UDC 005.963.1:629.7.-027.3 **doi: 10.32620/reks.2024.3.12**

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MODELS AND INFORMATION TECHNOLOGY OF AGING MANAGEMENT OF MAN-MADE SYSTEMS IN THE CONDITIONS OF MODERN RISKS

The urgent task of researching logistical measures and actions aimed at increasing the life of man-made systems is being formed and solved. The research being conducted is related to the management of complex, high-cost man-made systems (continuation of their resource) with long-term life (high-tech production, critical infrastructure, nuclear power, etc.).Therefore, the topic of the proposed publication, which examines the sequence of logistical actions in planning projects for managing the aging of man-made systems, is relevant. The purpose of this research is to create a complex of mathematical and agent models that can be used to analyze the problem of age degradation and plan actions to manage the aging of man-made systems. The problems that arose due to the aging of the man-made system are analyzed, such as: outdated technological equipment, the effects of climate change risks, regular disruption of energy supply, acts of terrorism, and military threats. Much attention is paid to critical man-made systems with high risks of impact on the environment and people, which are associated with their aging. A systematic analysis of the sequence of logistic actions related to the management of the aging of the man-made system was carried out. A number of possible strategies for aging management are emerging, such as: modernization and replacement of obsolete equipment; reducing the risks of impact on the environment of critical man-made systems, which requires the extension of their resources. The limited capabilities of enterprises are considered when determining the costs of preventive measures to extend the life of a man-made system. An analysis of influencing factors (external and internal) on the aging process of man-made systems is also conducted. Significant influencing factors are separated using virtual experiments and expert assessments. To identify outdated system components, a method is proposed based on assessing their condition with the help of experts and lexicographic ordering of a set of component variants. A cost optimization model is being created for the implementation of measures and actions to manage the of the man-made system. An agent model is formed on the Any Logic platform to analyze the sequence of logistic actions related to the management of man-made system. An example of extending the life of high-tech aircraft production is provided. The scientific novelty of the study is related to the solution of the urgent problem of the formation of strategies, models, and project planning methods for the management of the aging of man-made systems, which contributes to the extension of their existence and the reduction of the risks of impact on the environment and people. The results of this study should be used by the management of enterprises in planning projects related to the management of the aging of man-made systems.

Keywords: *man-made system aging management; critical infrastructures of enterprises, risks of man-made system, damaged system components; factors influencing aging; cost optimization; modeling of logistic actions, simulation modeling, agent modeling, integer optimization.*

1. Introduction

High-tech systems were created with a long life, which was planned in the past economic conditions and the forecast of the development of the economy at that time [1, 2]. However, the modern operating conditions of man-made systems are very different from those of the past, leading to the acceleration of system degradation, which is extremely dangerous for the environment and people [3, 4]. Therefore, there was a need to plan projects aimed at managing the aging of large man-made systems (high-tech production [5], nuclear power plants [6], infrastructure of large cities [7, 8], etc.).The concept of aging was first introduced by the IAEA commission on nuclear power plants. There were aging management projects aimed at extending the life of a nuclear power plant as a high-cost system with increased risks of impact on the environment and people and the possibility of emergencies. The IAEA commission was asked to develop models for analyzing life span and its extension, as well as planning actions for aging management. Aging management includes a whole set of measures, which includes: finding obsolete components, reducing the risks of impact on the

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

environment, forecasting the development of possible emergency situations, and increasing the stability of functioning. The analysis of existing publications reveals various approaches, methods, and models aimed at slowing down the degradation of systems [9, 10]. Special attention is paid to the formation of aging management projects related to various goals for extending the life of man-made systems [11,12]. The work under review presents the results of research into possible strategies for managing the aging of man-made systems and creates models and a method for planning projects related to aging management, which contributes to extending the terms of their existence in the future.

1.1. Motivation

Aging of man-made systems is an acute problem that arises during the operation of high-value, long-lived systems. Over time, the man-made systems began to influence ecology and change the climate, leading to global climate change. Emissions into the atmosphere and extraordinary situations lead to the need to manage the aging of such systems. A direction of aging management is to extend the life of the man-made system. For this purpose, measures should be planned and significant funds should be allocated to reduce the risks of impact on the external environment. Nuclear power plants and their closure can lead to many dangerous factors and the emergence of extraordinary situations. Therefore, projects on aging management are relevant and require research and the formation of scientifically based methods and models for the formal description of the aging process and its management (aging forecasting, modeling risks associated with aging, planning activities, etc.). It is also relevant to create information technology that allows monitoring the state of a man-made system, predicting its behavior and planning actions aimed at reducing risks and extending the system's life.

Planning projects regarding the extension of the existence of man-made systems requires analysis of their conditions and operating conditions [13, 14]. It is necessary to identify the external and internal factors that accelerate the degradation of a system, as well as the components that are most vulnerable to aging, which affects the general state of a man-made system [15]. Furthermore, it is necessary to plan and implement preventive measures to prolong the life of the man-made systems [16].

Therefore, the topic of the proposed research is relevant, in which modeling of a possible strategy for managing the aging of man-made systems that function under complex modern conditions (climate threats, disruption of energy supply, terrorism and military threats, etc.) is carried out.

1.2. State of the art

Aging of man-made systems is associated with the degradation of its components, which affects the stability and safety of the system's operation. Thus, a whole set of problems arises, which are primarily related to the safety of the system’s existence and the reduction of the environmental impact on the external environment and people (emissions into the atmosphere, disturbance of the state of groundwater, the appearance of pollution of rivers and seas, etc.). Such negative phenomena have led to the emergence of problems related to aging management, slowing down the degradation of the man-made system, planning expensive measures with long implementation periods, and the formation of international programs for researching aging management (for example, programs and projects for managing the aging of nuclear power plants by the IAEA commission).

When planning logistical actions aimed at extending the life of man-made systems, it is possible to highlight problems in publications on this topic and require analysis and research for successful aging management:

1. The problem of the influence of the environment on the aging of the technogenic system [17, 18].
2. Problem of age-related degradation of man-made systems [19, 20].
3. The problem of system components vulnerable to aging [21, 22].
4. The problem of forecasting the occurrence of extraordinary situations associated with the aging of the technogenic system [23, 24].
5. Planning measures and actions aimed at slowing down the degradation of man-made systems due to aging [25, 26].
6. The problem of forming projects and creating information technology related to the management of the aging of the man-made systems [27, 28].

The list of problems is not complete and may be supplemented by new problems related to the changing political and economic environment. Terrorist and military threats have worsened the state of man-made systems and led to a sharp increase in the risks associated with man-made systems (for example, Zaporizhzhia NPP, which is under occupation and has a high risk of emergency situations).

Thus, the study of a set of logistical actions, which are aimed at slowing down the degradation of man-made systems, will ensure the successful implementation of projects related to the management of their aging.

1.3. Objectives and the approach

There is a contradiction between the need to plan effective preventive actions to slow down the degradation of the system over time and the imperfection of existing research methods and information technologies and the lack of a systematic analysis of the aging management strategy. This contradiction is the object of research in the proposed publication, which presents models of applied information technology for planning strategies for managing the aging of man-made systems, which ensures the extension of their operating life under the modern conditions of a changing environment.

The purpose of this study is to create a set of mathematical and agent models that can be used to analyze the problem of aging and plan actions to manage the aging of man-made systems.

In accordance with the research goal, it is necessary to solve the following tasks:

1. To conduct a systematic analysis of the aging of the technological system.

2. To form a set of strategies for managing the aging of the man-made system.

3. Create a model of the formation of essential factors of the external and internal environment that affect the aging of the man-made system.

4. To develop a method for identifying the components of man-made systems vulnerable to aging.

5. To optimize costs for the implementation of preventive measures and measures to extend the life of the man-made system.

6. To develop an agent model of information technology for planning logistical actions regarding the management of the aging of the technological system.

7. Provide an example of measures and actions related to the management of the aging of high-tech production.

2. Materials and methods of the research

2.1. Systemic analysis of aging of man-made system

When creating complex systems in technical tasks and regulatory documents regarding operation, the term "existence" of the man-made system is specified when all requirements and conditions of operation are met. However, modern conditions in which the technogenic system functions have deteriorated sharply have led to the emergence of threats (Z) related to the acceleration of aging. Systems of critical purpose (for example, a nuclear power plant) can lead to emergency situations and environmental pollution that affects the environment of people's existence.Therefore, identifying a set of factors (F) that significantly affect the state of the system and lead to the acceleration of aging is an urgent task that must be solved when forming projects related to the management of the aging of man-made systems. The component composition of a man-made system includes various components that have different sensitivities to aging. Therefore, the selection of components (P), which are most sensitive to aging, is an urgent task that must be solved to plan preventive actions (L), which are aimed at replacing or extending the component's resource. There is a logistic sequence of actions that must be carried out in relation to the management of the aging of the man-made systems. This sequence can be represented in the form of a logistic chain as follows:

Identification of a set of factors that violate the operating conditions of the system (F): identification of threats to accelerated aging of the system (Z): selection of vulnerable components of the system, sensitive to degradation and aging (P) – planning of design actions (L) necessary to extend the life of the system -no system.

This logistics chain is the object of research in this work, for which models, methods, and applied information technology for managing the aging of man-made systems are created.

2.2. Formation of a set of management strategies for the aging of the man-made system

In order to extend the life of a man-made system, it is necessary to form aging management strategies that slow down the degradation of the system over time. The choice of an aging management strategy from a set of possible ones (ST) depends on the state of the man-made system, the influence of external and internal environmental factors, management capabilities (including financial ones), and the implementation of preventive actions against aging, etc**.** Therefore, in this study, we will consider possible strategies for slowing down aging and will not rely on their completeness. After analysis of the publications, the following possible strategies for managing the aging of the man-made systems were formed:

1. A strategy based on cost optimization when planning preventive actions against the aging of the man-made system. This strategy is related to the limited possibilities of enterprises to extend the life of man-made systems [29].

2. Strategy for the modernization of the man-made system, which is aimed at significantly extending the life of a man-made system by modernizing equipment and components or replacing outdated components. This strategy is based on the restoration of an enterprise through full or partial modernization [30].

3. A strategy related to reducing the risks of man-made systems' impact on the environment due to aging. This strategy is suitable for critical objects and process-

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

es. For example, managing the aging of a nuclear power plant [31].

4. Strategy for diversification of man-made system. This strategy is aimed at the replacement of outdated, non-competitive products and the release of new innovative products, which requires the exclusion of processes and objects of production that are physically and morally obsolete as well as the involvement of new innovative technologies. By removing such objects and processes and replacing them, a new organizational and technological structure of production is formed, which leads to the rejuvenation of the man-made system and a significant extension of its existence.

5. Mixed strategy, which is formed as a combination of possible strategies 1-4. In this case, the goals of aging management projects may include modernization, diversification, and reduction of the risks to environmental impact [32].

2.3. Model of the formation of essential factors of the external and internal environment that affect the aging of the technogenic system

Two sets of factors affect the acceleration of the aging of the man-made system: factors of the external environment (Q_1) and internal factors related to the system (Q_2), which functions for a long time. It can be noted that Q_1 factors, to a greater extent, are not controllable but depend on changes in the state of the external environment (for example, the climatic conditions of system operation, the behavior of external energy supply and the presence of aggressive actions in relation to the system). To analyze external factors (Q_1), it is necessary to have statistics on their changes in the past years, to forecast their behavior, in the future, and to use the assessments of experts who operate the man-made system in the long term.

Identifying significant factors from the set (Q_1) will allow, in the future, to neutralize or reduce their impact by planning and conducting preventive actions. To identify essential factors from the set (Q_1), we use the method of purposeful planning of experiments, in which the evaluations of experts (specialists in the design and operation of man-made systems) are used as feedback (V). Here, we provide an example of such an assessment. As a plan for conducting a virtual experiment, we will use a full factorial experiment (FFE), in which the number of experiments is $N = 2^n$, where n is the number of possible factors (Q_1) that affect system aging. Let, as an example, factor X_1 is responsible for the influence of changes in climatic conditions on the state of the system; X_2 – characterizes the impact of energy supply disruptions on system aging; X_3 is responsible for the impact of external threats on system aging (terrorism, military threats, etc.). In this case, the FFE plan includes N = 8 experiments (Table 1). To assess the possible correlation of the influence of factors X_1, X_2, X_3 on the aging of the system, we will enter columns X_1X_2, X_1X_3, X_2X_3, $X_1X_2X_3$. The extreme (right) column represents the recall value (V) obtained from expert ratings. We use quantitative values for recall (V) in the form of point-scale values (0÷10). For the illustrated example, the recall estimates (V) of the experts are presented in Table 1. The formation of experiments (in the form of FFE plan terms) is simple with the help of binary counter values. For example, the terms of the FFE plan (individual experiments) in the form of binary counter values are as follows:

1. 000
2. 001
3. 010
4. 100
5. 100
6. 101
7. 110
8. 111.

Table 1

Virtual experimentation with external factors

	X_1	X_2	X_3	X_1X_2	X_1X_3	X_2X_3	$X_1X_2X_3$	V
1	-1	-1	-1	+1	+1	+1	-1	1
2	-1	-1	+1	+1	-1	-1	+1	3
3	-1	+1	-1	-1	+1	-1	+1	5
4	-1	+1	+1	-1	-1	+1	-1	8
5	+1	-1	-1	-1	-1	+1	+1	2
6	+1	-1	+1	-1	+1	-1	-1	5
7	+1	+1	-1	+1	-1	-1	-1	7
8	+1	+1	+1	+1	+1	+1	+1	10

To conduct an experiment, according to the FFE plan, it is necessary to represent "0" as "-1", where "-1" denotes the lower value of the factor. For "1", we have the factor value in the form of "+1", where "+1" denotes the upper value of the factor. Thus, the lower and upper values of factors X_1, X_2, X_3 will represent the ranges of changes in factors in the history of operation of the man-made system. Next, experts conduct virtual experiments using recall scores (V). After conducting many virtual experiments, it is possible to form a regression dependence (incomplete quadratic for FFE), in which the value of the influence of external factors (Q_1) is manifested, as well as their possible correlation:

$$V=a_0+a_1X_1+a_2X_2+a_3X_3+a_{12}X_1X_2+ +a_{13}X_1X_3+a_{23}X_2X_3+ +a_{123}X_1X_2X_3.$$

For the illustrated example (see Table 1), we have the following regression dependence (the calculation was carried out according to the FFE formulas):

$$V=5.125+0.875X_1+2.375X_2+1.375X_3+ +0.125X_1X_2+0.125X_1X_3+ +0.125X_2X_3-0.125X_1X_2X_3.$$

The value of the coefficients in the regression dependence at X_1, X_2, X_3 indicates the influence of the factors on the response (V). For example, factor X_2 (regular disruption of energy supply) is the most significant, factor X_3 (terrorist and military threats) is less significant, and X_1 (climate threats) is the least significant. Therefore, in order to plan preventive actions that will be aimed at reducing the impact of external factors on the aging of the system, first of all, it is necessary to consider the energy supply (for example, the use of autonomous sources of energy supply). The correlation of factors X_1, X_2, X_3 is the same and essentially does not affect the aging of the system. When forming a set of internal factors (Q_2) that affect the aging of the man-made system, it is necessary to consider the possibility of managing them to reduce their influence on the degradation of the system. The internal factors of technogenic system aging include:

- violation of operating conditions;
- violation of the technological process of production;
- an increase in the load of the man-made system (work in the peak mode), which often occurs during operation;
- physical wear and tear of technological equipment;
- the occurrence of several freelance situations.

The number of factors (Q_2) can be increased depending on the specifics of the operation of a specific man-made system. Assessment of the influence of internal factors on the man-made system can be carried out with the help of virtual experiments and expert assessments using the FFE.

2.4. The method for identifying aging-sensitive components of a man-made system

When the man-made system ages, its components undergo different levels of degradation over time. Therefore, it is important to identify the most outdated components of a man-made system and form a series according to the degree of their aging, which, in the future, will allow planning of replacement or modernization of old components. To identify the most outdated components of a man-made system, it is necessary to form a metric for assessing aging. The simplest presentation of the aging of individual components of a man-made system can be carried out with the help of qualitative assessments. The set of aging characteristics of the man-made system (S) can be represented as follows:

- the level of deviation of the values of the technical characteristics of the component due to the long operation period (Y_1);
- increase in the number of failures and failures in the robot components (Y_2);
- increase in violations of energy supply components (Y_3);
- the presence, in an obvious form, of physical wear of the component (Y_4);
- violation of the temperature regime during operation of the component (Y_5);
- presence of abnormal vibrations and noise effects (Y_6), etc.

The list of aging characteristics (S) can be increased depending on the characteristics of a specific man-made system. Each characteristic of aging will be presented with the help of a linguistic variable and qualitative assessment values formed with the help of experts.

Let's consider an illustrated example of assessing the aging of man-made system components with the help of expert qualitative assessments. Let the linguistic variables Y_1, Y_2, Y_3, Y_4 be used for the set of aging characteristics (S). We present qualitative definitions of linguistic variables in the form of letters in the Latin alphabet as follows:

$$Y_1 = \begin{cases} \text{A – a very large deviation} \\ \quad \text{of technical characteristics;} \\ \text{B – a large deviation} \\ \quad \text{of technical characteristics;} \\ \text{C – satisfactory deviation} \\ \quad \text{of technical characteristics,} \end{cases} \tag{1}$$

$$Y_2 = \begin{cases} \text{A – a very large number} \\ \quad \text{of component failures;} \\ \text{B – a large number} \\ \quad \text{of component failures;} \\ \text{C – is a satisfactory number} \\ \quad \text{of component failures,} \end{cases} \tag{2}$$

$$Y_3 = \begin{cases} \text{A – very high energy supply} \\ \quad \text{of the component;} \\ \text{B – high energy supply} \\ \quad \text{of the component;} \\ \text{C – the most significant energy supply} \\ \quad \text{of the component,} \end{cases} \tag{3}$$

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

$$Y_4 = \begin{cases} A \text{ – very great physical wear} \\ \quad \text{of the component;} \\ B \text{ – great wear} \\ \quad \text{of the component;} \\ C \text{ – sufficient wear} \\ \quad \text{of the component,} \end{cases} \quad (4)$$

To assess the obsolescence of a component, the set of characteristics (S) must be presented in the form of a series, where the most important characteristic regarding aging (according to experts) will be on the first place, and the least important will be on the last.

Let, for example, the ordered set of characteristics of the components of a man-made system (S) have the form:

$$Y_1, Y_2, Y_4, Y_3.$$

Each component of the man-made system will be evaluated using the presented series of aging characteristics. For example, there are four components in a man-made system. Each component is evaluated by experts using qualitative values of aging characteristics (S) and the formed series Y_1, Y_2, Y_4, Y_3:

1. B, C, B, A
2. A, B, C, B
3. C, B, B, A
4. A, C, B, B.

In order to carry out preventive actions regarding the aging of the man-made system, in the form of modernization or replacement of outdated components, it is necessary to arrange the set of components of the system according to the value of the quality characteristics of aging (S), as well as to consider their importance (Y_1, Y_2, Y_4, Y_3). Such ordering, considering the values of linguistic variables, represents alphabetical ordering, as in a dictionary (lexicographic ordering). For our example, the lexicographic arrangement appears as follows:

2. A, B, C, B
4. A, C, B, B
1. B, C, B, A
3. C, B, B, A.

Thus, the most outdated component is the second component, and the least outdated component is the third component. Therefore, in the further implementation of preventive actions regarding the aging of the man-made systems, it is necessary to begin with the second component. The number of outdated components that can be modernized (continuation of the resource) or changed is related to the limited capabilities of the enterprise.

The developed method makes it possible to identify the most outdated components of a man-made system, which must be changed or modernized in the future.

2.5. Cost optimization model for implementing preventive actions and measures to extend the life of the technogenic system

Extending the life of a complex technogenic system is a costly process that must exist the entire life of the system. Therefore, there is a problem of cost optimization in the conditions of limited enterprise opportunities and the variability of the external political and economic environment.

When optimizing costs, it is necessary to take into account the factors that affect the state of of the man-made system (see point 2.3), as well as, first, consider those components of the system that are the most outdated and subject to modernization or replacement (see point 2.4). Cost optimization is related to the choice of a strategy for managing the aging of the man-made system, as well as the capabilities of the enterprise (see point 2.2).

Let's consider the optimization of costs related to the aging management of a critical man-made system (for example, a nuclear power plant), which has a high risk of emergency situations and environmental impacts (see point 2.2).

The goal of the project, in relation to the management of the aging of the critical man-made systems, will be to minimize the risks of system failures during the extension of their existence. The components of a critical man-made system have various failure risks that affect the occurrence of emergency events and increase with the aging of the system. Costs for preventive actions to continue the existence of a critical man-made system are aimed at reducing the overall risk of possible pollution in the environment.

We will use the method of integer (boolean) programming to mathematically model the risk reduction of a critical man-made system. A possible choice of measures and actions aimed at reducing risks and extending the life of a critical man-made system can be determined using the boolean variable x_{ij}, where i is responsible for the i-th outdated component of the man-made system and j refers to the selection of measures and actions to reduce the risk of functioning of the i-th obsolete component:

$$x_{ij} = \begin{cases} 1, \text{ if for the i-th outdated component} \\ \quad \text{the j-th event is used regarding} \\ \quad \text{reducing the risk of its functioning;} \\ 0, \text{ otherwise,} \end{cases} \quad (5)$$

where $\sum_{j=1}^{m_i} x_{ij} = 1$, which means the mandatory choice of a possible preventive measure to reduce the risk.

m_i is a set of possible measures to reduce the risk of functioning of the i-th component of a critical man-made system.

Then, the total risk of failure R, which must be reduced to extend the life of a critical man-made system, has the form:

$$R = \sum_{i=1}^{N} \sum_{j=1}^{m_i} r_{ij} x_{ij}, \quad (6)$$

where r_{ij} is the risk of failure of the i-th component, which is expected after the implementation of a possible j-th measure to extend the resources of the i-th component.

Costs of implementing preventive measures aimed at extending the life of critical man-made system:

$$W = \sum_{i=1}^{N} \sum_{j=1}^{m_i} w_{ij} x_{ij}, \quad (7)$$

where w_{ij} are costs aimed at reducing the risk of failures of the i-th component after carrying out the possible j-th preventive measure to extend the resource of the i-th obsolete component.

The term defining the existence of a critical man-made system after performing preventive measures before its aging will be:

$$T = \sum_{i=1}^{N} \sum_{j=1}^{m_i} t_{ij} x_{ij}, \quad (8)$$

where t_{ij} is the term of operation of the i-th component after the j-th possible measure to extend its resource (conditional value, which is presented in the form of sums of terms). This presentation is valid for the consistent operation of the components of the man-made system. For the parallel operation of the system components, the concept of min must be used, which makes it possible to determine the operating time of the man-made system based on the value of the operating time of the most unreliable system component. That is, it is necessary to find:

$$\min_{i,j}(t_{ij} x_{ij}), \quad (9)$$

for all j and i ($j=\overline{1, m_i}$, $i=\overline{1, N}$). Here, min is associated with a pessimistic estimate of the the work time of parallel-working components of the man-made system after taking preventive measures before its existence. This assessment depends on the influence of some external threats (which is characteristic of a state of war).

For the serial-parallel operation of the components of the man-made system, it is necessary to separate the components that work in series. For them, the total time period T_1 is related to formula (8). For those components working in parallel, the time period T_2 is related to the formula (9). Then the term of operation of the man-made system will be:

$$T = T_1 + T_2. \quad (10)$$

It is necessary to minimize the overall risk of failure of a critical man-made systems as follows:

$$\min R, \; R = \sum_{i=1}^{N} \sum_{j=1}^{m_i} r_{ij} x_{ij}. \quad (11)$$

At the same time, the term will be extended after the implementation of preventive measures before the aging of the man-made system:

$$T \geq T', \quad (12)$$

where T' is the planned operation period of the critical man-made system after implementing preventive measures before its aging. The value of T is calculated according to formulas (8) – (10).

It is necessary to consider the possible costs of taking measures to extend the life of a critical man-made system:

$$W \leq W', \; W = \sum_{i=1}^{N} \sum_{j=1}^{m_i} w_{ij} x_{ij}, \quad (13)$$

where W' is the planned costs of performing preventive actions and measures to extend the life of a critical man-made system.

It should be noted that in the problem considered above, the optimization of preventive measures regarding the aging of the man-made system does not depend on the choice of aging management strategy (see point 2.2).

For the optimization task, which we will consider further, preventive measures to extend the life of the system are related to the modernization strategy, which

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

uses the modernization or replacement of individual components of the man-made system. Therefore, the second task is a special case of the first. For optimization, we enter the boolean variable x_i:

$$x_{ij} = \begin{cases} 1, \text{ if for the i-th obsolete component} \\ \quad \text{man-made system is carried out} \\ \quad \text{modernization to extend its resource;} \\ 0, \text{ otherwise, when a substitute is used} \\ \quad \text{outdated i-th component to a new one.} \end{cases} \quad (14)$$

Then, the costs W associated with the strategy of modernizing the man-made system to extend its service life, will be:

$$W = \sum_{i=1}^{N} w_i^{'} x_i + \sum_{i=1}^{N} w_i^{''} (1 - x_i), \quad (15)$$

where w_i' is the cost of modernizing the outdated i-th component to extend its service life;

w_i" – the costs of replacing the i-th obsolete component with a new one.

The term of operation of the man-made system after performing actions related to its aging:

$$T = \sum_{i=1}^{N} t_i^{'} x_i + \sum_{i=1}^{N} t_i^{''} (1 - x_i), \quad (16)$$

This is true for the consistent operation of the man-made system components. For parallel operation, the component must be found (analogous to formula (9)):

$$\min_i [t_i^{'} x_i + t_i^{''} (1 - x_i)], \quad (17)$$

where t_i' is the service life of the i-th component after modernization, which is associated with aging;

t_i" is the service life of the i-th component after its replacement with a new one.

It is necessary to minimize the costs of modernization of the man-made system, which is related to its aging:

$$\min W, \; W = \sum_{i=1}^{N} w_i^{'} x_i + \sum_{i=1}^{N} w_i^{''} (1 - x_i). \quad (18)$$

At the same time, it is necessary to ensure a new term of operation for a man-made system:

$$T \geq Tc', \; T = \sum_{i=1}^{N} t_i^{'} x_i + \sum_{i=1}^{N} t_i^{''} (1 - x_i), \quad (19)$$

We use formula (16) for sequential operation of man-made system components, and formula (17) for parallel operation of man-made system components. Where T' is the planned period of operation of the technogenic system after its modernization.

2.6. An agent model of information technology for planning logistic actions related to the management of the aging of a technogenic system

An agent simulation model was developed using information technology with the help of the Any Logic platform, which considers the main logistical actions for managing the aging of the man-made system. The model is related to the modernization strategy of a man-made system (see point 2.2). Simulation modeling makes it possible to explore, in time, a parallel-sequential sequence of actions associated with measures to manage aging. Information technology makes it possible to form both plans and plan graphs of measures to manage the man-made system. For modeling, the following sequence of logistic actions aimed at the modernization of the outdated man-made system was formed:

- formation of the structure and composition of the components of outdated man-made systems;
- analysis of the state of a man-made system by identifying a set of obsolete components (PZ) that essentially affect the life of the man-made system;
- formation of a set of suppliers who produce or have ready-made components for replacement of obsolete components (PK);
- formation of ways to supply components to replace obsolete ones;
- modernization of outdated components (PM);
- performing installation work to replace outdated components;
- performing commissioning work related to updating the man-made system;
- analysis of the results of actions taken to extend the life of the man-made system.

The simulation model is formed in the form of a set of agents and uses Any Logic information technology. The agents included:

1. Agent "structure" of man-made system.
2. "Obsolete for replacement" agent.
3. Agent "obsolete for modernization".
4. Agent "suppliers".
5. "Supply logistics" agent.
6. "Modernization of obsolete" agent.
7. Agent "replacement of obsolete ones".
8. Agent "commissioning".
9. "Simulation management" agent.

10. Agent "simulation results".

In Fig. 1 presents the structural diagram of the agent simulation model Any Logic information technology for the modernization of the outdated man-made system.

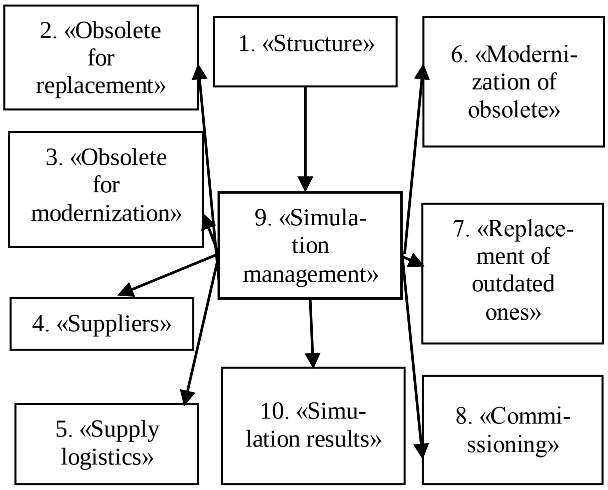

Fig. 1. Structural diagram of the agent simulation model of the modernization of an outdated man-made system

3. Results of measures and actions related to the management of the aging of high-tech production

As an illustrated example to demonstrate the effectiveness of the proposed approach and applied information technology, we consider the issue of aging management of high-tech aircraft production (HTAP). The aging management strategy is based on the modernization of HTAP, which includes restructuring, replacing outdated technical equipment, and transitioning to a new innovative product, etc. (see point 2.2). We will consider the limited capabilities of high-tech aviation production. As the most important indicator of modernization for extending the term of high-tech production, we will use the costs of preventive measures against the aging of HTAP. As risks, we will use the risk of the project on aging management of HTAP. The main components of HTAP that are expected to be used in modernization include:

1. Technological equipment.
2. Development (or supply) of engines.
3. Development (or supply) of avionics.
4. Working personnel.
5. Production management system.

We represent the choice of restructuring method (modernization or replacement component) using the boolean variable x_i:

$$x_1 = \begin{cases} 1, \text{ if modernization is carried out} \\ \quad \text{outdated technological equipment;} \\ 0, \text{ if a replacement is made} \\ \quad \text{outdated technological equipment.} \end{cases}$$

$$x_2 = \begin{cases} 1, \text{ if we modernize} \\ \quad \text{existing engines are obsolete;} \\ 0, \text{ if we use new engines} \\ \quad \text{(development or purchase),} \end{cases}$$

$$x_3 = \begin{cases} 1, \text{ if we modernize} \\ \quad \text{outdated avionics;} \\ 0, \text{ if we use new avionics} \\ \quad \text{(development or purchase),} \end{cases}$$

$$x_4 = \begin{cases} 1, \text{ if we carry out} \\ \quad \text{personnel retraining;} \\ 0, \text{ if we form new staff,} \end{cases}$$

$$x_5 = \begin{cases} 1, \text{ if we modernize} \\ \quad \text{HTAP management system} \\ \quad \text{(introduction of new management methods);} \\ 0, \text{ if we use new} \\ \quad \text{digital management system of HTAP} \\ \quad \text{(digital transformation of production} \\ \quad \text{based on Industry 4.0, virtual management).} \end{cases}$$

We will form possible options related to the aging management of HTAP using the modernization strategy. With the help of a binary counter, we form a set of options (see point 2.3). Number of components that will be used for modernizations ($n = 5$). Therefore, the number of variants $N=2^n=32$. In the Table 1 presents possible modernizations options for HTAP. We use:

1. Costs for modernization of HTAP (W).
2. Extension of the service life of HTAP (T).
3. Risks of the project regarding aging management of HTAP (R).

For ease of evaluation of indicators W, T, R, we will use qualitative assessments of experts (specialists) in the field of HTAP in the form of linguistic variables (see item 2.4):

$$W = \begin{cases} A - \text{ minimum expenses;} \\ B - \text{ satisfactory expenses;} \\ C - \text{ big expenses,} \end{cases}$$

$$T = \begin{cases} A - \text{is a substantial continuation} \\ \quad \text{of production term of HTAP;} \\ B - \text{is a satisfactory continuation} \\ \quad \text{of production term of HTAP;} \\ C - \text{is an insignificant extension} \\ \quad \text{of production term of HTAP,} \end{cases}$$

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

R= { A – minimal risks HTAP modernization project;
B – satisfactory risks HTAP modernization project;
C – maximum risks HTAP modernization project.

In the Table 2 presents the values of experts' estimates for each (possible) variant of modernizations of HTAP.

Table 2

Possible options for modernization of HTAP

No.	x_1 technical equipment	x_2 engine	x_3 avionics	x_4 personnel	x_5 management system	W, Costs	T, Term of existence	R, Project risk
1.	0	0	0	0	0	A	C	A
2.	0	0	0	0	1	B	C	B
3.	0	0	0	1	0	B	C	B
4.	0	0	0	1	1	B	B	B
5.	0	0	1	0	0	A	C	A
6.	0	0	1	0	1	B	C	A
7.	0	0	1	1	0	B	C	B
8.	0	0	1	1	1	B	B	B
9.	0	1	0	0	0	B	B	B
10.	0	1	0	0	1	B	B	B
11.	0	1	0	1	0	B	B	B
12.	0	1	0	1	1	B	A	B
13.	0	1	1	0	0	B	B	B
14.	0	1	1	0	1	B	A	B
15.	0	1	1	1	0	B	A	B
16.	0	1	1	1	1	B	A	B
17.	0	0	0	0	0	C	B	C
18.	0	0	0	0	1	C	B	C
19.	1	0	0	1	0	C	B	C
20.	1	0	0	1	1	C	B	C
21.	1	0	1	0	0	C	B	C
22.	1	0	1	0	1	C	B	C
23.	1	0	1	1	0	C	B	C
24.	1	0	1	1	1	C	A	C
25.	1	1	0	0	0	C	A	C
26.	1	1	0	0	1	C	B	C
27.	1	1	0	1	0	C	A	C
28.	1	1	0	1	1	C	A	C
29.	1	1	1	0	0	C	B	C
30.	1	1	1	0	1	C	A	C
31.	1	1	1	1	0	C	A	C
32.	1	1	1	1	1	C	A	C

We evaluate the importance of modernizations indicators with their arrangement. Let the most important indicator be costs (W) under the conditions of limited opportunities for the enterprise to implement the modernizations strategy. Then, the sequence of indicators is as follows: W, T, R.

We will perform a lexicographic arrangement of the options in the Table 1 (see item 2.4). We obtain a set of ordered options in the following form:

1. A C A
5. A C A
12. B A B
14. B A B
15. B A B
16. B A B
4. B B B
8. B B B
9. B B B
10. B B B
11. B B B
13. B B B
6. B C A
2. B C B
3. B C B
7. B C B
24. C A C
25. C A C
27. C A C
28. C A C
30. C A C
31. C A C
32. C A C
17. C B C
18. C B C
19. C B C
20 C B C
21. C B C
22. C B C
23. C B C
26. C B C
29. C B C.

Considering the capabilities of an aviation enterprise, we introduce restrictions on W, T, R indicators in the following form:

$$W'=B, T'=A, R'=B.$$

Restrictions in the form BAB is lexicographically being arranged in a set of ordered options. We will get:

1. A C A
5. A C A
BAB
12. B A B

14. B A B
15. B A B
16. B A B
4. B B B
8. B B B
9. B B B
10. B B B
11. B B B
13. B B B
6. B C A
2. B C B
3. B C B
7. B C B
24. C A C
25. C A C
27. C A C
28. C A C
30. C A C
31. C A C
32. C A C
17. C B C
18. C B C
19. C B C
20 C B C
21. C B C
22. C B C
23. C B C
26. C B C
29. C B C.

Thus, options 12, 14, 15, 16 are better for performing a modernizations strategy to prolong the existence of competitive production of aviation equipment under the limited capabilities of the enterprise. The selection of a possible one depends on the decisions of the company's managers and experts.

4. Discussion

A systematic presentation of the logistical actions related to the implementation of preventive measures to extend the life of a man-made system is provided. The set of scenarios for managing the aging of man-made systems is analyzed. Special attention should be paid to the management of the aging of critical man-made objects and processes that pose great risks to the environment and people. The study and selection of essential factors of the influence of the external environment on the state and aging of the man-made system is carried out with the help of virtual experiments and expert assessments. Qualitative assessments of experts and linguistic variables were used to identify the most outdated (critical) components of the man-made system. The costs associated with extending the life of a man-made system are modeled. An agent simulation model is being developed to study the sequence of logistic actions that are related to the management of the aging of the man-made system.

The information technology of interactive agent simulation modeling is used in this study to model measures for aging management. Here, a set of agents is described, and a structural scheme of the agent model is presented.

An illustrated example of the use of the modernizations strategy for outdated high-tech production of aviation equipment is provided.

The use of a complex of logically connected models allows for the planning of works and the formation of projects related to the management of the aging of man-made systems.

The effectiveness of the proposed complex of optimization models and simulation modeling is related to assessing the main logistic indicators for aging management. The article shows that it is possible to use both quantitative evaluations (for example, point evaluations in the plans of a virtual experiment) and qualitative evaluations (values of linguistic variables) of experts – specialists in the field of operation and repair of man-made systems. This allows us to draw conclusions about the effectiveness of the proposed approach and the possibility of its application for assessing the aging of man-made systems, both quantitative and qualitative, depending on the possibility of their use in managing management of man-made systems.

The formal presentation of the methodology for the study of logistical actions for managing the aging of man-made systems consists of the following stages:

1. Choosing a strategy for managing the aging of the technological system.
2. Identification of influencing factors (external and internal) on the aging process of man-made system.
3. Formation of a set of outdated system components, consisting of modernizations (resource extension) or replacement.
4. Minimization of costs for preventive actions and measures to manage the aging of the man-made system.
5. Modeling of the logistics of implementing preventive measures and actions related to the management of the aging of the man-made system.

Implementation of the set of developed models was performed on the agent platform of Any Logic information technology. The results of this research will allow specialists involved in the modernizations of the man-made system to plan and perform preventive measures and actions related to aging management. This will ensure an increase in the life of complex man-made systems and a reduction in the risks of environmental impacts (this is especially relevant for critical man-made systems).

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

Future research will focus on the use of applied information technology in the planning of actions on projects for the management of the aging of high-tech production within the framework of the state program for the recovery of enterprises associated with the creation of new aviation equipment in the post-war period of the country.

5. Conclusions

A study of modeling and planning logistical actions aimed at extending the life of a man-made system was conducted.

An analysis of the problems associated with the aging of man-made systems and their impact on the environment was conducted. A set of possible scenarios for managing the aging of man-made systems has been formed. A systematic presentation of the logistical chain of preventive measures and actions related to the aging of the man-made systems was created. A model was created to identify the significant factors influencing the aging of the man-made systems. With the help of qualitative assessments by experts, a search was made for the most outdated system components. Optimization of costs related to the implementation of measures and actions to extend the service life of the technogenic system has been carried out. An agent simulation model of information technology was created to study the sequence of logistic actions related to the planning and formation of man-made system aging management projects. An illustrated example of modernization of high-tech production of aviation equipment to increase the life of competitive production is given.

The scientific novelty of the conducted research is related to the modeling and formation of effective measures to manage the aging of the man-made systems, by using the developed complex of models and information technology to simulate simulation of logistical actions to manage aging.

An aging model was selected, presented in the form of an optimization model, in which the risks of aging, the cost of measures related to aging, and lifespan extension were investigated. This model ensures that rational measures are selected when planning actions to manage aging.

The results of the research make it possible to develop recommendations regarding the effectiveness of planned actions in the project of managing the aging of the man-made systems.

The proposed approach makes it possible to analyze the aging process of man-made systems and plan actions related to aging management in order to prolong its existence.

Contribution of authors: systematic presentation of logistical actions related to aging of the system and the formation of possible aging management strategies – **Oleg Fedorovich**; analysis of factors affecting the aging of the man-made system and identification of critical components – **Liudmyla Lutai**; optimization of costs related to aging management – **Oleg Uruskiy**; creation of a logistics model for the supply of components to replace outdated ones – **Sergii Gubka**; agent modeling of logistics actions related to aging of the system – **Yuliia Leshchenko.**

Conflict of Interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

This research was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence methods while creating the presented work.

All authors have read and approved the published version of this manuscript.

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Received 17.07.2024, Accepted 20.08.2024

МОДЕЛІ ТА ІНФОРМАЦІЙНА ТЕХНОЛОГІЯ УПРАВЛІННЯ СТАРІННЯМ ТЕХНОГЕННИХ СИСТЕМ В УМОВАХ СУЧАСНИХ РИЗИКІВ

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Формується та вирішується актуальна задача дослідження логістичних заходів та дій, які спрямовані на збільшення терміну існування техногенної системи. Дослідження, яке проводиться, пов'язане з управлінням складними дорогими техногенними системами (продовження їх ресурсу) з довгим терміном існування (високотехнологічне виробництво, критична інфраструктура, атомна енергетика, тощо). В запропонованій публікації досліджується послідовність логістичних дій для планування проектів управління старінням техногенних систем. Метою дослідження є створення комплексу математичних та агентної моделей, за допомогою яких можна аналізувати проблему вікової деградації та планувати проектні дії щодо управління старінням техногенних систем. Аналізуються проблеми, які виникли з-за старіння техногенної системи, такі як: застаріле технологічне обладнання, впливи ризиків зміни клімату, регулярне порушення енергопостачання, дії терористичних та військових загроз, тощо. Велику увагу приділено критичним техногенним системам з високими ризиками впливу на довкілля та людей, що пов'язане з їх старінням. Проводиться системний аналіз послідовності логістичних дій щодо управління старінням техногенної системи. Формується множина можливих стратегій щодо управління старінням, таких як: модернізація та заміна застарілого обладнання; зниження ризиків впливу на довкілля критичних техногенних систем, що потребує продовження їх ресурсу, тощо. Враховуються обмежені можливості підприємств до витрат на превентивні заходи для продовження терміну експлуатації техногенної системи. Проводиться аналіз факторів впливу (зовнішніх та внутрішніх) на процес старіння техногенної системи. Відокремлюються суттєві фактори впливу за допомогою віртуальних експериментів та оцінок експертів. Для виявлення застарілих компонент системи запропоновано метод, який заснований на оцінюванні їх стану за допомогою експертів та лексикографічного впорядковування множини варіантів компонент. Створюється модель оптимізації витрат щодо проведення заходів та дій для управління старінням техногенної системи. Формується агентна модель на платформі Any Logic для аналізу послідовності логістичних дій щодо управління старінням техногенної системи. Наводиться приклад продовження

терміну існування високотехнологічного виробництва авіаційної техніки. Наукова новизна дослідження пов'язана з вирішенням актуальної задачі формування стратегій, моделей та методу планування проектів щодо управління старінням техногенних систем, що сприяє подовженню терміну їх існування та зниженню ризиків впливу на довкілля та людей. Результати дослідження доцільно використовувати керівництву підприємств для планування проектів щодо управління старінням техногенних систем.

Ключові слова: управління старінням техногенної системи; критичні інфраструктури підприємств; ризики техногенної системи; зношені компоненти системи; фактори впливу на старіння; оптимізація витрат; моделювання логістичних дій; імітаційне моделювання; агентне моделювання; цілочисельна оптимізація.

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