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DETERMINING THE PERFORMANCE INDICATORS OF EMPLOYING COMBINED METHODS FOR REMOVING SPACE OBJECTS FROM NEAR-EARTH ORBITS

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A methodology for assessing the relative effectiveness of alternative options for building space object diversion systems has been improved. An algorithm for assessing the effectiveness of the system of removal of space objects from near-Earth orbit based on the method of integral assessment is given. It makes it possible to simplify the process of optimal choice of the method to divert space objects and determine efficiency in the early phases of the life cycle of rocket and space technology objects. The use of the appropriate toolset makes it possible to build a system for assessing the effectiveness of projects for the removal of space objects from low Earth orbits using various diversion methods (active, passive, combined). The analysis of defining world indicators of evaluation of objects of rocket and space technology based on regulations by international space agencies has been carried out. An indicator of the total integrated relative efficiency of projects of space object diversion systems from low Earth orbits has been proposed, which makes it possible to build the removal of passive, active, and combined methods for leveling the risks of space activities. It is argued that the selected combined system using an autophagic launch vehicle could reduce environmental losses and, as a result, reduce compensation payments to owners of space objects. The possibilities of building combined systems with reusable engines have been considered in order to reduce such indicators as the period of diversion and reduction of operating costs due to fuel economy

Keywords: rocket and space technology, space object, space debris, combined diversion system, low Earth orbits

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1. Introduction

In the era of New Space, Humanity faces a global problem regarding the rational use of outer orbital space. Sustainable space development will only be possible when space users implement technologies and practices suitable to avoid accumulating objects in orbit. Man-made debris in orbital space has reached catastrophic proportions. As of 2020, about 65 % of space objects (SOs) belong to the class of uncontrolled space objects [1].

As a result, the 21st century saw the Clean Space concept at the global level [2]. This initiative has three directions: EcoDesign – designing projects to address the impact of space debris on the environment; CleanSat – designing measures to reduce the formation of space debris; eDeorbit – removal of large objects of space debris from orbit [2].

Within the framework of that concept, innovative projects are increasingly being devised to build a system of a combined way to divert space objects from near-Earth orbits. This actualizes the scientific search in the field of project management of space projects: determining the efficiency, risks, barriers, etc.

The insufficient level of scientific principles for the construction and selection of effective systems for the removal of artificial space objects remains an unresolved task of sustainable development of space activities in many countries. Fragmentation in the choice of design solutions for the removal of space objects from near-Earth orbits leads to the clutter of the space orbit and the emergence of various risks of activity, primarily environmental risks.

Thus, the further development of the basics of designing effective systems for the removal of space objects from low

Earth orbits is an important scientific and practical task. For the development of the space industry in the world, this is an urgent scientific and practical issue that requires further refinement and solution.

Therefore, there is a need for in-depth analysis and methodological clarification of a set of issues related to determining the specificity of the introduction of design solutions for the removal of space objects from near-Earth orbits. It is becoming increasingly difficult for companies in the space industry to define the set of performance indicators of project solution tools necessary to create long-term relationships in the market and achieve customer satisfaction.

2. Literature review and problem statement

When determining the indicators of choosing a design solution for the system of removal of space objects from low Earth orbits, it is necessary to take into consideration the limitations of technical and economic feasibility.

Work [3] substantiates the need to compare technical and economic efficiency in two phases of the life cycle of space technology: R&D and production, taking into consideration uncertainty factors. However, the scientific apparatus of the study is not sufficiently substantiated – a reasonable choice of indicators affecting the evaluation of project effectiveness has not been carried out.

The expediency of applying parameters of type efficiency-cost is emphasized in work [4]. To this end, it is proposed to use a comparative assessment of the effectiveness of variants of aerospace systems to carry out taking into consideration the very specific volume of estimated tasks. This statement contradicts the postulates of economic theory – in determining comparative efficiency as an effect value, resource savings are taken.

In work [5], it is proposed to assess the overall effectiveness of the system of de-orbiting a small spacecraft. At the same time, the following design features are taken into consideration: the dependence of the de-orbiting technique on the intended purpose of the device, the height, and inclination of the orbit of its functioning, as well as additional requirements such as mass, cost. Obviously, the performance assessment carried out is not a general efficiency – only the technical effectiveness of the proposed solutions is determined. This significantly narrows the possibility of taking into consideration the allocation (distributive) efficiency.

Work [6] emphasizes that when choosing projects in the aerospace industry, economic indicators are taken into consideration: net profit from investments, the profitability of capital investments, the profitability of assets. In addition, the authors define such non-monetary factors as social significance, environmental safety, the market potential of products, etc. [6].

Thus, the authors of [7] emphasize the importance of determining the technical capabilities and economic feasibility of implementing the necessary measures. Work [8] thoroughly considers the need to implement project capacity at the initial stage of the implementation of the project of removal of space objects from near-Earth orbits.

Work [9] identifies the need to take into consideration external factors in determining the effectiveness of space debris disposal projects. However, when defining the criteria for restriction at the stage of the utilization of rocket and space technology, it is not enough to take into consideration only the service life.

The possibility of analyzing the initial data regarding the provision of basic resources, substantiation of the prospects for their use or receipt is defined in [10]. Study [11] analyzed the environmental impact in the implementation of rocket and space technology projects.

Paper [12] considers methods of compensation for the risks of the life cycle of sophisticated knowledge-intensive projects in the field of rocket and space technology as a necessary condition for determining the effectiveness of design decisions.

Methods for removing space objects from near-Earth orbits are divided into active and passive [13]. More scientific research is emerging that focuses on the development of combined methods for the removal of space objects from near-Earth orbits as a combination of active and passive techniques [14]. Given the prospects of the combined method as an alternative competitive system to other systems for cleaning the Earth's orbit, it is necessary to scientifically justify the design of the combined removal of space objects into the dense layers of the Earth's atmosphere. This requires systematizing the results obtained and determining the boundaries of the area of its most effective use.

However, the studies considered to determine the parameters of the choice of systems for removing artificial space objects are fragmentary. Namely, there is no single comprehensive approach to solving the task of determining the indicators for choosing a design solution for de-orbiting artificial space objects after the expiration of service life.

All this gives grounds to assert that it is expedient to conduct a study on the substantiation of parameters for the choice of design solutions for de-orbiting artificial space objects using modern scientific tools.

3. The aim and objectives of the study

The purpose of this work is to scientifically substantiate the choice of designing effective solutions for space object diversion systems from low Earth orbits. This will make it possible to improve the methodical approach to determining the indicators for assessing the relative effectiveness of alternative options for building systems for the removal of space objects from near-Earth orbits.

To accomplish the aim, the following tasks have been set:

– to propose indicators for assessing the systems for removing space objects from near-Earth orbits;

– to propose an indicator of the integrated relative efficiency of space object diversion systems from near-Earth orbits using various de-orbiting methods (active, passive, combined).

4. The study materials and methods

The object of research is the decision-making process regarding the effectiveness of the use of combined methods for de-orbiting space objects.

The main hypothesis of the study assumes that the selected combined system for de-orbiting space objects is effective. It will reduce environmental losses and reduce compensation payments to owners of space objects.

The simplification of the proposed research is based on the principle of Ceteris paribus. Namely, the implementation of projects takes place under the same conditions. Conditions are determined by the following groups of factors: technical, economic, political, social, etc.

The scientific assumption is stochastic in nature. The existence of relatively different possible options for the functioning of space object diversion systems. Limitations in stochastic economic models are set in different ways. The inferred optimal variants of space object de-orbiting systems have an appropriate level of probability of their implementation.

The method of relative integrated evaluation combines the properties of the convolution method and the method of selecting the main indicator. A given method can be used when choosing a system for removing artificial space objects from orbit to assess efficiency in the early stages of design. Especially at the following phases of the life cycle of rocket and space technology: "Mission analysis/needs definition"; "Feasibility"; "Preliminary design"; "Detailed design". The main advantage of the method is the ability to compare one alternative with another, which is carried out on the basis of calculating the coefficient of relative integrated evaluation.

To implement the method of integrated relative assessment of the effectiveness of the system for removing SOs from near-Earth orbits, it is necessary to determine the significance of indicators, namely, the value of coefficients relative to priority. It is important to take into consideration the opinion of internal experts of the company [15]. The ultimate goal of the assessment is to minimize time and reduce the cost of removing SOs from low Earth orbits. This must be taken into consideration at the stage of formation of a combination of priority coefficients.

The calculation of the coefficients of integrated relative assessment (K_i) of the efficiency of the system for removing space objects from near-Earth orbits is carried out taking into consideration the postulate of changes in indicators (N_i):

$$\left\{ \begin{aligned} K_i &= \frac{N_{ib}}{N_i}, \text{where } N_i \to \min, \\ K_i &= \frac{N_i}{N_{ib}}, \text{where } N_i \to \max, \end{aligned} \right\}, \quad (1)$$

where K_i is the coefficient of integrated relative evaluation;

N_i – an indicator of the effectiveness of the corresponding alternative version of the space object de-orbiting system;

N_{ib} – an indicator of the effectiveness of the basic version of the space object de-orbiting system;

i – an alternative version of the system for removing space objects.

The total coefficient of integrated relative efficiency is determined by the sum of indicators, taking into consideration the priority coefficients:

$$K = \frac{\sum_{i=1}^{n} K_i \times \omega_i}{\sum_{i=1}^{n} \omega_i}, \quad (2)$$

where K is the coefficient of integrated relative efficiency;

ω_i – priority factors;

n – the number of variants of the system for removing space objects.

When forming a group of alternative options for building a system for the removal of SOs from near-Earth orbit, it is necessary to take into consideration the relevant factors. In particular, the following factors: alternatives have the same goals; indicators of economic efficiency are based on the single price scale independent of the year of creation and deployment of a system; priorities of all indicators are invariant for all alternatives [16].

The choice of the optimal option for constructing a model of the system for removing space objects from near-Earth orbit is carried out using the appropriate algorithm in order to conduct a project performance analysis (Fig. 1).

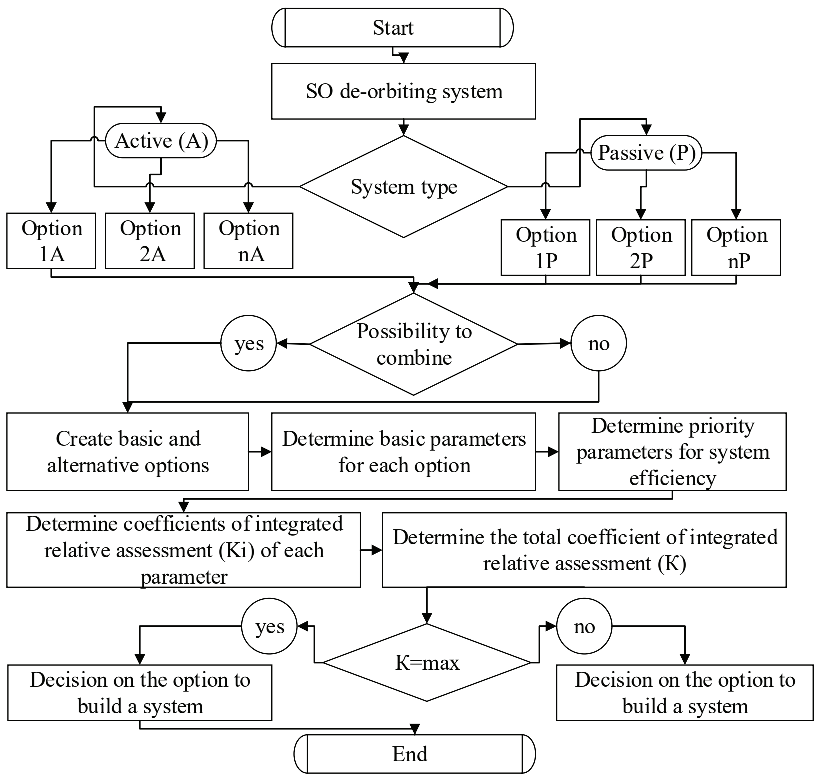

Fig. 1. Algorithm for assessing the effectiveness of the system for removing a space object from near-Earth orbit

It should be noted that the choice of the optimal option for constructing a system for removing SO from near-Earth orbit is carried out on the basis of the maximum cumulative coefficient of integrated relative efficiency assessment (K=max).

5. The results of research to substantiate the choice of design solutions for systems for removing space objects from near-Earth orbit

5. 1. Selection of parameters for evaluating the systems for removing space objects from near-Earth orbit

The information base for calculating the performance indicators of the choice of options for the removal of space objects from near-Earth orbits is the data acquired during the experimental work that we performed.

During the study, an analysis of the proposed ways to combat the problem of the clutter of space debris was carried out [17]. According to the results of the study, the following design solutions were chosen:

A1. De-orbiting system based on the use of liquid rocket engine (LRE T).

A2. De-orbiting system based on the use of solid fuel thrust rocket engine (SRE T).

A3. De-orbiting system based on the use of an electric rocket installation (ERI).

P1. De-orbiting system based on the use of a rope system.

P2. De-orbiting system based on the use of an aerodynamic system.

P3. De-orbiting system based on the use of solar sails.

K1. Combined de-orbiting system based on the use of autophagic systems for removing space objects.

Seven variants of ways to remove space objects from near-Earth orbit were chosen: three active systems (A1–A3), three passive systems (P1–P3), one combined system (K1). K1 "Combined removing system based on the use of autophagic systems for de-orbiting space objects" is made on the basis of a jet engine installation (JEI), an aerodynamic sailing device, and ultralight autophagic rocket carriers. The basic option (B) as a reference option, which corresponds to the characteristics given in [18].

It is necessary to determine the effectiveness of space debris disposal complying with existing standards/guidelines from international organizations in the field of space sustainable activities [18]:

– the maximum service life of a piece of equipment in orbit up to 2000 km should not exceed 25 years, after which it is subject to disposal;

– compliance with the technological capabilities of the platform – to what extent onboard systems make it possible to perform autonomous maneuvers to be carried out from orbit/transition to another orbit without interference from the Earth;

– criteria for determining the end of the service life of rocket and space equipment;

– achieving a 90 percent probability of successful de-orbiting of spent satellites and analysis of the operation of large satellite groups, etc.

When analyzing and selecting the implementation of systems for removing space objects from near-Earth orbits, it is advisable to take into consideration the following indicators (N1–N5). It should be noted the following in relation to indicators. N1 is a key indicator in determining the effectiveness of the use of methods for removing space objects from orbits [19–22]. N2, N4, N5 are proposed by the authors of [23] for the energy management sector. The authors of [24] adapted indicators specifically for space debris disposal projects. N3 is our proposal based on empirical research.

N1. The cost of the system for removing space objects from near-Earth orbit (B). The cost of creating a de-orbiting system can be determined by summing up the cost of manufacturing (the cost of creating, testing, and assembling), operation, and maintenance (O&M). The calculation is carried out on the basis of postulates set out in [20].

N2. The cost of the "lifetime" of building systems for removing space objects from near-Earth orbits is determined as follows [24]:

$$LCC = I - S + M + R + E, \tag{3}$$

where LCC is the cost of "lifetime" (project); I – capital expenditures (investment); S – liquidation value; M – operating costs; R – replacement costs; E – energy costs.

N3. The ratio of the cost of de-orbiting systems to the cost of the spacecraft. According to the working hypothesis, if the cost (B) of systems for removing space objects from near-Earth orbit will be equal to the elimination cost (LV) of the spacecraft, it is economically feasible to use the chosen version of the de-orbiting system.

N4. The given payback period of the de-orbiting system in changes in cost in operation and maintenance (O&M) is determined as follows [24]:

$$APP = \frac{I}{ES_r + Mm_r}, \tag{4}$$

where APP is the payback period given taking into consideration O&M; ES_r – annual energy savings of the project for the period of analysis; Mm_r – different operating and maintenance costs for the analysis period; r is the period of analysis.

N5. The cost of deferred decisions. Potential savings are equal to the same potential losses if the company does not apply systems for removing space object from near-Earth orbits [24]:

$$CoD = -\left(E_r + O\&M_r\right) + I_r, \tag{5}$$

where CoD is the cost of deferred decisions; E_r – saving energy costs over a period; I_r is an initial investment.

Table 1 gives the main design indicators of the choice of options for removing space objects from near-Earth orbits based on the selected options and indicators. Project indicators are designed for a test SO. This is the stage of the carrier rocket "Cyclone-4" (made by DP "VO PMZ named after O. M. Makarov").

When evaluating the system of choice of variants of systems for removing space objects from near-Earth orbit, the factor of subjectivity is minimized. Therefore, it is advisable to use it in the analysis of complex systems of heterogeneous methods for de-orbiting (Table 1), which are design solutions.

Table 1

Project indicators for choosing options for removing space objects from near-Earth orbit

No. of entry	Indicator	Designation	Variants of systems for removing space objects from near-Earth orbit							
			B	A1	A2	A3	P1	P2	P3	K1
1	The cost of the system, USD thousand	N1	420	630	740	810	119	156	190	510
2	Life time costs, USD thousand	N2	42	94.5	118.4	145.8	8.925	14.04	22.8	30.6
3	Coefficient of the ratio of the cost of de-orbiting systems to the cost of the spacecraft, share	N3	0.1	0.14	0.18	0.22	0.07	0.08	0.08	0.9
4	The payback period of the de-orbiting system to changes in the cost of operation and maintenance (O&M), year	N4	7	8	9	10	3	4	4	5
5	Cost of deferred decisions, USD thousand	N5	134.4	220.5	266.4	340.2	14.28	21.84	30.4	163.2

The next stage of the algorithm for assessing the effectiveness of the system for removing space objects from near-Earth orbit (Fig. 1) is to determine the coefficients of priorities (ω_i). When justifying the choice of options for the de-orbiting system, five design parameters were selected (Table 1).

An expert assessment was carried out on the basis of a competence approach, taking into consideration the ranks from [25, 26]. Determining the number of experts in the group was calculated on the basis of selective observation [27]. As experts, 10 specialists in the chosen area were selected. The experts are employees from Yuzhnoye KB, the Institute of Technical Mechanics of the National Academy of Sciences of Ukraine, and the State Space Agency of Ukraine. Selected experts have a high level of competence based on self-esteem. The consistency of opinions by experts was calculated according to the coefficient of Kendell's rank correlation [28]. The coefficient is 0.681; this indicates a high consistency of experts.

The assessment of priorities by experts is given in Table 2.

Table 2

The value of priority coefficients of performance indicators for the systems for removing space objects from near-Earth orbit

Expert	Indicator					
	N1	N2	N3	N4	N5	Total
1	0.4	0.1	0.2	0.1	0.2	1
2	0.2	0.5	0.1	0.1	0.1	1
3	0.3	0.3	0.1	0.1	0.2	1
4	0.1	0.1	0.2	0.3	0.3	1
5	0.2	0.1	0.2	0.4	0.1	1
6	0.2	0.1	0.1	0.1	0.5	1
7	0.2	0.2	0.2	0.2	0.2	1
8	0.5	0.1	0.1	0.2	0.1	1
9	0.3	0.1	0.1	0.4	0.1	1
10	0.1	0.3	0.2	0.2	0.2	1
The sum of the ranks obtained for each indicator	1.71	1.11	0.71	2.1	2	5.53
Deviation from the average sum of ranks	1.11	0.71	2.1	2	5.53	1.11
Quadratic deviation of the sum of ranks	2.92	1.23	0.50	4.41	4.00	8.66
Average grade for gradation by indicator	0.25	0.19	0.15	0.21	0.2	1

According to expert evaluation, the priority coefficients take the following values: $\omega_1=0.25$; $\omega_2=0.19$; $\omega_3=0.15$; $\omega_4=0.21$; $\omega_5=0.2$.

5. 2. Determining the indicator of the total coefficient of the integrated relative efficiency of space object de-orbiting systems

Limiting the long existence of space equipment in near-Earth orbits requires at the initial stage of design to include in the on-board systems of the spacecraft means for its de-orbiting. In this regard, the task arises to assess the effectiveness of the system for removing space objects from near-Earth orbit. The results of calculating performance indicators of the systems for removing space objects from near-Earth orbit are given in Table 3.

The total coefficient of the integrated relative efficiency of de-orbiting systems is calculated from (2). The calculation results are given in Fig. 2.

Table 3

The value of performance indicators of the systems for removing space objects from near-Earth orbit

Option	N'1	N'2	N'3	N'4	N'5
B	1	1	1	1	1
A1	1.50	2.25	1.40	1.14	1.64
A2	2.82	2.82	1.80	1.29	1.98
A3	1.93	3.47	2.20	1.43	2.53
P1	0.28	0.21	0.70	0.43	0.11
P2	0.37	0.33	0.80	0.57	0.16
P3	0.45	0.54	0.80	0.57	0.23
K1	1.21	0.73	9.00	0.71	1.21

The results of the calculations determine the option with the highest value of the total coefficient – a combined de-orbiting system based on the use of autophagic systems for removing space objects. Subject to the use of autophagic technology, it is expected that the cost of removing cleaning tools will be much lower than the cost of that by modern RN [18]. In this regard, Ukraine, as the owner of autophagic technology, will have prerequisites for the sale of services for cleaning near-Earth orbits and could dominate that market.

As regards the specified active de-orbiting systems, all three systems of active methods have a total coefficient of integrated relative efficiency exceeding 1 (K>1). This indicates the possibility of using these systems, and the most effective is the system equipped with ERI. The main advantages of ERI are two components: a high specific pulse and the use of environmentally friendly fuel. Disadvantages include the high cost of the system when managing the process of de-orbiting from the Earth and high energy consumption. They can be compensated when forming de-orbiting systems in a complex way based on an active system equipped with ERI.

All considered passive variants of systems for removing space objects from near-Earth orbits have a value of the total coefficient of integrated relative efficiency less than 1 (K<1). In order to increase the efficiency of systems, it is recommended to use them in combination with active systems.

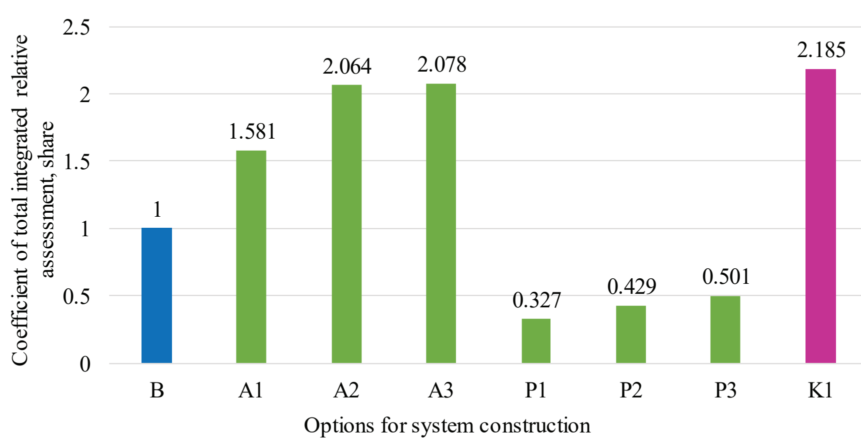

Fig. 2. Histogram assessing the effectiveness of the system for removing space objects from near-Earth orbit

6. Discussion of results of the substantiation of the choice of design solutions for de-orbiting space objects

In contrast to existing scientific and methodological approaches [3–13], we used a method of the total integrated relative efficiency of projects for removing space objects. Applying this method makes it possible to determine the plane of alternative projects and build a common vector of the optimal option for choosing a system for removing space objects from near-Earth orbit.

Evaluation of the effectiveness of a system for de-orbiting a space object is carried out using the proposed algorithm (Fig. 1). In this case, a method for evaluating integrated relative efficiency (1) to (2) has been chosen. The choice of options for de-orbiting space objects can be determined using project indicators (3) to (5), Table 1. They are selected on the basis of postulates of the concept of the life cycle of artificial SOs. The value of prioritization coefficients of performance indicators of SO de-orbiting systems is determined on the basis of expert evaluation (Table 2).

The indicator of the integrated relative efficiency of space object de-orbiting systems made it possible to choose a combined method (Table 3, Fig. 2). It leads to a decrease in the following indicators: the de-orbiting period and a decrease in operating costs due to fuel economy.

In order to eliminate possible shortcomings and violations of the balance of interests, competence, and degree of involvement of project agents, it is important to note some recommendations for implementation:

1. The built alternative option makes it possible to make a decision to reduce environmental damage. This is possible due to the introduction to clean near-Earth orbits from non-functioning space objects of autophagic launch vehicles, which self-destruct in the process of operation and do not cause additional pollution to the environment [29, 30].

2. Under modern conditions of development of the world economy, industrial enterprises of the aerospace industry implement an optimal strategy based on resource saving and consider efficiency as an important component of innovative development of industry.

3. The use of reusable engines and the choice of a circuit for turning on the jet engine installation (JEI) will increase the efficiency of the combined method for de-orbiting large-sized space objects. Unlike the existing active and passive techniques, using the combined de-orbiting will make it possible to ensure the removal of space debris objects from the earth's orbit within a specified period and with minimal fuel consumption [14, 30–32].

The results could be used in the implementation of design work at enterprises engaged in the creation of tools for cleaning near-Earth space.

Our study, however, does not solve all the topical issues related to managing projects involving the systems for removing space objects from near-Earth orbits. Promising for further scientific developments is the introduction of modern methods for determining the cost; improvement of the cost calculation system, taking into consideration the postulates of "responsibility centers", budgeting, combining, etc.

7. Conclusions

1. The indicators of evaluation of the systems for de-orbiting space objects have been determined: the cost of "living time", the ratio of the cost of de-orbiting systems to the cost of the spacecraft, the reduced payback period of the de-orbiting system in changes in cost (O&M), the cost of deferred decisions. The choice of alternative systems for the removal of space objects is proposed to be carried out on the basis of the method of integrated relative evaluation of efficiency. Owing to its application, it is possible to obtain a set of alternative variants of space technology projects in accordance with the principles of sustainable space development.

2. We have proposed an indicator – the total coefficient of the integrated relative efficiency of projects involving systems for removing space objects from low Earth orbits. It makes it possible to evaluate in the early phases of the life cycle of space equipment a combination of de-orbiting methods (active and passive) to offset risks, in particular, environmental ones.

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