Principles of forming procedures for justifying the economic efficiency of space debris removal processes

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Abstract. Near-Earth space pollution can be classified as an international problem. The research considers variation technical and technological innovative projects that can decide this problem, as well as methods for calculating the costs of their realization. Cost and labor intensity modeling takes into account the concept of designing systems for the disposal of cataloged space debris. Unitized approaches to technical and economic assessment of the feasibility of space debris disposal concepts are considered and a mechanism for justifying economic efficiency is developed, which includes the following synergistic differentiated principles: the objectivity and subjectivity, the accuracy and reliability increasing, the marginal cost estimation, the probabilistic risk assessment accounting, the principle of logical-probabilistic modeling of development obsolescence in outer space, the principle of risk assessment and monitoring of space projects. The proposed mechanism for evaluating the economic efficiency based on additive factors can be used for economic justification of scientific, technical and experimental-design developments of space vehicles for technological designated purpose.

1. Introduction
Space around the Earth is a shared resource that has been virtually unregulated since the beginning of human space activities. Large objects such as high-stage rocket bodies, boosters, and non-functional satellites are potential sources of orbital debris that pose a serious threat to active satellites. In order to reduce the risk of an uncontrolled increase in the amount of debris, large objects must be removed from orbit. Orbital or space debris mean any artificial object in orbit around the Earth that is no longer useful. A lot of different technical concepts and technological processes for combating space debris have been currently proposed [1].

All cataloged objects are divided into the following groups or regions by orbit type: LEO – low-Earth orbits; MEO – medium Earth orbits, objects in orbits between LEO and GEO; GEO – geostationary orbits; GTO – GEO transfer orbits, objects in transition orbits to the GEO region; HEO – highly eccentric orbits [2].

This raises the international challenge of collecting and disposing of space debris. The problem of technological execution of utilization spacecraft can be solved by taking into account a reliable feasibility study of the effectiveness of the design concept development and its operation, which is currently represented by variable innovative solutions.

The purpose of this work is to solve organizational and economic problems of effective implementation of space debris control processes to ensure the safe operation of space systems in low
earth orbits in conditions of technogenic clogging. The object of the study is a set of processes for combating space debris in the region of low earth orbits. The subject of the study is the mechanism for justifying the economic efficiency of space debris removal processes.

2. Methodology
The proposed concept of the mechanism for justifying the economic efficiency of technical and technological hardware processes for combating space debris is based on the additive action of six basic principles (table 1).

Table 1. Mechanism for justifying the cost-effectiveness of space debris management processes.

| I. Objectivity and subjectivity principle |
|-----------------------------------------|
| I.1. Prospects of scientific and technical techniques and principles used to achieve this goal |
| I.2. Technical significance of the research and development |
| I.3. Average values of coefficients of scientific and technical significance of developments |
| I.4. Sophisticated system target model of the equipment object being evaluated ("tree of goals") |

| II. Accuracy and reliability increasing principle |
|-----------------------------------------------|
| II.1. Collecting and analyzing indicators for the implementation of similar R&D Analog methods |
| II.2. Analyzing the specialists’ collective opinion Expert methods |
| II.3. Pricing methods for pricing similar products Standard and estimate methods |
| II.4. Summing the resources required for the implementation of the project solution in current prices and tariffs |

| III. Marginal cost estimation principle |
|--------------------------------------|
| III.1. Technical specification, technical proposal |
| III.2. Conceptual design |
| III.3. Working design |
| III.4. Prototype production |
| III.5. Factory testing |
| III.6. State testing |
| III.7. Adjusting design documentation |

| IV. Probabilistic risk assessment accounting principle |
|-----------------------------------------------------|
| IV.1. Information collection |
| IV.2. Identifying the initiating events |
| IV.3. Scenario development |
| IV.4. Logic simulation |
| IV.5. Impact analysis |
| IV.6. Results assessment |

| V. Principle of logical and probabilistic modeling of development obsolescence in outer space |
|-------------------------------------------------------------------------------------------|
| V.1. Monte Carlo simulation |
| V.2. Stochastic model of on-orbit obsolescence |

Criteria:
1. Working with expensive assets over a long period of time to recover their cost;
2. Taking into account the marginal cost of spacecraft durability.

| VI. Principle of risk assessment and monitoring of space projects |
|------------------------------------------------------------------|
| VI.1. Risk identification and classification |
| VI.2. Risk analysis |
| VI.3. Risk reduction |

- risk assessment, including identification, analysis and prioritization of risks
- risk management, including risk management planning, risk prevention measures, follow-up actions and corrective actions

The objectivity and subjectivity principle involves the use of objective methods based on the factor of maximizing the utilization period of the utilizer structure in space; subjective methods that assess the
prospects of scientific and technical techniques and principles used to achieve them; significance of technical research and development; focus on the average specific normative values of the coefficients of the scientific and technical significance of the developments that characterize the object; using the deployed target system models taking into account design features of the project [3-5].

The accuracy and reliability increasing principle involves the differentiated application of various methodologies for estimating costs, which are calculated based on unrelated positions from which the process of implementing the technical features of an innovative project is considered [6]. The calculations uncertainty interval makes it possible to obtain a reliable estimate using the L. Hurwitz formula [7].

To collect information base on completed projects in the field of application under consideration and comparative analysis of technical and economic indicators for the implementation of such research and development works (R&D), it is proposed to apply the analog methods. The cost of R&D using analog methods can be estimated based on the cost of R&D that is similar in the direction of the field of activity, previously performed and similar developments in accordance with the existing technical specifications. Analog methods can be used to calculate the cost of standard work at various stages of the life cycle [2].

The analysis of the collective opinion of specialists is based on the expert assessments methods: the associations method, the preference vectors method, the focal objects method, the individual expert survey and the midpoint method.

The use of pricing methods in forming the costs for similar products is based on estimated and regulatory (cost/resource) methods. At the same time, R&D expenses are formed primarily by the following items: salary, material expenses, depreciation, and equipment purchase costs.

It is proposed to determine the resources required for the implementation of the project solution in current (projected) prices and tariffs using parametric methods that make it possible to calculate the estimated R&D cost with a high degree of probability. Parametric methods are best used at the initial stages of the feasibility study, as well as to determine the base contract price.

The marginal cost estimation principle involves calculating the technical price, which shows the break-even point during the project implementation. Determination of the technical cost for R&D implementation can be described in accordance with the developed algorithm.

The algorithm for forming the price of a spacecraft for debris disposal includes the basic principles and conditions that determine the sequence of methods that together make it possible to present variable calculations for determining the contract price to the customer. The calculation methods used are based on existing legal documents. The distribution of costs is carried out by the main stages of the technical project development: technical specification and proposal; preliminary design; working design; prototype production; factory testing; state tests; adjustment of design documentation.

The probabilistic risk assessment accounting principle involves the formation of an integrated structure of probabilistic scenario risk assessment based on space-time situational modeling and involves six functional stages:

1) Information collection – information is collected and systematized to provide a complete understanding of the structure of the system being implemented, its components, as well as expected functions and situational behavior when implementing a technical task. Up-to-date information includes a variety of qualitative and quantitative data in various formats, including detailed R&D descriptions, layouts, functional descriptions, and available failure and performance data.

2) Initiating events identification – it is used to identify potential hazards and threats to the project that may lead to an abnormal event or initiate a sequence of events with a negative outcome. This includes reviewing and identifying the causes of these events. This step is based on experience, data, and consideration of all possible hypothetical situations.

3) Scenario development – for each initiating event, a cause-and-effect chain is created that leads from the initial event to possible outcomes (consequences). The scenario elements included in this causal sequence are potential success and failure events, hardware, software, human intervention, barriers, and measures to dampen the effects of risk.
4) Logical modeling – a set of logical models is built for the scenarios. Modeling methods such as failure trees and event trees are used to document known relationships between scenario elements. These models are quantified by probabilities based on information collected from component and event databases, as well as operational experience.

5) Impact analysis – at this stage, hypothetical consequences are modeled (for example, laser failure in outer space) for each scenario, potential losses are quantified using a combination of deterministic physical models and probability loss functions, which are quantified by cost criteria. The uncertainty of expected consequences is analyzed.

6) Results assessment – the total risk is calculated by integrating all elements. Sensitivity and uncertainty analysis is performed to assess the impact of various modeling assumptions on risk. Depending on the purpose of the study, the results obtained are further studied.

The assessment results are compared with thresholds for acceptable risk values or acceptability for R&D implementation, and the most likely scenarios and contributing components are identified, ranked, and the main types of uncertainty are identified. After completing these six steps, there is feedback from the project's risk management activities that can change the system, data sources, or other aspects of the analysis. This feedback process continues until you have achieved the purpose of analysis.

The principle of logical-probabilistic modeling of development obsolescence in outer space involves taking into account the following factors of losses in space: reducing the service life of the satellite or losing the operational capabilities of the satellite.

1) Most space systems are not available in orbit for maintenance and upgrades after launch. This feature of space systems reinforces the importance of a carefully thought-out strategy for reducing wear and tear in spacecraft development.

2) Since production and launch costs account for a significant proportion of the total mission cost, current design practices tend to aim for the longest technically achievable design life. The rationale for this choice is to take into account, on the one hand, the factors of working with expensive assets over a long period of time to restore their value, and on the other hand, taking into account the marginal cost and durability of spacecraft.

The second approach provides a less expensive option for implementing the spacecraft according to cost criteria, and as a result, it assumes that the launch of the spacecraft with the longest service life can provide the maximum return on the operation of the spacecraft for the disposal of space debris according to technical and economic criteria. However, under such operating conditions, spacecraft are characterized by obsolescence, since functioning orbital systems cannot be upgraded during their long service life in orbit. It is more likely that original technologies and new market needs may appear before the spacecraft development is completed, or replacement analogues may make the spacecraft obsolete. The high degree of complexity of spacecraft makes it even more difficult to make changes to the original design during development. Thus, obsolescence in orbit can be defined as a decrease in the residual value (or attractiveness) of the spacecraft and services that are in orbit, as a result of exogenous events, such as the emergence of better technology, i.e. technological obsolescence. Thus, the spacecraft itself can be qualified as space debris, and its disposal should be carried out with minimal costs and risks. The recycling process for debris collectors should be part of the project feasibility study. It is proposed to use the following methods of situational modeling:

- Monte Carlo simulation is used for risk assessment and analysis under conditions of uncertainty. When creating such models, any factor that is characterized by uncertainty varies by a range of values, the probability distribution. Then multiple calculations are performed for the formulated hypothetical situations, and each time a different set of random values of the probability functions for the manifestation of technical and economic parameters is used;

- stochastic model of obsolescence in orbit – the model consists of two parts working in parallel to reflect the impact of the initial maturity level at the start of development on the probability of obsolescence after the spacecraft is in orbit. Both models operate in a discrete time status, the unit of
time considered is one month. The first is a model of obsolescence, and the second is a model of technological maturation.

The principle of risk assessment and monitoring of space projects involves comparing risks with each other at the next stages of the management process, it is possible to use appropriate methods to respond to the occurrence of risks. The purpose of project risk management is to identify and analyze them according to the criterion of maximum management efficiency. The risk management process is usually divided into three categories: identification and classification, analysis, and risk reduction.

Project risk management is one of the main problems solved during project implementation. Differentiated measures for effective risk management should be developed for each potential key participant. Risk management is a systematic, permanent process of identifying, analyzing, and responding to negative events throughout the project life. The two-stage process of project risk management should be noted: risk assessment, including identification, analysis and prioritization of risks, and risk management, including risk management planning.

Risk assessment is the process of assessing the probability of an event and its consequences. This step can help you choose less risky projects and eliminate the existing risk. At the first stage, using one of the risk identification tools, the main threats and opportunities that can affect the project processes and results are identified. After identifying the main risks, the second stage involves accurately assessing the frequency of adverse effects, and then ranking the various risks based on the results of the assessment [8].

The synergistic influence of all these principles and the considered methodology makes it possible to form a mechanism for justifying the economic efficiency of space debris control processes, taking into account the technical and technological features of the developed concepts for the design of orbiters at all stages of the life cycle.

3. Results and discussion

The comparative analysis of the design concepts of space debris abatement vehicles based on their basic technical and economic characteristics shows the following [9]:

- Laser-based method. Laser-based active debris removal, the concept of removal is a powerful laser, for debris sublimation, from earth or from space. Advantages: low cost and high degree of implementability. Disadvantages: range and angle of action are limited.
- Satellite-based method. Satellite-based concept, a way to actively remove debris – an application to a satellite (a manipulator arm) that grabs the debris and pushes it around. Advantages: low cost and high degree of implementability. Disadvantages: range and angle of action are limited.
- Tether-based method. The concept is attaching long wires to a piece of debris, and the Earth is a magnetic field acting on it to slowly return it to the atmosphere. Advantages: minimal energy and maintenance costs. Disadvantages: low speed and, consequently, performance.
- General method. The concept of the methods conjunction suggests that a variety of active methods of debris removal are integrated into a single system and operated synchronously. The technical and technological strategy focuses on prioritizing debris, sorting non-technical tasks, and using autonomous spacecraft. Advantages: low cost and high degree of implementability. Disadvantages: range and angle of action are limited.
- Ion beam control method. Ion beam control (IBC), concept – placing a tracking satellite and projecting ion beams onto the debris to perform a push and ejection from orbit. Advantages: High performance and implementability. Disadvantages: Significant operating costs.
- Sail method. The concept is to use a large surface fabric to capture the pressure of solar radiation and use it as a way of movement or control. The work begins with the analysis of the time of sail descent, using the principle of controlling the orientation of the network, the descent from orbit. The sails open, move, and inflate, using a magnet to attract debris in Earth's Geosynchronous Orbit. Advantages: Low operating costs in terms of fuel or energy. Disadvantages: Low performance, low degree of manageability.
– Unconventional method. The concept of unconventional methods includes innovative ideas that help in removing debris that cannot be implemented using mastered technologies, such as know-how-controlled magnetic field plasma. Advantages: High efficiency. Disadvantages: Technical and technological unimplementability.

– Dynamic system-bases method. Dynamic systems for debris removal include a technology for changing the orbital parameters of space debris by various perturbations, both natural and artificial. Advantages: Easy solution. Disadvantages: Low performance [10].

The cost spacecraft depends on the weight of the structure. The weight of spacecraft removing of space debris ranges from 2000 kg to 3000 kg. Correlation function allows to calculate that the cost of the spacecraft weighing 2300 kg is approximately 90 million USD.

Technologies to prevent the formation of space debris play an important role in the disposal of space debris. One of the ways to combat space debris is to repair spacecraft. In October 2019, the MEV-1 (2 326 kg) repair robot produced by Northrop Grumman docked with the IS-901 (4 723 kg) telecommunications satellite to extend its service life for another five years. In August 2020, the MEV-2 repair robot (2 875 kg) was launched. This program continues.

4. Conclusion
The analysis showed that all methods are at the conceptual or experimental stage of development, require additional technical and economic research to develop commercially viable platforms, and have an insufficient stage of experimental development. Others have technological and technical problems. Some of the unusual concepts, such as the unconventional and dynamic approach, are only a possible variant vector for the development of the idea. Any new approach to solving the problem of space debris disposal is aimed at solving an urgent global problem, and must pass technical and economic monitoring to determine the degree of effective and safe implementation.

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