Determining the expediency of modernizing technical systems based on an evolutionary approach

Shostak Vladyslav¹, Yerko Viktor², Kryzhanivskyi Yevhen³, Liubarets Andrii⁴, Perehonchuk Vladyslav⁵

¹ Candidate of Technical Science (PhD); Chief of State Research Aviation Institute; Ukraine
² Candidate of Technical Sciences (PhD), Senior Researcher, Head of the research unit - Deputy Head of the research department; State Research Institute of Aviation; Ukraine
³ Candidate of Technical Science (PhD), Head of the Department; State enterprise «SKDB «LUCH»; Ukraine
⁴ Candidate of Technical Science (PhD), Head of the Sector; State enterprise «SKDB «LUCH»; Ukraine
⁵ Master, Head of the Sector; State enterprise «SKDB «LUCH»; Ukraine

Abstract.
A methodical approach to determining the necessity and expediency of modernization of complex technical systems based on the evolutionary approach is presented, which is based on the results of the analysis of technical and economic factors affecting the decision-making regarding modernization. Modernization is considered as a stage of evolution in the development of complex technical systems, and as a way to overcome the consequences of moral and physical aging and continue effective exploitation. At the same time, the process of evolution is described by some S-shaped law, which is characterized by the following stages - genesis, industrial production, conservation and development, reduction in the efficiency of application and the end of the life cycle.

Keywords:
cost of modernization
evolution
methodical approach
modernization
moral obsolescence
component part
complex technical system
technical excellence

This work is distributed under the terms of the Creative Commons Attribution–ShareAlike 4.0 International License (https://creativecommons.org/licenses/by-sa/4.0/).
The experience of hostilities convincingly shows that the vast majority of weapons and military equipment (AME) used by both sides were developed back in the 80s and 90s of the last century, while their modernization made it possible not only to improve the basic tactical and technical characteristics, but also and extend the service life. This approach, aimed at reducing the costs of military departments regarding guided weapons of various purposes, is characteristic of many countries of the world. Thus, the US Ministry of Defense was allocated 46.7 million dollars for re-certification and modernization of missiles for anti-aircraft systems "Patriot", which are in service with the armies of 12 countries in Europe and Asia.

At the same time, modernization will be understood as a set of measures for the technical improvement of the AME model with the aim of improving the main tactical and technical characteristics, including increasing the level of reliability, functioning and efficiency of use for the intended purpose by changing its design, components, equipment, and elements. In a broader sense, this is a complex scientific and technical problem that requires a systemic solution that takes into account the results of the analysis of the intended combat use, the place of the modernized sample in the AME system, the costs of carrying out these measures, possible options for structural improvements of the sample, the capabilities of enterprises, etc. [1,2].

Most modern AME samples consist of a large number of components (elements, blocks, aggregates, systems, etc.), each of which performs its functions, is built on the use of certain physical principles and has connections with others, while their structure is determined by the combat purpose. At the same time, they all have common features regarding the organization, construction and composition, that is, they are typical representatives of complex technical systems, which allows us to consider them from the standpoint of the theory of complex technical systems (CTS) in organizational and functional aspects [3].

As a CTS, the authors consider aircraft and their guided weapon (GW) as the most dynamically developing types of AME. The analysis of AME development programs carried out in
the world indicates the priority of increasing their combat capabilities precisely due to the modernization of existing models. At the same time, the acquired experience has shown that the decision to choose one or another option for modernization is key and requires appropriate justification. This approach, for example, was manifested in the development and implementation of modernization programs for B-52H aircraft, starting from the Pacer Plank level and up to the B-52H level [4, 5], F-16 - up to the Block 50/52 level, ...., Block 70/72 [6, 7], etc.

In this aspect, a classic example of the continuity and sequence of modernization of guided weapons (GW) is the development of short-/medium-range air-to-air guided missiles of the Sidewinder family (USA), the latest modification of which, AIM-9X, continues the development line of AIM 9B, C missiles, D, E, G, J, K, H, L, M, P for almost 60 years. At the same time, despite all the differences in construction, design elements and functioning algorithms, all of them are designed for use with launchers of the LAU-7A type and coupling with aircraft, including obsolete ones, according to the MIL STD 1530 standard [8].

Table 1 shows data on the number of upgrades of air-to-air guided missiles of some leading countries of the world [8].

<table>
<thead>
<tr>
<th>Name, country</th>
<th>Year of acceptance into service. The year of the last modernization</th>
<th>Number of upgrades</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIM-9, USA</td>
<td>1956 – 2012</td>
<td>12</td>
</tr>
<tr>
<td>MICA, France</td>
<td>1996 – 2008</td>
<td>7</td>
</tr>
<tr>
<td>Python, Israel</td>
<td>1982 – 2005</td>
<td>3</td>
</tr>
<tr>
<td>P-77 (AA-12 by classification NATO), Russia</td>
<td>1994 – 2013</td>
<td>3</td>
</tr>
<tr>
<td>IRIS-T, Germany</td>
<td>2003 – 2009</td>
<td>2</td>
</tr>
</tbody>
</table>
This approach to the gradual modernization of weapons samples is characteristic of many countries of the world. At the same time, we note that one of the directions of modernization of missiles of this class is to ensure the possibility of their use in air defense systems. So, for example, the IRIS-T aviation guided missile in SLS and SLM modifications is used in medium-range tactical anti-aircraft missile systems.

The purpose of the article is to develop a methodical approach to determining the necessity and expediency of modernizing AMEs based on an evolutionary approach, which will allow overcoming the consequences of their physical and moral aging and have a positive impact on the maintenance of the combat capability of the Armed Forces.

For CTS, which have been in operation for a long time, the second form of partial moral aging is characteristic, which is associated with a decrease in the cost of production and with a significant improvement in the performance characteristics of the samples that appear. Replacement of CTS in use requires attracting significant funds for the purchase of new models, therefore the issue of effective use of the existing fleet remains relevant. In addition, the cost of disposal can be quite significant, which is due to the cost of technological processes.

The evolution of any CTS is described by an S-shaped law (Fig. 1), which is characterized by the following stages: genesis (segment $t_0 - t_1$), industrial release (segment $t_1 - t_2$), conservation and development (segment $t_2 - t_3$), reduction of application efficiency and end of life cycle (segment $t_3 - \infty$).

The nature of the S-shaped curve (Fig. 1, curve 1) after the point $t_2$ indicates a decrease in the efficiency of operation. During this period, a new or modernized sample should be put into production [9].

The positive effect of the operation of the existing CTS continues after the point $t_2$. However, when superimposing the curve of the cost of maintaining their serviceability (Fig. 1, curve 2) on an S-shaped curve, it can be seen that the further the process curve goes beyond the point $t_2$, the more expensive
maintenance becomes, and in the saturation zone \( t_3 \) the cost of serviceability goes to infinity.

![Evolution of a complex technical system](image)

**Figure 1**

Evolution of a complex technical system

From which we can conclude that research and design work on modernization should be carried out at the interval \( t_2 - t_3 \). In this interval, you should compare the costs of maintenance and the costs of modernization. The content \( S \) of such a law is described by the expression

\[
x(\delta_i) = k \cdot E \cdot x(\delta_{i-1}),
\]

where \( x(\delta_i) \) - the characteristics value at a given time; \( x(\delta_{i-1}) \) - the characteristics value at the previous moment in time; \( E \) - the maximum value of characteristics increase; \( k \) - the proportionality factor, which depends on the type of CTS, technology development, etc.

It follows from expression (1) that any characteristics has a maximum value of increase \( E \), which depends on the
MILITARY AFFAIRS AND NATIONAL SECURITY

design of the CTS, the technical characteristics of its constituent parts, and the development of scientific and technical progress.

The need for modernization (approaching the interval \( t_2 - t_3 \)) is significantly influenced by the processes of moral and physical aging, which occur independently of each other and are characterized by different speeds, the duration of the transition of CTS to the limit state, but have one result - the impossibility of its intended use.

The transitional state during the physical aging of the CTS is reflected by the defining parameters that are still within the tolerance field and is characterized by a constant intensity of failures, but under the influence of external factors, degradation of its elements is already taking place, which leads to failures or a decrease in combat effectiveness. The transition state during moral aging of CTS still ensures effective use for its intended purpose and is able to compete with global analogues in determining performance characteristics.

The critical state occurs after the transitional state and is characterized by an increase in the intensity of failures in the case of physical aging and (or) a marginal decrease in the effectiveness of application in the case of moral aging.

Therefore, the methodical approach to determining the necessity and expediency of CTS modernization includes:
- assessment of the technical feasibility of modernization (assessment of the material base for modernization; availability of media; assessment of residual resource);
- analysis of world experience in modernization and assessment of technical excellence of CTS, which is planned to be modernized;
- choosing a rational modernization option;
- study of the influence of the constituent parts of CTS on the effectiveness of the intended use;
- assessment of the economic feasibility of carrying out modernization.

When choosing a CTS for modernization, it is recommended to use the progressive standard method, which allows you to
determine the indicator of technical excellence (TD), to trace a fairly long period of its development and to predict the presence of one or more standards of the same purpose, that is, a group of samples that are the most studied in theoretical and practical terms. If any objects possess certain qualities, then the measurements in the ranking scale allow us to answer the question about the difference in these qualities. At the same time, for greater reliability of obtaining the final result, it is necessary to select as many samples as possible in the group of standards, but in practice it is advisable to limit yourself to 5...8 [10]. Most often, the ranking scale of measurements (order scale) is used if it is necessary to determine the complex indicator of the object, and its heterogeneous characteristics are determined in different units of measurement. Since the performance characteristics and structural and technical characteristics of even the same type of samples can have different units of measurement, it is advisable to use a ranking scale of measurements [11] to determine the complex indicator of TP.

For this, at the initial stage, the main parameters (partial indicators) of the GW sample are selected, which determine the outline and requirements for it, ensure its most effective application and are the starting point for determining the complex TP indicator. It should be noted that the number of partial indicators selected for the study can be arbitrary. The more partial indicators, the more reliable the final result will be.

To determine the comprehensive indicator of the TP level of the AME sample, it is necessary to determine the rank of individual partial indicators in order of increasing or decreasing value. If the largest value of the partial indicator improves technical excellence, then it is given (a rank is assigned) a score of 10, and if it worsens - 1. In case of the same values of the indicator in several samples, it is necessary to divide the sum of places by their number.

After determining the ranks, the TP coefficient ($K_{TP}$) of the studied GW is calculated, which corresponds to a complex indicator of its TP level.
MILITARY AFFAIRS
AND NATIONAL SECURITY

\[ K_{TP} = \frac{\sum r}{a_i + b_j}, \]

where \( \sum r \) - the sum of the ranks of the SC of the studied sample; \( a_i \) - the number of examined samples; \( b_j \) - the number of indicators by which TP is determined.

The higher the sum of the ranks and the TP coefficient, the higher the TP level of the AME sample.

The economic efficiency of modernization \( K_E \), which is carried out during the restoration of the technical condition, can be estimated by the ratio that characterizes the level of specific costs

\[ K_E = \frac{K_0}{K_{TP}}, \]

where \( K_0 \) - the cost factor of serial repair of the AME sample.

At the same time, there is a certain "saturation limit" of quality, that is, starting from a certain point in time, the improvement of combat effectiveness indicators will require higher costs, which will lead to an increase in the indicator \( K_E \).

To assess the feasibility of modernization, one should analyze [9] the severity of the consequences and the frequency of failures of GW subsystems according to the parameter \( C_i \):

\[ C_i = B_{i1} \cdot B_{i2} \cdot B_{i3}, \]

where \( B_{i1} \) - the assessment of the probability of potential failure of that \( i \) component of AME; \( B_{i2} \) - assessment of the
probability of timely failure detection \( i \) component part of AME; \( B_n \) - assessment of the seriousness of the consequences of failure \( i \) component part of AME.

The value is estimated based on operational and test data. The most significant failures are identified by comparing the criticality \( i \) the failure of a component \( C_{LV} \) with some limit value (product of the average values of the estimates \( B_j \)).

To assess the consequences of failures of CTS subsystems, the principles of system analysis are used, according to which hierarchical graphs of negative events (failures) and their consequences are built. The interrelationship of failures is evaluated using algebra-logic functions, which allows to draw a conclusion about the functioning of the AME sample as a whole based on the assessment of the impact of the loss of performance of some subsystem [12].

Research carried out over the past 15 years by the State Enterprise "SKDB "LUCH", the State Research Institute of Chemical Products, the State Research Institute of Aviation, and the Central Research Institute of Armaments and Military Equipment allowed us to identify general problematic issues that affect the technical condition and operational safety of AME [12]. As an example, the table shows the distribution of components of air-to-air guided missiles. The list was formed taking into account the gradual decrease in the intensity of their failures from group A to group B and the decrease in the impact on the effectiveness of their use - from group A to group C.

<table>
<thead>
<tr>
<th>Group A</th>
<th>Group B</th>
<th>Group C</th>
</tr>
</thead>
<tbody>
<tr>
<td>homing head</td>
<td>gas power units</td>
<td>rocket engine</td>
</tr>
<tr>
<td>control unit</td>
<td>block of chemical elements</td>
<td>warheads</td>
</tr>
<tr>
<td>non-contact detonator</td>
<td>turbogenerators</td>
<td>safety and actuating mechanisms</td>
</tr>
<tr>
<td>steering drive</td>
<td></td>
<td>lighters</td>
</tr>
</tbody>
</table>
To assess the economic feasibility of modernization, it is proposed to be guided by the principle of military-economic rationality, according to which the price of a modernized AME model is rational from a military-economic point of view, if the following conditions are met [13]:
- full costs for the implementation of the life cycle of the modernized sample do not exceed similar costs when used to solve the tasks;
- the costs are sufficient for the implementation of the entire set of measures and works on the modernization of the sample.

For the economic justification of modernization, it is necessary to perform a military-economic evaluation. Among the most well-known approaches, it is worth highlighting the methodology that determines the effect of modernization as the difference between the cost of performing a combat task with an existing and modernized model. At the same time, it should be emphasized that GW are characterized by their relatively low cost compared to the cost of potential targets [13].

To determine the cost of the task, the entire technical resource is included in the calculation, while in the case of the modernization of the AME sample, which is already in service, only its residual resource should be taken into account. In addition, in the process of making a decision on modernization, it is necessary to have information about the possibility of its implementation in conditions of limited funding. In this connection, the question arises about the possible directions of modernization and options for their combination, which can give the greatest effect with a given amount of funding.

As a criterion of the military-economic efficiency of modernization, we accept the difference in the cost of performing a combat task with existing and modernized samples [14]

\[ E = Q_R - Q_M, \]

where is \( E \) - the value of the military-economic effect;
**MILITARY AFFAIRS AND NATIONAL SECURITY**

\( Q_c \) — the cost of performing a combat task with an existing model; \( Q_m \) — the cost of performing a combat task with a modernized model.

If as a result of the calculations \( E > 0 \), modernization is appropriate. Otherwise, modernization is impractical. If \( E = 0 \), then the decision should be made taking into account other non-economic factors.

In the general case, the cost of performing a combat task is determined by the expression

\[
Q = Q_c \cdot n_c,
\]

where \( n_c \) — the number of \( GW \) samples needed to perform a combat mission;

\( Q_c \) — the cost of one sample.

For \( GW \), it is possible to accept \( Q \approx Q_c \), since one missile is usually used to perform a combat mission (hitting one target), i.e. \( n_B = 1 \).

We denote the cost of the existing and modernized \( GW \) samples as \( Q_{CR} \) and \( Q_{CM} \), respectively. Then expression (2) takes the form

\[
E = Q_{CR} \cdot n_{CR} - Q_{CM} \cdot n_{CM},
\]

where \( n_{CR} \) and \( n_{CM} \) are the number of basic and modernized products involved in the combat mission, respectively.

Thus, carrying out modernization assumes that the cost of performing a combat mission will increase due to additional costs associated with:

- carrying out research and development works \( Q_{RDW} \);
- additional technological production equipment $Q_{TE}$;
- by changing costs for the production of a modernized sample ($Q_{PM}$) in relation to the existing one ($Q_{PR}$)

$$\Delta Q_{PM} = Q_{PM} - Q_{PR}.$$ 

Thus, evaluating the effectiveness of the modernization of CTS is a complex, science-intensive, complex process that must take into account the peculiarities of the subject of modernization. After the formation of a set of possible options for modernization, it is necessary to conduct a military-economic analysis aimed at determining some optimal option, taking into account the ratio of costs for development, production, operation and combat effectiveness that is achieved. At the same time, the set of admissible alternative options for modernization should not include those options for the technical implementation of the modernized model, the costs of development and production of which will exceed the admissible limits.

The vector optimization method can be used to choose a rational modernization option [12]


where $i = 1...n$, $n$ - the number of possible modernization options, $(T,P,C)$ - numerical indicators of technical excellence, technical condition of system components, time parameters, costs and risks of the $i$-th modernization option.

Therefore, modernization is a process that requires the determination of clear time frames for implementation, which depend, first of all, on the ability of the AME sample to compete with global analogues in terms of defining characteristics. When conducting research on the justification of the need and feasibility of modernization, it is necessary to take into account:
- statistical data on failures of products that are planned to be modernized;
- residual resource / service life;
- rational directions of modernization;
- economic effect of modernization.

Carrying out the modernization of AME will make it possible to overcome the consequences of physical and moral aging, which will positively affect the level of combat capability, save budget funds and continue effective operation.

Therefore, modernization, as a stage of the evolution of AME development, is an important scientific and industrial problem that requires a comprehensive approach to its solution, taking into account the peculiarities of each case.

References:


[9] Шатров А.М., Крижанівський Є.С. Методологічні аспекти організації ремонту з модернізацією керованих авіаційних засобів ураження при
MILITARY AFFAIRS AND NATIONAL SECURITY


