

# APPROACHES TO OPTIMIZING THE LIFE CYCLE ARCTIC TRANSPORT EQUIPMENT

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Operating transport equipment in the Arctic is associated with high risks due to the increased likelihood of technical failures under extreme conditions. Fuel and lubricant spills, pollutant emissions during accidents, and the need for emergency rescue operations have a significant negative impact on fragile Arctic ecosystems [1-5]. To minimize damage, an economic and technical model for determining the optimal service life of vehicles has been developed. The model is based on minimizing total costs, including maintenance costs and the expected cost of mission failure (CMF), which aggregates, among other things, potential costs. Equipment reliability degradation is described by an S-shaped function. The methodology has been tested using data from domestic and foreign models of Arctic equipment. Calculations have revealed optimal replacement periods of 6 years for domestic equipment and 10-11 years for foreign equipment. It has been established that the key driver for write-offs is not rising maintenance costs, but rather the exponential growth of risks. The model allows for the justification of a fleet renewal strategy aimed at reducing the frequency of incidents with negative consequences and can be expanded to assess the environmental footprint of equipment lifecycles.

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**Introduction**

The development of the Arctic region, which boasts significant natural resource reserves and important transportation potential, requires the creation and maintenance of specialized transportation infrastructure [1-8]. Extreme climatic conditions, including extremely low temperatures, storm winds, and challenging ice conditions, place critical stress on equipment [9, 10]. Given the fragile Arctic ecosystem, the consequences of technical failures and accidents are particularly significant, as they can lead to large-scale pollution, disruption of soil and vegetation cover, and negative impacts on biodiversity [11].

The efficiency of transportation and logistics operations in the Arctic is determined not only by the balance between capital (CAPEX) and operating (OPEX) costs but also by taking into account other risks [12]. The cost of equipment failure in such conditions includes not only direct repair costs but also complex system costs, combined into the cost of mission failure (CMF). The CMF structure includes potential losses associated with downtime of production facilities, the costs of eliminating the consequences of emergency situations, including environmental damage, and penalties for failure to fulfill environmental and contractual obligations. These costs can be many times greater than the book value of the transport unit itself, highlighting the need to develop reliable and environmentally oriented approaches to managing transport infrastructure in the Arctic.

An analysis of modern approaches to industrial fleet management shows that prevailing lifecycle cost (LCC) models use linear or overly simplified equipment degradation and depreciation functions [13]. Such models do not correctly account for the stochastic nature of failures and the nonlinear growth of operational risks, including environmental ones, typical of work in extreme environmental conditions. In particular, they ignore the potential for a sharp increase in the frequency of incidents that can lead to significant consequences, such as oil spills, soil disturbance, and damage to biodiversity [14]. Thus, a significant scientific and methodological gap is emerging in the development of integrated approaches that enable the quantitative assessment and optimization of fleet renewal schedules, directly considering not only the economic but also the environmental consequences of failures. A pressing challenge is the creation of a methodology that integrates probabilistic reliability models, environmental risk assessments, and economic calculations, thereby minimizing the cumulative impact of industrial activity on Arctic ecosystems [15].

To address these environmental and economic challenges, this study developed a comprehensive economic and technical model aimed at determining the safe operating period of vehicles in Arctic conditions [16]. The model is based on minimizing the objective function of total annual costs, which includes both deterministic maintenance costs and the expected value of mission failures. This approach enables the integration of time-varying technical reliability parameters with long-term performance indicators of the industrial fleet. The aim of this study is to develop and test a mathematical model for determining the optimal service life of Arctic transport equipment from a risk-minimizing perspective. The model takes into account the nonlinear dynamics of the growth probability of failure depending on the age of the equipment and stochastic environmental factors, and also enables a comparative analysis of various fleet lifecycle management strategies.

The scientific novelty of this study lies in the integration of an environmental component into the cost of mission failure (CMF) indicator as a key element of the objective function for optimizing the Arctic fleet. The developed model is a strategic planning tool that allows for the justification of a renewal schedule for a heterogeneous fleet of vehicles based on minimizing cumulative risks and economic costs throughout the entire lifecycle, thereby reducing the negative impact of industrial activity on fragile Arctic ecosystems.

**Materials & Methods**

The study is based on the method of economic-technical modeling of the vehicle lifecycle. This method allows for a dynamic assessment of the total cost of ownership of an equipment fleet by integrating deterministic operational costs and stochastic risks associated with failures. The modeling is conducted for a heterogeneous fleet that includes both domestic and foreign models of motor transport equipment adapted for operation in Arctic conditions.

The initial data for the modeling are the technical-operational and cost parameters of four representative equipment models. These parameters, presented in Table 1, include the initial cost, the basic annual maintenance cost for new equipment, the baseline probability of failure per typical mission, and the aggregated Cost of Mission Failure (CMF).

Table 1

Initial Parameters of Arctic Transport Equipment Models

Model	Origin	Class	Initial Cost, RUB	Base Maintenance Cost, RUB/year	Base Failure Probability	Cost of Mission Failure (CMF), RUB
KAMAZ-6355 "Arktika"	Domestic	Truck	15,000,000	800,000	0.05	50,000,000
TREKOL-39294	Domestic	All-Terrain Vehicle	7,000,000	450,000	0.08	30,000,000
BvS10 "Beowulf"	Foreign	All-Terrain Vehicle	45,000,000	1,200,000	0.02	40,000,000
Foremost Commander C	Foreign	Truck	60,000,000	1,800,000	0.03	70,000,000

The central element of the model is the formalization of the equipment degradation process over time. The annual maintenance costs,  $C_{maint}(t)$ , for equipment of age  $t$  years are modeled using linear growth, reflecting the planned increase in the volume and complexity of repair work [17]:

$$C_{maint}(t) = C_{maint_{base}} \cdot (1 + r_m \cdot (t - 1)) \tag{1}$$

where:  $C_{maint_{base}}$  – is the base annual maintenance cost;  $r_m$  – is the annual growth rate of maintenance cost;  $t$  – is the year of operation.

The annual failure probability of the equipment,  $P_{failure}(t)$ , is modeled using an S-shaped (sigmoid) function. This approach allows for a more realistic representation of the three lifecycle phases: an initial "run-in" period with slow risk growth, a period of normal operation with accelerating growth, and a final "wear-out" period where the failure probability approaches its maximum value:

$$P_{failure}(t) = P_{failure_{base}} + (P_{max} - P_{failure_{base}}) \cdot \frac{1}{1 + e^{-k \cdot (t - t_0)}} \quad (2)$$

where:  $P_{failure_{base}}$  – is the base annual failure probability;  $P_{max}$  – is the maximum theoretical failure probability;  $t_0$  – is the inflection point of the curve (average service life);  $k$  – is the coefficient determining the steepness of the growth.

Based on these dynamic parameters, the objective function is formed – the total annual costs  $C_{total}(t)$ , consisting of maintenance costs and the expected value of the cost of mission failures  $E[CMF(t)]$ :

$$C_{total}(t) = C_{maint}(t) + E[CMF(t)] \quad (3)$$

here the expected value is calculated as:

$$E[CMF(t)] = P_{failure}(t) \cdot CMF_{base} \cdot N_{missions} \quad (4)$$

where:  $CMF_{base}$  – is the base cost of a single mission failure;  $N_{missions}$  – is the average annual number of missions.

The criterion for determining the optimal service life  $T^*$  is the minimization of the average total cost of ownership over the entire operational period. This metric,  $C_{avg_{total}}(T)$ , accounts for both the initial capital expenditure  $C_{initial}$  and the sum of all operational costs

$$C_{avg_{total}}(T) = \frac{1}{T} \left( C_{initial} + \sum_{t=1}^T C_{operational}(t) \right) \quad (5)$$

The optimal service life  $T^*$  corresponds to the year in which this function reaches its minimum:

$$T^* = \arg \min_T \{ C_{avg_{cumulative}}(T) \} \quad (6)$$

Within the computational experiment, the following unified parameters were adopted for all models:

Table 2

Simulation parameters

Parameter	Notation	Value	Note
Maximum modeling period	$T_{max}$	25 years	Planning horizon for the equipment lifecycle.
Maintenance cost growth rate	$r_m$	0.10	Reflects the linear annual increase in maintenance cost.
Failure severity factor	$S_f$	0.3	Share of CMF lost in an average failure.
Max. failure probability	$P_{max}$	0.85	Asymptotic limit for the S-shaped curve.
<b>Parameters S-curve (t, 0, k)</b>			
For domestic equipment	$t_0, k$	9 years, 0.4	Inflection point and growth steepness of the curve.
For foreign equipment	$t_0, k$	12 years, 0.35	Inflection point and growth steepness of the curve.

The modeling process itself can be represented in a simplified form by the following diagram (Fig. 1). The software implementation of the modeling was carried out using Jupyter Notebook [18].

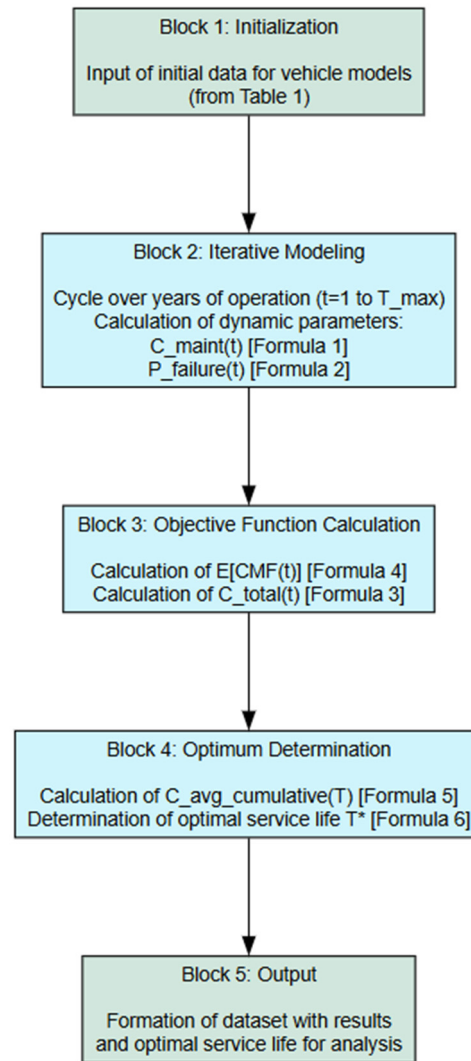


Fig. 1. Simplified diagram of the modeling process

Results

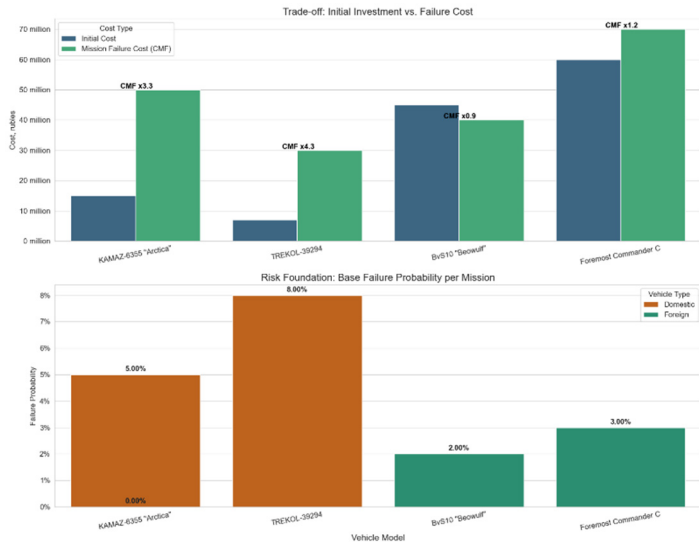
The application of the described methodology to the initial data allowed for the quantitative assessment of the dynamics of operational costs and the determination of economically optimal service lives for each of the equipment models under consideration. The modeling results are presented as a series of graphs illustrating key dependencies.

An initial analysis of the input data reveals fundamental differences in the economic structure and technical risks between domestic and foreign models. Figure 2 presents an integrated analysis comparing the cost indicators and baseline reliability of the equipment.

The upper sub-plot (A) is a grouped bar chart comparing the initial cost and the Cost of Mission Failure (CMF) for each model. Annotations above the CMF bars show the risk multiplier – the ratio of CMF to the initial cost. The lower sub-plot (B) is a bar chart illustrating the baseline failure probability permission for each model, with precise percentage values indicated.

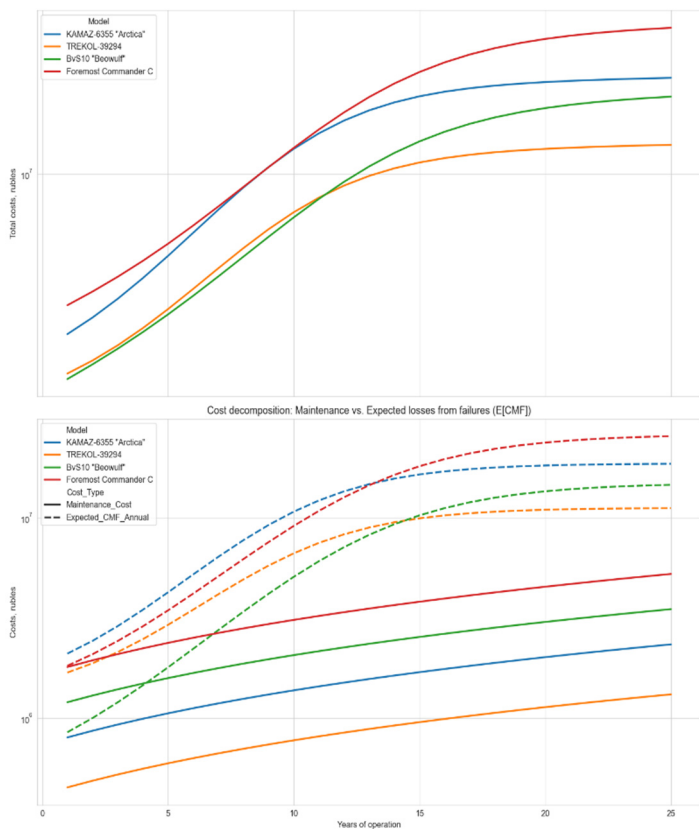
The upper graph (Fig. 2, A) demonstrates that for domestic models, the cost of mission failure exceeds their initial cost by a factor of 3.3-4.3. For foreign analogues, this ratio is less than 1.0.

The lower graph (Fig. 2, B) shows that the baseline failure probability for domestic models (5% and 8%) is 2-4 times higher than for foreign ones (2% and 3%).



**Fig. 2.** Integrated comparative analysis of economic and technical parameters of Arctic equipment

Dynamic modeling of the equipment lifecycle over a 20-year operational period allowed for the calculation of the change in total annual costs, including maintenance expenses and the expected value of losses from failures. The dynamics of these costs are presented in Figure 3.



**Fig. 3.** Dynamics of total annual costs over the lifecycle and cost decomposition

The graph of the dynamics of total annual costs consists of line charts showing the change in total annual costs (on a logarithmic scale) for the four equipment models as a function of the year of operation. Each line corresponds to one model.

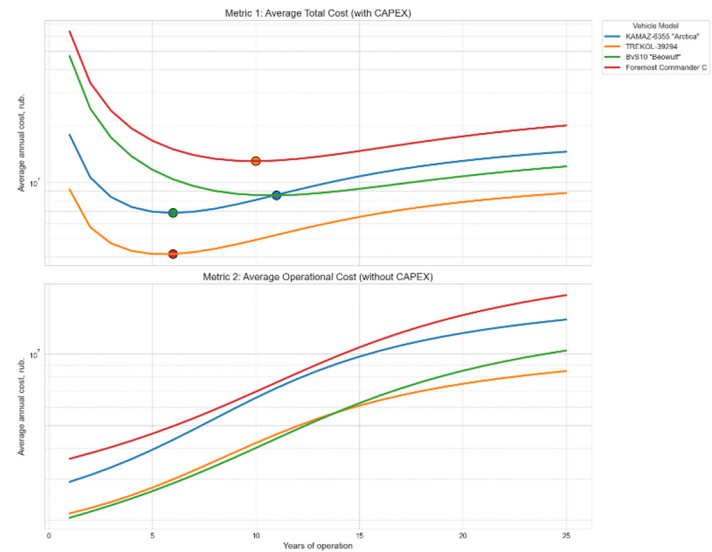
The analysis of the graph in Figure 3 shows that all models are characterized by a non-linear, near-exponential growth of total costs after a certain period of operation. The most intensive growth is observed for the "TREKOL-39294" and "KAMAZ-6355 'Arktika'" models.

To identify the factors driving this growth, a decomposition of the total costs into two components was performed: deterministic maintenance costs and probabilistic costs associated with failure risks (E[CMF]).

The decomposition graph consists of line charts where, for each model, two curves are shown: one (solid) reflects the growth of maintenance costs, and the second (dashed) shows the growth of the expected value of the cost of mission failures (E[CMF]). The vertical axis is presented on a logarithmic scale.

The figure indicates that in the initial stages of the lifecycle (1-5 years), maintenance costs are the main contributor to total costs. However, after 5-7 years of operation, an intersection point is observed for all models, after which the expected value of losses from failures begins to dominate the cost of maintenance, becoming the determining factor in the growth of total costs.

Based on the calculated total annual costs, the optimal service life for each model was determined by minimizing the average total cost of ownership over the period. The dynamics of this indicator and the optimum points for each model are presented in Figure 4.



**Fig. 4.** Determination of the optimal service life

The graph consists of line charts showing the change in the average annual cost of ownership over the entire operational period for each model. Points on the curves mark the minimums, corresponding to the economically optimal year for equipment replacement.

The calculations show that the average total cost curves have a distinct U-shape. The minimum points of these curves, which determine the optimal service life, are summarized in Table 3.

Table 3

Results of Optimal Service Life Calculation

Model	Origin	Optimal Replacement Year
KAMAZ-6355 "Arktika"	Domestic	6
TREKOL-39294	Domestic	6
BvS10 "Beowulf"	Foreign	11
Foremost Commander C	Foreign	10

The results presented in Table 3 show that the economically justified operational period for domestic models is 6 years, whereas for their foreign analogues, this period reaches 10-11 years.

### Discussion

The obtained results demonstrate that an environmentally-oriented model of the equipment lifecycle in extreme Arctic conditions is fundamentally determined by the dynamics of operational risks, including environmental ones, rather than solely by deterministic maintenance costs. The use of an S-shaped aging function, in contrast to simplified linear or exponential models, allows for a more accurate assessment of the equipment degradation process, taking into account its impact on the environment [19]. The introduction of the inflection point parameter ( $t_0$ ) makes it possible to quantitatively determine the critical moment after which the accelerated growth in failure probability renders further operation of the equipment environmentally and economically impractical due to a disproportionate increase in the expected value of the cost of mission failure ( $E[CMF]$ ), which includes potential environmental damage.

This approach allows for the identification of the point at which the risks of emergency situations with significant environmental consequences—such as fuel spills, pollutant emissions, and damage to fragile Arctic ecosystems—begin to increase exponentially. Thus, the model provides a scientifically substantiated criterion for making decisions about decommissioning equipment before the onset of a period of heightened environmental risks, which contributes to minimizing the anthropogenic impact on the environment of the Arctic region [20].

The analysis of the results shows that it is the  $E[CMF]$ , not the maintenance cost, that drives the growth of total costs in the middle and late stages of the lifecycle. This fact confirms that strategic decisions about fleet renewal in the Arctic should be based primarily on risk management. The optimal replacement time occurs not when the equipment is physically worn out, but when the average cost of ownership, which includes the amortized risk, reaches its minimum [21]. Continuing operation beyond this point means that each subsequent year of ownership becomes less economically advantageous.

A comparative analysis of domestic and foreign models reveals not a qualitative superiority, but a fundamental difference in optimal management strategies. The high initial cost of foreign equipment can be interpreted as a capital investment in extending the operational period with an acceptable level of risk, which is reflected in a later inflection point ( $t_0 = 11$  years) of the S-shaped curve. The optimal service life of 10-13 years for these models corresponds to a strategy of long-term asset ownership [21].

For domestic equipment, characterized by lower initial investments but also an earlier onset of the accelerated wear-out phase ( $t_0 = 9$  years), the model prescribes a different strategy. The optimal service life of 7-9 years indicates the advisability of a shorter fleet renewal cycle. This approach allows for maintaining the average age and, consequently, the average risk level of the entire fleet at an economically acceptable level, managing risks not through the durability of an individual unit, but through operational flexibility and renewal frequency [22].

The proposed methodology has the potential for expansion to heterogeneous fleets that include unmanned systems. For such systems, both the cost structure (elimination of crew costs, changes in the structure of maintenance costs) and the reliability function parameters (new types of failures related to electronics and communication channels) will change. The flexibility of the model allows for the integration of these changes and for conducting a comparative analysis to determine the optimal balance between manned and unmanned platforms for specific transport tasks in the Arctic [23, 24].

It should be acknowledged that the accuracy of the modeling depends on the quality of the input expert parameters ( $t_0$ ,  $k$ ,  $S_f$ ). Further development of this research involves the collection and statistical analysis of real operational data on failures of Arctic equipment. This will allow for the verification and calibration of the model parameters, increasing its predictive accuracy and transforming it from a strategic tool into a tactical decision support system.

### Conclusion

A model has been developed that provides a quantitative tool for strategic service life planning of Arctic transport equipment. It takes into account not only economic factors but also, indirectly, environmental factors through the cost of mission failure (CMF). It has been established that the optimal service life of domestic equipment (6 years) is significantly shorter than that of foreign equivalents (10-11 years), indicating the need for different fleet management strategies. It has been revealed that the key factor determining the need for equipment replacement is the nonlinear growth of operational risks (the probability of failure), rather than direct maintenance costs. A new approach has been proposed that enables a transition from reactive management (repair after failure) to proactive strategic fleet renewal planning, which provides the basis for reducing damage and increasing the resilience of transport operations in fragile Arctic ecosystems. The model has been found to be flexible and can be adapted to the effectiveness of various fleet management strategies, for example, by incorporating specific costs for eliminating environmental damage into the CMF.

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## ПОДХОДЫ К ОПТИМИЗАЦИИ ЖИЗНЕННОГО ЦИКЛА АРКТИЧЕСКОЙ ТРАНСПОРТНОЙ ТЕХНИКИ

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**Аннотация**

Эксплуатация транспортной техники в Арктике сопряжена с высокими рисками, обусловленными повышенной вероятностью технических отказов в экстремальных условиях. Разливы горюче-смазочных материалов, выбросы загрязняющих веществ при авариях и необходимость проведения аварийно-спасательных операций оказывают значительное негативное воздействие на хрупкие арктические экосистемы [1-5]. Для минимизации ущерба разработана экономико-техническая модель определения оптимального срока службы транспортных средств. Модель основана на минимизации совокупных издержек, включающих затраты на техническое обслуживание и математическое ожидание стоимости срыва миссии (Cost of Mission Failure, CMF), которая агрегирует, в том числе, потенциальные издержки. Дegradaция надежности техники описана S-образной функцией. Методология апробирована на данных по отечественным и зарубежным моделям арктической техники. Расчеты выявили оптимальные сроки замены: 6 лет для отечественной и 10-11 лет для зарубежной техники. Установлено, что ключевым драйвером для списания является не рост затрат на обслуживание, а экспоненциальный рост рисков. Модель позволяет обосновать стратегию обновления парка, направленную на снижение частоты инцидентов с негативными последствиями, и может быть расширена для оценки экологического следа жизненного цикла техники.

**Ключевые слова:** арктическая транспортная техника, риски, жизненный цикл оборудования, стоимость срыва миссии (CMF), оптимизация сроков эксплуатации, управление рисками, устойчивое развитие Арктики

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