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## MULTICRITERIA ASPECT OF OPTIMAL CHOICE MODEL IN THE ADAPTIVE RESOURCE MANAGEMENT PROBLEM OF A MANUFACTURING COMPANY

Konstantin Frolov  

Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia

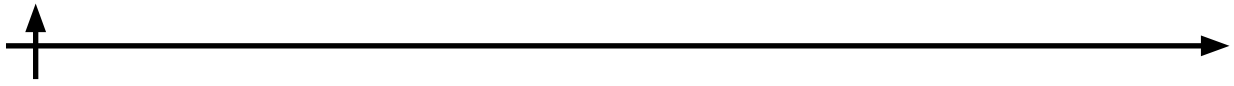
 [frolov\\_kv@spbstu.ru](mailto:frolov_kv@spbstu.ru)

**Abstract.** An approach to selecting a resource allocation option in economic systems based on a single criterion does not align with the objective reality of management. In this regard, the emphasis on multi-criteria choice, which is most relevant for a manufacturing company, requires no justification as it is more attractive in terms of reflecting the objective scenario of resource management. The aim of this study is to develop an abstract formalized model and methodological support for the theoretical-methodological apparatus that incorporates several choice criteria: flexibility in scheduling operations (operational flexibility), stability, and economic efficiency. These aspects of activity should not be viewed as static entities but rather with consideration of dynamics arising from the organization's functioning in a competitive environment, changing principles of fiscal regulation, and the influence of natural factors. The methodological basis of the research includes multi-criteria choice theory, operations research, and adaptive control theory (Lotov and Pospelova, 2008). The paper proposes a model intended for use within a rolling planning horizon; the model incorporates a mechanism for dynamic calibration of weight coefficients based on Bayesian updating and an algorithm for constructing the Pareto front. Approaches are proposed for assessing key performance indicators related to resource allocation, delays in operational decision-making, and the enterprise's ability to respond to unplanned disturbances. The work may be useful in the context of developing the theory of adaptive control in economic systems; the proposed provisions can serve as arguments for designing tools for intelligent decision support systems in manufacturing companies.

**Keywords:** multi-criteria optimization, adaptive resource management, economic model, Pareto optimality, manufacturing company, dynamic allocation, supply chain resilience

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## МНОГОКРИТЕРИАЛЬНЫЙ АСПЕКТ ЭКОНОМИЧЕСКОЙ МОДЕЛИ ОПТИМАЛЬНОГО ВЫБОРА В ЗАДАЧЕ АДАПТИВНОГО УПРАВЛЕНИЯ РЕСУРСАМИ ПРОИЗВОДСТВЕННОЙ КОМПАНИИ

Константин Фролов  

Санкт-Петербургский политехнический университет Петра Великого,  
Санкт-Петербург, Россия

 [frolov\\_kv@spbstu.ru](mailto:frolov_kv@spbstu.ru)

**Аннотация.** Подход к выбору варианта распределения ресурсов в экономических системах, основанный на использовании одного критерия, не соответствует объективной картине управления. В этой связи акцент на многокритериальном выборе, наиболее актуальный для производственной компании, не требует обоснования как более привлекательный с точки зрения отражения объективного сценария управления ресурсами. Цель исследования – разработка абстрактной формализованной модели и методологического сопровождения теоретико-методологического аппарата, в которых нашли отражение несколько критериев выбора: гибкость в формировании графика операций (операционная гибкость), устойчивость, экономическая эффективность. Эти аспекты деятельности должны рассматриваться не как замороженные сущности, а с учетом динамики, являющейся следствием отражения функционирования организации в конкурентной среде, с изменяющимися принципами фискального регулирования и влияния природы. Методологический базис исследования – теория многокритериального выбора, исследования операций и теория адаптивного управления (Lotov and Pospelova, 2008). В работе предложена модель, ориентированная на использование в скользящем горизонте планирования, в модель включен механизм динамической калибровки весовых коэффициентов на основе байесовского обновления и алгоритм построения Парето-фронта. Предложены подходы к оценке ключевых показателей эффективности, имеющих отношение к распределению ресурсов, задержке принятия оперативных управленческих решений и способность предприятия реагировать на незапланированные воздействия. Работа может быть полезной в контексте развития теории адаптивного управления в экономических системах; предложенные положения могут быть использованы как аргументы для разработки инструментов интеллектуальных систем поддержки решений в производственных компаниях.

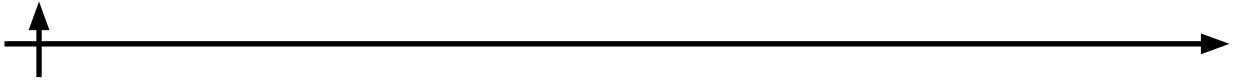
**Ключевые слова:** многокритериальная оптимизация, адаптивное управление ресурсами, экономическая модель, Парето-оптимальность, производственная компания, динамическое распределение, устойчивость цепочек поставок

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### Introduction

Modern industrial manufacturing operates under conditions of uncertainty driven by global economic changes, technological transformation (Industry 4.0 and 5.0), as well as the tightening of environmental and social standards (ESG – Environmental, Social, and Governance – business management principles based on environmental responsibility, high social relevance, and quality corporate governance). In such a scenario, planning models focused on cost minimization or output maximization under fixed parameters demonstrate their inadequacy



in addressing real-world challenges and cannot be considered effective. The limitation of the traditional approach lies in its neglect of systemic production dynamics, the absence of modern tools that provide an adaptive response to changes in demand, prices for components, raw materials and semi-finished products, and the availability of labor resources. From the perspective of formal problem representation, it is necessary to recognize that the mutual influence of these parameters complicates the reduction of a multidimensional objective function to a single aggregated indicator (Steuer, 1986; Deb, 2001).

The relevance of this study is driven by the need for a comprehensive analysis of approaches to transitioning toward adaptive resource management systems capable of revising strategic and tactical decisions in real time based on incoming information, while maintaining a balance between economic, operational, and objectives traditionally classified under sustainable development (ecology, occupational health and safety, and industrial safety) (Keeney and Raiffa, 1993). The multi-criteria nature of the problem becomes key, as optimization according to a single criterion (e.g., output volume) often leads to neglecting the impact of other criteria (flexibility, supply reliability, environmental compliance) on the overall outcome, which in the long term reduces the overall resilience of the enterprise in a competitive market.

The problem lies in the absence of a coherent methodology for formulating an economic model that accounts for the principles of multi-criteria choice, adaptive adjustment mechanisms, and constraints related to production tasks – both at the plant level and at the shop floor level. Most proposed solutions are oriented toward solving particular problems (production planning, production supply, etc.), or are static (fixed criterion weights, lack of learning mechanisms), or, by relying on combinatorial optimization methods, lead to the curse of dimensionality, which precludes their operational application.

The aim of this work is to develop and test an economic model of optimal choice that accounts for the multi-criteria nature of the adaptive resource management problem in a manufacturing company. To achieve this aim, the following tasks are addressed:

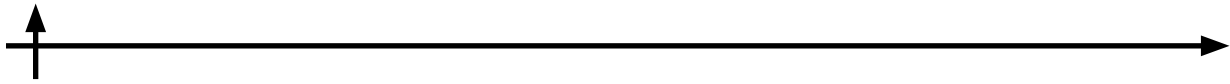
1. Proposing a theoretical-methodological approach to multi-criteria choice in the context of adaptive management of production resources;
2. Formalizing an economic model that includes dynamic objective functions, constraints, and a mechanism for adaptive preference calibration;
3. Assessing the efficiency, stability, and managerial applicability of the model.

The methodological basis of the research draws on the apparatus of multi-criteria optimization theory (Pareto dominance, scalarization methods, outranking approaches), the principles of closed-loop adaptive control, and dynamic programming methods (Zeleny, 1982). The informational foundation consists of publicly available data, which enabled the formation of a benchmarking base for analysis.

The structure of the paper corresponds to the stated tasks and includes an abstract, an introduction, three substantive sections, a conclusion, and a list of sources consulted by the author during the preparation of the study.

### **Theoretical and methodological foundations of multi-criteria choice for the adaptive resource management problem**

Adaptive resource management of a manufacturing company represents a continuous process of reallocating material, labor, financial, energy, and production assets in response to unplanned changes in the external environment. In this context, a change within a company's division not foreseen by the operations plan is treated by another division as a change in the external environment: structural decomposition allows for the identification of subsystems, generally ordered within a hierarchy, and each division acts as an element of the external environment for another



in the context of the particular tasks addressed by that division. Unlike reactive management, the adaptive approach presupposes the presence of prediction, learning, and proactive correction mechanisms, which necessitates formalization within dynamic economic models.

Traditional optimal choice theory, closely related to applied problems in neoclassical microeconomics, is based on the principle of utility maximization or cost minimization under given budget and technological constraints. However, in conditions involving the production of multiple products, the execution of operations within a value chain, and non-stationary markets, a single optimization criterion becomes inadequate (Ivanov et al., 2023; Simchi-Levi et al., 2021). Economic reality requires accounting for several target indicators grouped into three categories:

1. Economic efficiency: net present value (NPV), return on assets (ROA), capital turnover ratio, and production cost level.
2. Operational flexibility and reliability: order fulfillment time, equipment availability factor, safety stock level, and resilience to supply chain disruptions.
3. Compliance with environmental regulatory requirements focused on carbon footprint, industrial energy efficiency indicators, adherence to ESG standards, and corporate social performance indicators (employee turnover rate, injury rate, amount of fines resulting from industrial safety audits).

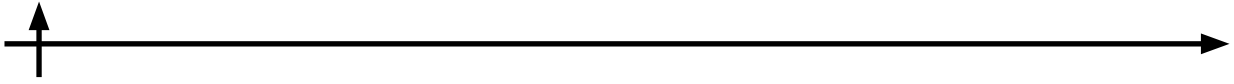
These criteria typically influence one another, competing for resources. For example, reducing safety stock lowers logistics costs but increases the risk of a decline in the actual service level agreement (SLA) due to a shortage of manufactured products. Increasing equipment utilization reduces unit fixed costs but diminishes flexibility in responding to changes in the product mix. This is precisely why the resource management problem most accurately reflects reality when formalized as a multi-criteria choice problem, requiring the construction of a set of efficient (Pareto-optimal or Slater-optimal) solutions for its resolution.

The theoretical apparatus of multi-criteria optimization (MCDM/MOO) offers a fairly comprehensible approach to handling conflicting objectives. The key concept of this approach is the Pareto front (or Pareto set) – the set of solutions (alternatives) for which improving one criterion is impossible without worsening at least one other. The economic interpretation of Pareto optimality in a production context means achieving a state in which resource reallocation cannot increase the overall value for stakeholders without losses in another dimension accounted for in the formal model describing the company's operations.

However, static construction of the Pareto front is insufficient for adaptive management. The production environment is characterized by non-stationary parameters: raw material prices, equipment productivity change, and demand fluctuates. Consequently, a mechanism for dynamic adjustment of criterion weights and revision of constraints in near real-time is required (Powell, 2007). These aspects make the use of adaptive control principles for solving applied problems practically evident, grounded in the provisions of feedback system theory and stochastic programming.

Known approaches to ensuring adaptability in the economic-production context highlight the following aspects:

- Rolling planning horizon, in which the search for an optimal resource allocation option is performed over a finite period, but the solution is applied only for the first step, after which the model is updated with new data;
- Bayesian parameter updating, which allows adjusting posterior probability distributions of demand, prices, and equipment failures as actual data become available;
- Dynamic preference calibration, in which criterion weights are recalculated based on assessing deviations of actual indicators from target trajectories.



The synthesis of multi-criteria optimization and adaptive control in its methodological representation makes it possible to overcome the limitations of traditional models. In particular, instead of a fixed objective function, a vector dynamic system is introduced, where each criterion evolves over time under the influence of control actions and changes in external scenario conditions. The economic interpretation of such a system lies in the transition from static equilibrium to a trajectory of dynamic efficiency, where optimality is understood not as a point but as a stable path in the resource state space.

Most studies in the field of production planning and management draw a distinction between the economic and operational (including engineering-technological) aspects. The focus of researchers oriented toward economic aspects includes financial metrics, while technological parameters are incorporated into models as static constraints. Operational models "exclude from radar" the company's financial parameters, such as the opportunity cost of capital. The approach proposed in this paper bridges this gap by integrating financial, production, and regulatory criteria into a single framework, representing a vector function that can formally change in real time, reflecting the adaptation of the system (enterprise) to the actual operating scenario.

### **Formalization of an economic model for optimal choice with adaptive constructs**

The development of an economic model for optimal choice in the adaptive resource management problem requires a clear definition of the state space, the set of admissible controls, the vector objective function, and the adaptive correction mechanism. Below is a structured formalization suitable for implementation in decision support systems, which, to achieve practical value, must be integrated with ERP and MES systems (GOST R ISO 9001-2015; Federal Law No. 296-FZ).

#### *State space and admissible controls*

Let a manufacturing company operate over a planning horizon  $T$ , divided into discrete intervals  $t = 0, 1, \dots, T$ . The state of the system at time  $t$  is described by a vector:

$$X_t = (R_t, D_t, P_t, E_t, Q_t)$$

where:

- $R_t$  — the vector of available resources (raw materials, components, labor hours, energy, financial limit);
- $D_t$  — the demand forecast by product category;
- $P_t$  — the vector of prices for resources and finished products;
- $E_t$  — the equipment status (availability factor, remaining useful life);
- $Q_t$  — the volume of work in progress and warehouse stocks.

The control action  $U_t$  includes resource allocation shares across production lines, procurement volumes, maintenance schedules, safety stock levels, and energy consumption parameters. The admissible set of resource allocation alternatives is determined by technological and economic constraints, as well as actions permissible from the perspective of regulatory requirements:

$$A_t U_t \leq b_t, U_t \geq 0$$

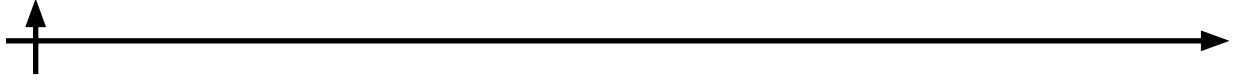
where  $A_t$  is the matrix of resource utilization coefficients, and  $b_t$  is the vector of available capacities and limits.

#### *Vector objective function and multi-criteria aspect of resource allocation choice*

The economic model is formulated as a problem of maximizing a vector function:

$$\max_{U_t} F(X_t, U_t) = [f_1, f_2, f_3]^T, \text{ where:}$$

1.  $f_1$  — economic efficiency: discounted profit flow over the horizon, adjusted for the opportunity cost of capital and holding costs;
2.  $f_2$  — operational flexibility: the inverse of the average order fulfillment time, weighted by



the probability of supply disruption and the reserve capacity utilization rate;

3.  $f_3$  – resilience and regulatory compliance: the negative value of the total carbon footprint, fines for non-compliance with ESG standards, and waste disposal costs.

Since the criteria are dimensionally heterogeneous and conflicting, direct comparison of vectors is impossible. To obtain a scalar equivalent, adaptive scalarization is applied (Bertsimas and Tsitsiklis, 1997):

$$J_t(U_t) = \sum_{k=1}^3 \omega_k(t) \cdot \tilde{f}_k(X_t, U_t),$$

where  $\tilde{f}_k$  – are normalized criteria (reduced to a common scale  $[0,1]$ ), and  $\omega_k(t)$  – are dynamic weight coefficients satisfying the conditions  $\sum \omega_k(t) = 1, \omega_k(t) > 0$ .

#### *Mechanism of adaptive weight calibration*

The key distinction of this model from static analogs is the endogenous updating of  $\omega_k(t)$ . The weight coefficients are recalculated based on assessing the deviation of actual trajectories from target ones:

$$\omega_k(t+1) = \omega_k(t) + \alpha \cdot \left( \frac{dL}{d\omega_k} \right) t$$

where  $\alpha$  is the adaptation step, and L – a loss function that accounts for the variance of the criteria, penalties for exceeding threshold values, and management priorities. In practice, the updating can be implemented either through an expert-analytical module (in accordance with the classical approach based on the interactive participation of criterion owners in the process of determining the Pareto region) or by using a machine learning subsystem trained on historical data on the consequences of decisions, effectively replacing the criterion owners (Wang et al., 2020; Ben-Tal et al., 2015).

Additionally, Bayesian updating of the probability distributions of the parameters Dt and Pt can be employed:

$$p(\Theta_{t+1} | data_t) \propto p(data_t | \Theta_t) \cdot p(\Theta_t),$$

if their probabilistic description is feasible. In this case, the model allows for adjusting demand and price forecasts as sales data and current market quotations become available.

#### *Solution algorithm and computational architecture*

The formulated problem belongs to the class of dynamic multi-criteria optimization problems with nonlinear constraints. A hybrid approach is applied to solve it:

1. At each time step t, an approximation of the Pareto front is constructed using a well-established algorithm, for example:

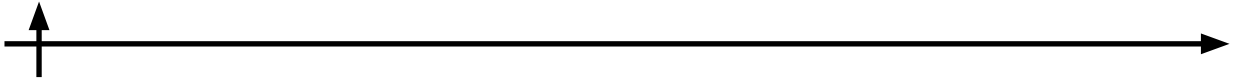
– NSGA-II (Non-dominated Sorting Genetic Algorithm II) – a genetic algorithm that finds the Pareto set in a single run using non-dominated sorting and crowding distance;

– MOEA/D (Multi-Objective Evolutionary Algorithm based on Decomposition) – an evolutionary algorithm based on decomposition. It is designed to solve complex optimization problems where two or more objective functions must be optimized simultaneously; instead of attempting to optimize all objectives at once, MOEA/D decomposes the multi-criteria problem into several single-criterion subproblems. These subproblems are optimized simultaneously using information from neighboring subproblems, enabling the algorithm to efficiently form the Pareto front;

2. From the set of efficient solutions, a reference solution is selected using the TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution), adapted to dynamic weights – a multi-criteria decision-making algorithm that ranks alternatives by selecting the one closest to the "positive ideal solution" and farthest from the "negative ideal solution";

3. Optimization is performed in a rolling horizon mode: the optimal trajectory  $\{U_t, \dots, U_{t+H}\}$  is calculated, only  $U_t$  is applied, after which the state is updated and the cycle repeats.

Computational complexity is reduced through decomposition by production groups and the



organization of parallel computations

To reduce the delay between the moment when a management intervention becomes necessary (the occurrence of unplanned events affecting outcomes) and the actual response to it, it is advisable to conduct predictive scenario modeling prior to decision-making. Such modeling should be organized within a simulation system that employs a digital twin of the enterprise, and the system itself must be integrated with the decision support system (Antonov et al., 2025; Bakhtizin et al., 2022; Kozlov and Lebedeva, 2023).

The economic interpretation of the model is that optimal choice ceases to be a one-time act and becomes an element of a continuous process. Adaptive mechanisms ensure resilience to disturbances from factors not accounted for during planning, while the multi-criteria nature guarantees that short-term financial gains are not achieved at the expense of long-term deterioration in operational resilience and non-compliance with regulatory requirements in the areas of industrial safety and ecology.

### **Practical application of the model**

The assessment of the practical significance of the developed model is based on the results of implementing adaptive control subsystems integrated with the enterprise management system at the shop floor level (MES) and the process control and detailed planning system (MES + APS). The logic of the adaptive control system's operation is built on the entities formed on the basis of the formal multi-criteria optimization model presented in Section 2 of the study. The adaptive control system was implemented at several discrete manufacturing enterprises specializing in the production of machinery and consumer goods. A significant portion of components, semi-finished products, and raw materials are supplied to the enterprise from external sources; product demand is uneven, with seasonal fluctuations, and environmental requirements as well as industrial safety requirements are taken into account in operations.

Based on the analysis of the adaptive control system's performance, conclusions are drawn regarding the validity of the approach to model formalization grounded in the theoretical framework of multi-criteria optimization, and quantitative estimates of achievable indicators are formulated, which can be used as benchmarks.

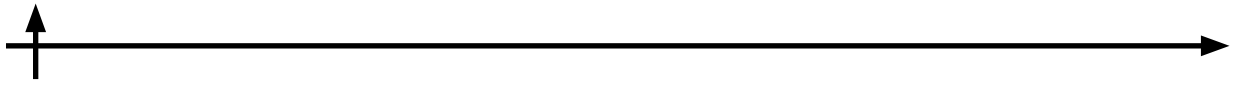
As a baseline formal scenario, the one implementing the proposed adaptive multi-criteria model with dynamic weight calibration and a rolling horizon is used.

To assess efficiency, an approach based on reference weights, considered as averaged values, may be employed. As a result, the following indicators may be recognized as achievable (Table 1).

**Table 1. Efficiency indicators.**

<b>Indicator</b>	<b>Value of the indicator</b>
Average costs	- 5%
Number of overdue production orders	4% of average
Inventory coverage level	80% (comparing with the before-implementation level)
ESG compliance rate	0,9
Reduction in operational decision-making time	2 times faster

Cost reduction is achieved by optimizing procurement schedules and reallocating equipment utilization. The order fulfillment rate has increased due to proactive adjustment of production plans upon signals of supply delays. The ESG index has improved through the integration of the energy efficiency criterion into the objective vector and the automatic shifting of energy-inten-



sive operations to periods of low tariff rates (European Commission, 2024).

For successful implementation of a solution based on the practical application of the model, it is recommended to adhere to several conditions:

- IT landscape: The information technology infrastructure supporting the model's informational aspects must ensure integration of IoT equipment sensors, external data (markets, logistics, regulatory databases) with MES/ERP systems (Ivanov and Frolov, 2023; Chatterjee and Mukherjee, 2023).

- Organizational readiness: Transition from hierarchical planning to cross-functional teams responsible for multi-criteria balancing.

- Data culture: Training personnel in interpreting the Pareto front and understanding the semantic relationships between criteria, thereby eliminating subjective distortion of weights.

The model does not replace managerial judgment but rather formalizes it, providing a transparent mechanism for assessing the consequences of decisions

### **Conclusion**

This study confirms the necessity and economic feasibility of a multi-criteria approach to the adaptive resource management problem in a manufacturing company. The developed model overcomes the limitations of traditional static and single-criterion analogs through the integration of a vector objective function, dynamic weight calibration mechanisms, and a rolling planning horizon (Gudkovskiy, 2025).

The theoretical contribution of this work lies in the synthesis of the principles of adaptive control, multi-criteria optimization, and the economic theory of dynamic efficiency. It has been shown that optimal choice in a production context should be interpreted not as a search for a single extremum, but as navigation along a trajectory of Pareto-efficient states, adjusted in real time based on incoming data and changes in strategic priorities.

The practical significance of the study is confirmed by the results of practical implementations: the proposed approach provides an increase in the integral efficiency of resource allocation by 10% or more, reduces decision-making latency, and enhances resilience to exogenous shocks. The model can be embedded into the architecture of digital twins of manufacturing enterprises and used as a core for decision support systems at the tactical and operational planning levels.

Limitations of the study are associated with high requirements for the quality and frequency of input data, as well as with computational complexity when scaling to holding structures with multiple interconnected sites. Furthermore, the calibration of weight coefficients partially depends on expert assessments, which may introduce a subjective component.

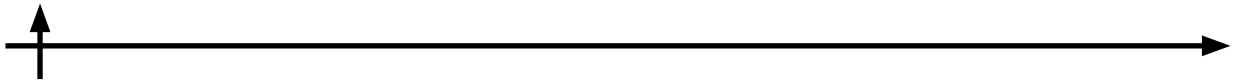
Prospects for further research include:

- Integration of deep learning algorithms for automatic identification of latent preferences and nonlinear trade-offs;

- Development of distributed versions of the model for networked production ecosystems using blockchain technologies to ensure data integrity;

- Expansion of criteria to include the social dimension (staff engagement, competency development) with their quantitative formalization within the economic framework.

In the context of the transformation of the industrial landscape, adaptive multi-criteria resource management ceases to be an optional tool and becomes a strategic imperative. The proposed model creates a scientifically grounded foundation for the transition from reactive control to proactive optimization, ensuring the sustainable development of manufacturing companies under conditions of uncertainty.

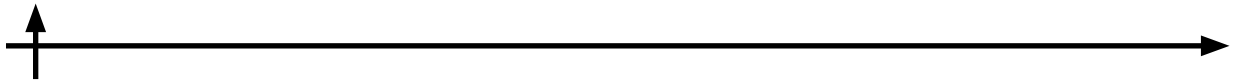


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#### INFORMATION ABOUT AUTHOR / ИНФОРМАЦИЯ ОБ АВТОРЕ

**FROLOV Konstantin V.** – Associate Professor, Candidate of Technical Sciences

E-mail: [frolov\\_kv@spbstu.ru](mailto:frolov_kv@spbstu.ru)

**ФРОЛОВ Константин Владимирович** – доцент, к.т.н.

E-mail: [frolov\\_kv@spbstu.ru](mailto:frolov_kv@spbstu.ru)

ORCID: <https://orcid.org/0000-0002-1341-2288>

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