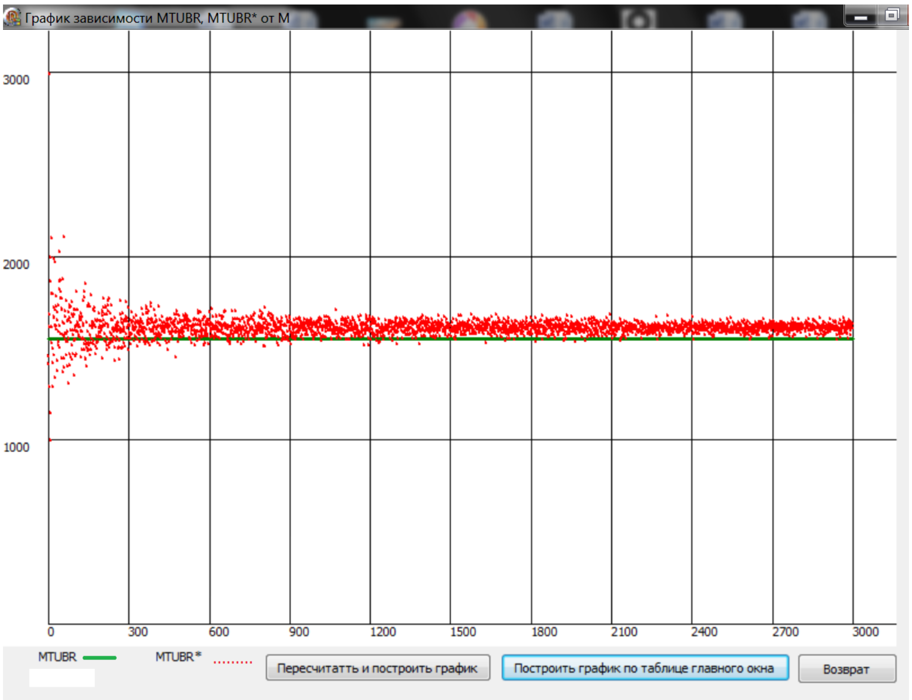



Fig. 4. The dependence of the MTBUR estimate from the number of realizations of the maintenance random process (*M*) for a finite interval of maintenance planning

As can be seen, the simulation results also show good agreement with the theoretical value of $MTBUR_W = 1553\,h$, predicted by equation (4). In this case, the convergence of the MTBUR estimate, which is $MTBUR_W^*$, to $MTBUR_W$ a bit lower than in the case of infinite interval of maintenance planning due to the relatively small service life warranty $T$.

However, when $M \geq 2500$ the relative deviation $\Delta$<5 %, which also confirms the adequacy of the analytical expression (4) to the actual maintenance process of avionics LRUs.

**Conclusions.** The algorithm and software have been developed for simulating the mean time between unscheduled removals, which is an important effectiveness measure of avionics systems maintenance. The expressions have been proposed for calculating the statistical estimates of mean time between unscheduled removals that take into account the characteristics of the flow of proper and false removals of avionic LRUs for a finite and an infinite interval of maintenance planning. It has been shown that the analytical expressions for the mean time between unscheduled removals, published earlier by the authors, adequately describe the actual maintenance process of modern avionic LRUs because the relative difference between the simulated and calculated values of this indicator does not exceed 5 %. These results allow the engineers to evaluate the mean time between unscheduled removals of avionics LRUs as in the design stage, so in the operation stage.

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В. В. Уланський, І. О. Мачалін

**Імітаційне моделювання середнього напрацювання на дострокове знімання радіоелектронних систем**

Розроблено алгоритм імітаційного моделювання для оцінювання середнього напрацювання на дострокове знімання (Mean Time Between Unscheduled Removals – MTBUR) періодично контрольованих радіоелектронних систем. Наведено загальні формули для статистичного оцінювання MTBUR. Зіставлено результати імітаційного моделювання MTBUR зі значеннями цього показника, обчисленими за аналітичним виразами. Показано задовільну збіжність результатів аналітичного й імітаційного моделювання.

В. В. Уланский, И. А. Мачалин

**Имитационное моделирование средней наработки на досрочный съем радиоэлектронных систем**

Разработан алгоритм имитационного моделирования для оценки средней наработки на досрочный съем (Mean Time Between Unscheduled Removals – MTBUR) периодически контролируемых радиоэлектронных систем. Приведены общие формулы для статистической оценки MTBUR. Сопоставлены результаты имитационного моделирования MTBUR со значениями этого показателя, вычисленными по аналитическим выражениям. Показано хорошую сходимость результатов аналитического и имитационного моделирования.