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EDITOR'S NOTE

Technology has ceased to be merely a supporting tool for economic processes – increasingly, it is becoming their architecture. Decision-making algorithms, artificial intelligence systems, and structured data management models are penetrating the most diverse fields, from financial protocols and cybersecurity to healthcare, logistics, and education. At the same time, the key challenge lies not so much in creating new technologies as in integrating them competently into existing business and management processes – with due regard for economic feasibility, regulatory requirements, and the real constraints faced by organizations.

It is precisely this theme – at the intersection of technological tools and the practice of economic and managerial analysis – that this issue of *Technoeconomics* addresses. The articles presented here share a common methodological vector: their authors do not merely describe technologies but build reproducible architectural and mathematical models that allow the economic effect of their implementation to be assessed – whether it concerns tokenomics stability, the effectiveness of AI agents, the quality of patient data, or a decision support system for marketplace sellers.

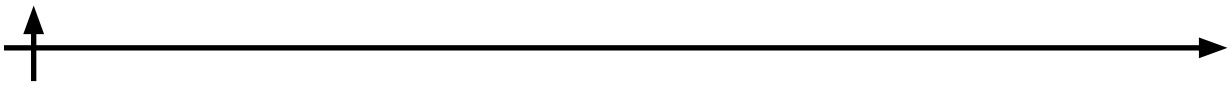
The issue opens with an article by **Yana Vasileva and Viktoria Sheleyko** devoted to the problem of selecting students for international exchange programs. Using IDEF0 notation, the authors model the business processes of a university's International Office in "as-is" and "to-be" states and develop a multi-criteria analysis model with weighting coefficients that eliminates the subjectivity and bottlenecks of the current selection procedure.

Valery Krasnov and Nikita Tsmugunov compare two architectural approaches to building intelligent agents based on large language models for transport management – deep integration with a corporate TMS and rapid low-code development on the n8n platform. The authors demonstrate that both solutions rely on a unified five-stage cognitive agent model and a hybrid architecture, yet differ fundamentally in payback speed and scalability.

Lev Kislyuk turns to the endogenous stability of token supply in algorithmic blockchain protocols. The author constructs a differential equation for circulating supply with feedback loops from issuance, burning, and staking, derives a sufficient stability condition using the Lyapunov method, and validates it on Ethereum data, proposing the resulting parameters as disclosure metrics under the MiCA regulation.

The fourth article by **Alena Yakovleva** compares the patterns of the international NIST Cybersecurity Framework 2.0 standard with the requirements of FSTEC Order No. 31. The article develops a correspondence matrix between CSF functions and groups of information security measures, shows that coverage of the Order's functions ranges from 40-60% for class K3 to 95–100% for class K1, and proposes a gap-analysis methodology for the practical integration of the two approaches.

Qinqin Liu writes about architecture and mathematical apparatus of a decision support system for marketplace sellers. The author proposes a model in ArchiMate notation covering four seller roles and four decision scenarios, together with a mathematical apparatus based on discrete-time hazard models and the Kolmogorov–Gabor polynomial for forecasting buyer behavior.



Finally, **Gleb Osipov** examines patient data management in a commercial multidisciplinary clinic. Based on an audit of the information infrastructure, the author describes procedures for data deduplication and profiling, builds a KPI system grounded in the Balanced Scorecard, and applies RFM segmentation to identify patients at high risk of churn, estimating the economic effect of customer base retention.

We hope that the works presented in this issue will prove useful to both researchers and practitioners working at the intersection of technology and economics.

Igor V.Ilin,
Editor in Chief, DrSc, Prof.

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APPLICATION OF THE MULTI-CRITERIA ANALYSIS METHOD TO OPTIMIZE THE SELECTION OF STUDENTS FOR INTERNATIONAL EXCHANGE PROGRAMS

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Abstract. This article provides a comprehensive analysis and subsequent optimization of the activities of the International Office operating in the structure of one of the institutes of Peter the Great St. Petersburg Polytechnic University. The relevance of the research is due to the need to increase the effectiveness of the selection of candidates for international academic programs in the face of increasing competition and stricter requirements for the quality of training of participants. The IDEF0 functional modeling methodology was chosen as the main research tool which made it possible to describe and structure the current business processes of the department in detail, fixing their AS-IS state. The analysis of the constructed models revealed a number of systemic problems and "bottlenecks" related to the subjectivity of decision-making and the lack of formalized criteria for evaluating applicants. The logical solution to eliminate the identified shortcomings was the development of a multi-criteria analysis model which formed the basis for creating improved processes in the "as it should be" state. In the practical part of the study, a system of evaluation criteria and corresponding weighting coefficients reflecting the university's priorities was elaborated in detail. The approbation of the developed model based on the hypothetical data of the students confirmed its efficiency, objectivity and practical significance for improving the quality of selection. The final conclusions substantiate the prospects and the possibility of further scaling the proposed model for the needs of other structural divisions of the university and similar organizations.

Keywords: unified university identity, interdisciplinary enrichment, business process modeling, IDEF0 notation, bottlenecks, multicriteria analysis methods, correction factor

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Научная статья
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ПРИМЕНЕНИЕ МЕТОДА МНОГОКРИТЕРИАЛЬНОГО АНАЛИЗА ДЛЯ ОПТИМИЗАЦИИ ОТБОРА СТУДЕНТОВ НА МЕЖДУНАРОДНЫЕ ПРОГРАММЫ ОБМЕНА

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Аннотация. В данной статье проводится всесторонний анализ и последующая оптимизация деятельности Международного офиса, функционирующего в структуре одного из институтов Санкт-Петербургского политехнического университета Петра Великого. Актуальность исследования обусловлена необходимостью повышения эффективности отбора кандидатов для международных академических программ в условиях растущей конкуренции и ужесточения требований к качеству подготовки участников. В качестве основного инструмента исследования была выбрана методология функционального моделирования IDEF0, позволившая детально описать и структурировать текущие бизнес-процессы подразделения, зафиксировав их состояние «как есть». Проведенный анализ построенных моделей выявил ряд системных проблем и узких мест, связанных с субъективностью принятия решений и отсутствием формализованных критериев оценки претендентов. Логическим обоснованным решением для устранения выявленных недостатков стала разработка модели многокритериального анализа, которая легла в основу создания усовершенствованных процессов в состоянии «как должно быть». В практической части исследования была детально проработана система оценочных критериев и соответствующих весовых коэффициентов, отражающих приоритеты университета. Апробация разработанной модели на основе гипотетических данных студентов подтвердила её работоспособность, объективность и практическую значимость для повышения качества отбора. В заключительных выводах обосновывается перспективность и возможность дальнейшего масштабирования предложенной модели для нужд других структурных подразделений университета и аналогичных организаций.

Ключевые слова: единая университетская идентичность, междисциплинарное обогащение, моделирование бизнес-процессов, нотация IDEF0, «узкие» места, методы многокритериального анализа, поправочный коэффициент

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Introduction

Academic mobility programs for students have always been very popular. However, in the last few years the number of students participating in such programs has decreased significantly due to both the epidemiological situation and geopolitical reasons. Nevertheless, the current situation has contributed to the search for a new vector of development. Over the past couple of years the number of partners in the Asian region and Latin American countries has increased dramatically (Nikolaev, 2025). The field of education is no exception: many universities conclude long-term cooperation agreements and implement joint development programs. Students go on semester-long exchange programs in countries such as China, Thailand, Indonesia, Ar-

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gentina, Brazil and Mexico (Grebennikova, 2020; Ryazantsev, 2019; Moilashova, 2021).

This article examines the problem of selecting students to participate in semester academic mobility programs using the example of the International Office of the Institute of Industrial Management, Economics and Trade (hereinafter – IIMET). Peter the Great St. Petersburg Polytechnic University (hereinafter – SPbPU). The solution to this issue is quite relevant for a number of reasons. First, with each semester, there is an increasing interest among students of various educational programs in the possibility of studying abroad. Secondly, partner universities set quotas for the number of students they can host. All this requires an improvement in the student selection procedure, which now takes into account only the average score and the level of English language proficiency (Kryuchkova, 2024; Kvasova, 2022; Varavva, 2021).

In addition, it is worth noting the need to attract to exchange programs not only students of international educational programs who study in English but also from other areas of study. All this may be a manifestation of the struggle against elitism, the desire for interdisciplinary enrichment and the formation of a unified university identity (Dolgova, 2025; Minaeva, 2022).

Thus, the purpose of this work, using the example of the IIMET of SPbPU International Office, is to consider the possibility of creating a multi-criteria analysis model that takes into account not only such factors as academic performance and English language proficiency but also other equally important aspects. The development of such a model will allow for a more objective approach to the student selection process, ensure their interest and select the best candidates (Dolganova, 2019; Kurbatskiy, 2019).

To achieve this goal, it is necessary to solve some tasks. First, using business process modeling, the first stage of participation in academic mobility programs in the "as is" state will be considered in detail. Secondly, on the basis of this model, "bottlenecks" will be identified and a model in the "as it should be" state will be developed, that is, an improved student selection process will be proposed. Thirdly, using the method of expert assessments, a system of criteria will be determined and their weighting coefficients will be assigned.

Materials and Methods

Scientific articles and textbooks by other authors in the field of business process modeling and multi-criteria analysis will be used as materials. In addition, statistical data will be used in the work.

To achieve the research objectives, sign modeling will be used. Special models will be created using the IDEF0 notation to find "bottlenecks" in business processes taking place in an International Office. A visual representation of business processes will allow to effectively identify places that require optimization and implementation of quality management tools. In addition, using models, it will be possible to present business processes in the "as it should be" state in order to evaluate the effectiveness of the proposed solutions and identify opportunities for further improvement (Kurbatskiy, 2019; Farshatova, 2022; Frolov, 2026).

Analysis and synthesis methods will be used to eliminate "bottlenecks" in business processes. By analyzing all the elements of the obtained business process models it will be possible to consider them separately and move to a lower level of decomposition.

With the help of synthesis, it will be possible to reassemble all the elements of the model together and see what results the proposed changes will lead to. It will also be possible to evaluate the effectiveness of all transformations.

Results and Discussion

Before proceeding to the direct modeling of business processes it is necessary to understand what the procedure for participation in academic mobility programs is. Thus, several main

stages were identified:

1. Assistance in the preparation of the competition application;
2. Competitive selection;
3. Visa preparation support;
4. Preparation of departure documents;
5. Support during exchange program;
6. Preparation of return documents;
7. Recalculation of learning outcomes.

As part of this work, the focus will be on optimizing the first two processes. However, first we need to present them in an AS-IS state. For this one of the business process modeling notations will be used.

Modeling notations are used to represent the processes taking place in an organization in a standardized and visual way (Zhumaeva, 2025; Nagornaya, n.d.; Baranov, 2022). In the framework of this work the notation IDEF0 (Integration Definition for Function Modeling – functional modeling methodology) will be used. The main characteristics include the following aspects: decomposition support, the principle of dominance, and the allocation of four types of arrows. Let's talk in more detail about each of them.

Decomposition support comes down to the fact that each function can be presented in more detail sequentially, thereby achieving the required level of detail. The principle of dominance means that the blocks are arranged diagonally. This means that the processes located at the top have an impact on those below. Speaking about the four types of arrows, it is worth mentioning that in addition to them the diagrams also contain the blocks mentioned above. The blocks represent processes that have arrows pointing to them on the left, right, top, and bottom. The following types of arrows are distinguished: "Input", "Output", "Mechanism" and "Control". The inputs are processed or used by the function and converted into outputs. There may be materials or requests at the entrance. Mechanisms are the means by which transformation takes place. These are usually personnel and equipment. Management refers to the conditions under which the function is performed. These include legislative acts, regulations, instructions, and rules. The outputs are the results of the process. It can be a product or a service (Lyamin, 2024).

An equally important characteristic of the IDEF0 notation is the presence of a context diagram. This is the topmost diagram representing the activity of the research object in a general way which shows its connection with the external environment (Zhumaeva, 2025; Kaliberda, 2025; Lyamin, 2024; Katkova, 2025). Figure 1 below shows a contextual diagram of the activities of the IIMET International Office.

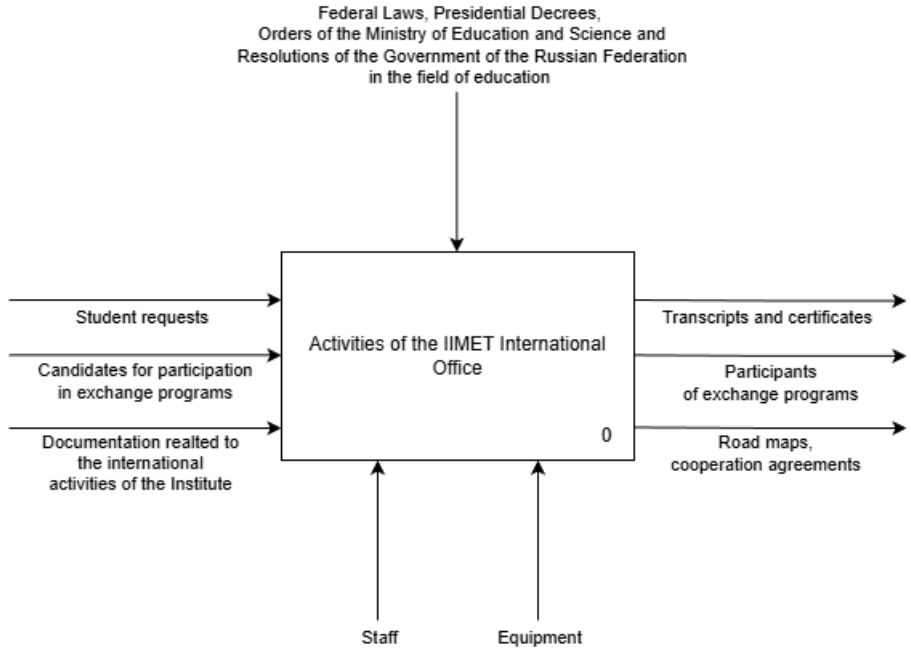


Fig. 1. Contextual diagram of the activities of the IIMET International Office (compiled by the author)

Since the International Office is engaged not only in exchange programs but also in working with the contingent (in particular issuing transcripts of records), as well as carrying out international activities. In this regard, the process landscape will look as shown in Figure 2.

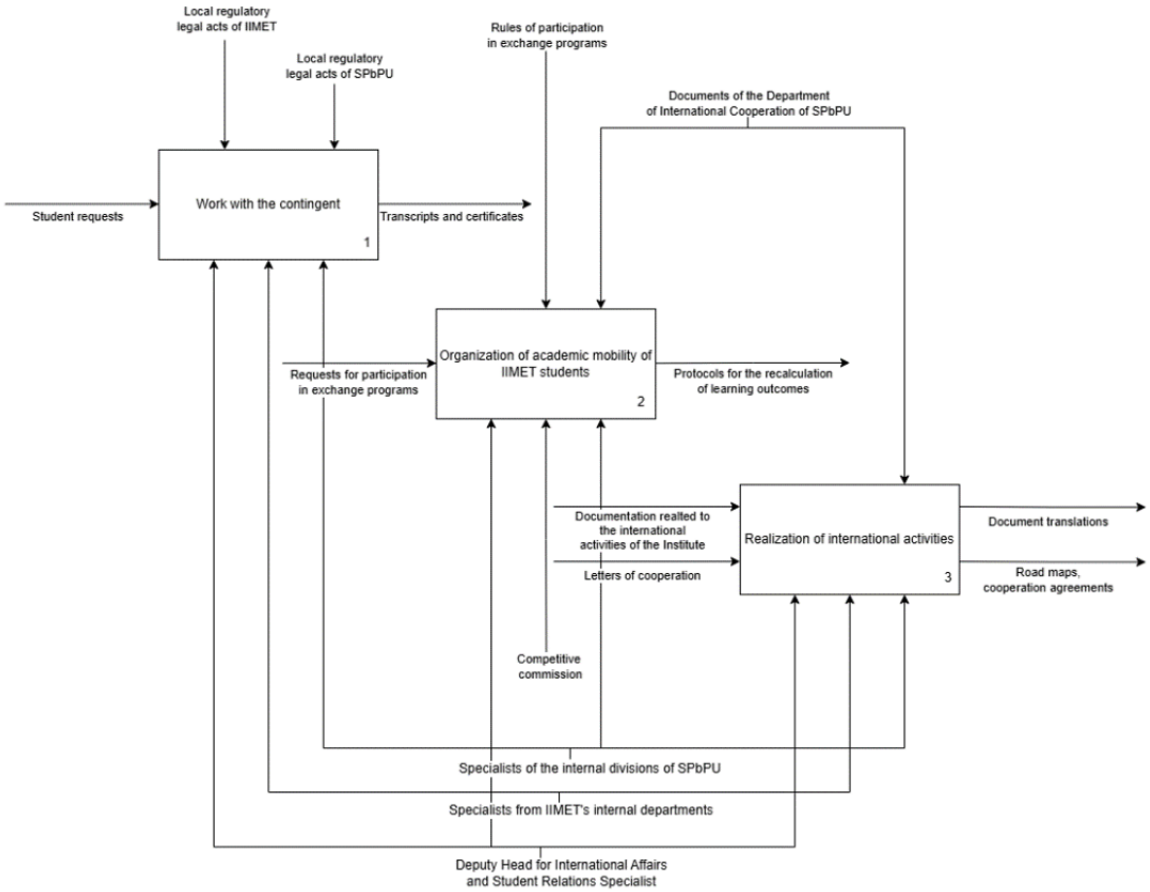


Fig. 2. Process landscape

Thus, the process of organizing and supporting academic mobility of students is central to the international activities of the Institute and involves multi-stage coordination. The initiation is related to the receipt of an external request or an internal student application. The key substantive stage is the formation and verification of the package of accompanying documents. The procedural part includes mandatory coordination at the level of specialists from a student relations specialist to the Deputy Head for International Affairs, which ensures legitimacy and compliance with internal regulations. The result is the official registration of the student's participation in the mobility program supported by the necessary administrative documents.

The process of managing international cooperation at the institutional level is strategic in nature and creates the infrastructure for individual mobility. It includes the stages of establishing partnerships, developing and legally processing bilateral documents – roadmaps and cooperation agreements.

Next, the decomposition of the process "Organization of academic mobility of IIMET students" will be carried out. The result is shown in Figure 3.

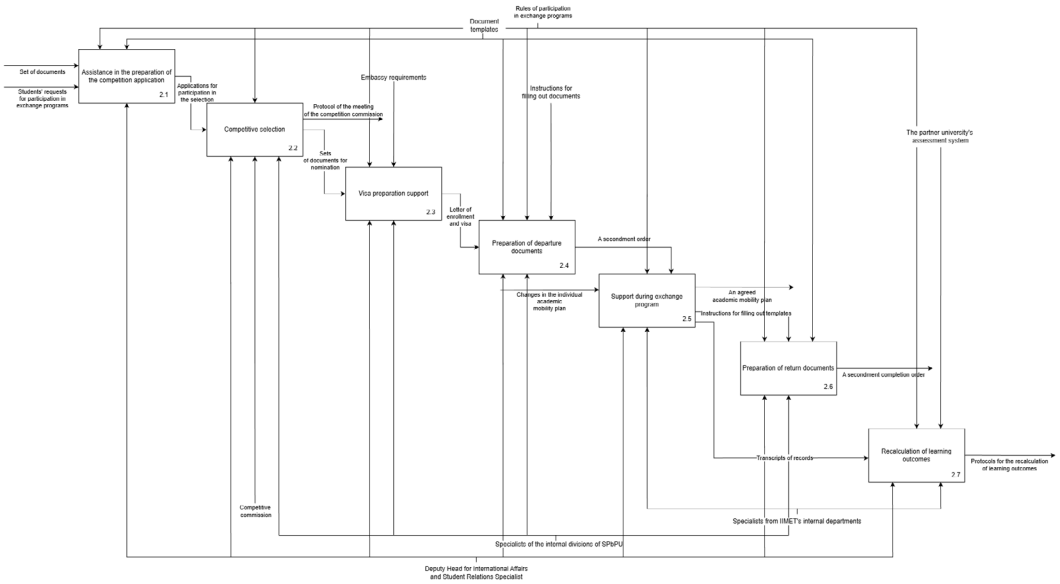


Fig. 3. Decomposition of the process "Organization of academic mobility of IIMET students" in the AS-IS state

As already mentioned, the focus of this work will be on the first two processes: "Assistance in the preparation of the competition application" and "Competitive selection". A sequential decomposition of these processes was performed. The resulting models are shown in Figures 4 and 5, respectively.

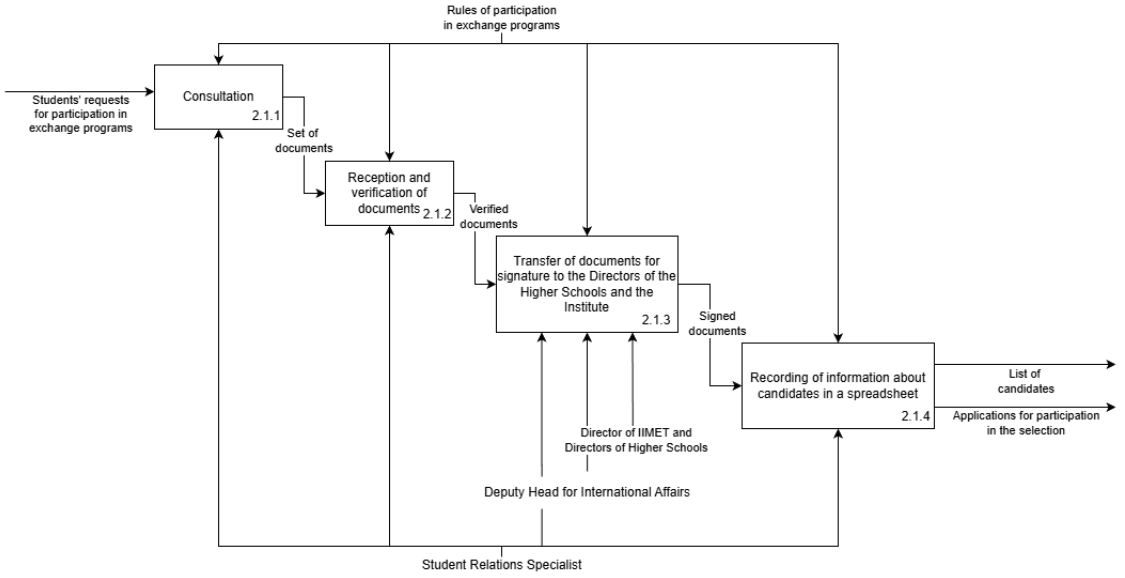


Fig. 4. Decomposition of the "Assistance in the preparation of the competition application" process in the AS-IS state

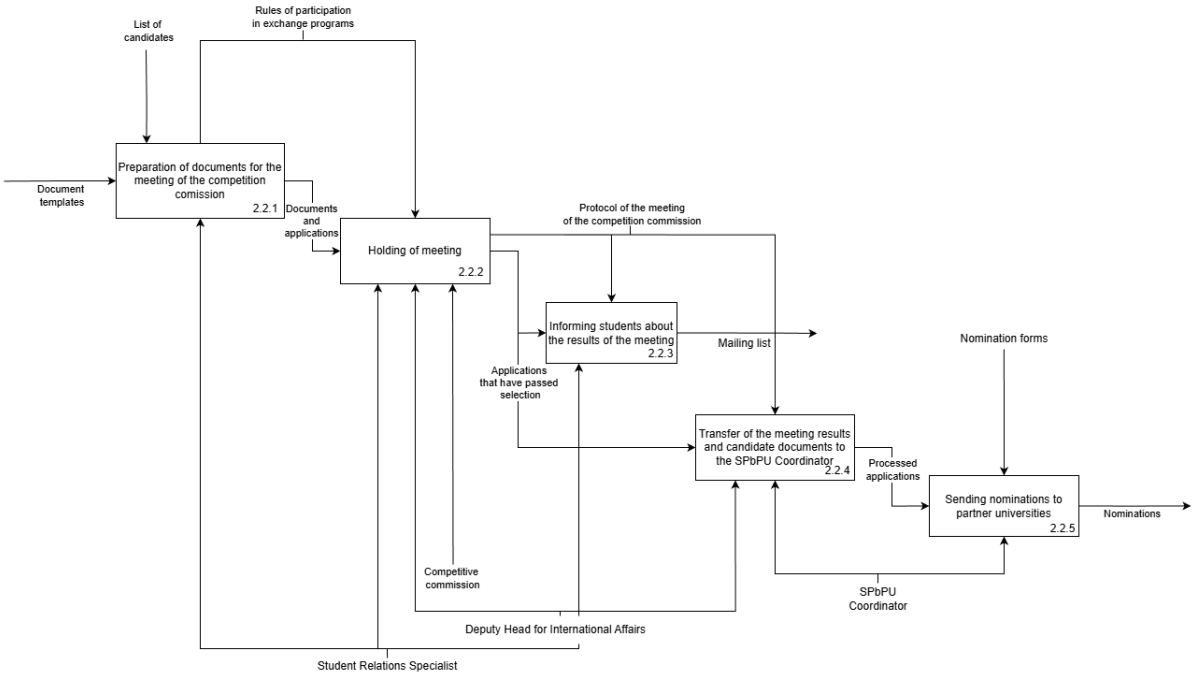


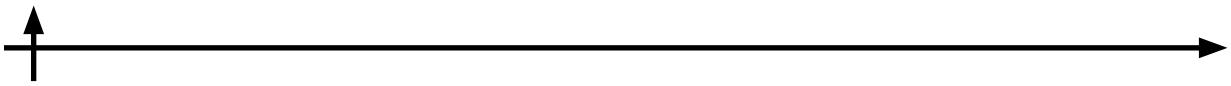
Fig. 5. Decomposition of the "Competitive selection" process in the AS-IS state

When the models are ready in the "as is" state, we can proceed to the search for "bottlenecks". A "bottleneck" is a component of a process that reduces its efficiency. These include the delay in executing operations at a particular stage, excessive resource utilization (both human, technical or financial), as well as unnecessary or duplicative functions. All this leads to higher costs and lower efficiency of business processes (Goncharov, 2023; Lyamin, 2025).

After analyzing the current state of the competition application preparation and selection processes the following "bottlenecks" can be identified:

1. excessive workload of the institute coordinator who participates in almost all subprocesses;

2. the need to physically transfer documents to a large number of people for approval and signature;



3. as such, there is no need for a meeting of the competition committee, provided that the decision on the nomination in the AS-IS state is made on the basis of formal criteria, that is, the average score and the level of English language proficiency.

Taking into account the requirements put forward by the Institute's management to increase the number of students in international educational programs, the following solution may be proposed to eliminate the identified problems. To improve the selection process, a special model has been developed that takes into account criteria such as the average score, the level of knowledge of English (or another foreign language depending on the program and the country where the partner university is located), the training program at the home university, as well as individual achievements.

Given that, as already noted, the number of students interested in exchange programs increases with each semester, this model will greatly simplify the selection process. In addition, using such a tool will eliminate the need for meetings of the competition committee. And if you consider that the deadlines for submitting documents from universities vary, this forces you to conduct them several times during the semester. Given the workload of the commission members, their holding is not always convenient and the presence of all participants is not always guaranteed. The introduction of such a model would also reduce the workload of the institute's coordinator who would no longer need to record information about those who wish to participate in a large number of tables.

In order to create a model, you need to follow certain steps. First of all it is necessary to develop a system of criteria that would allow for a comprehensive understanding of both the student's academic activities and his personal qualities. The following points were proposed as criteria:

1. Average score (K1) is the average score for the entire period of study. The average score will simply be multiplied by the weighting factor.

2. Foreign language proficiency level (K2) – certificates of third-party exams or an internal university exam confirming the level of language proficiency not lower than B2. If a student applies for a program implemented in another foreign language it is necessary to take into account the requirements of the partner university. Since B2 is the minimum for participation in the competition 1 will be given for it. For each subsequent level 0.1 will be added to one.

3. Motivation and extracurricular activities (K3) – having a portfolio and motivation letter. If a student is engaged in extracurricular activities then he will be given 1 for this, if not, then 0.

4. Compliance of the exchange program with the curriculum (K4) – since the sending university is interested in students returning with results, the recommended number of credits in the individual academic mobility plan is 20. However, if the head of the educational program agrees on a plan with fewer units, the International Office will also accept them. Nevertheless, it is worth noting that in this case the probability of an increase in the academic difference grows which the student will have to eliminate within the time limits set by the institute's directorate after his return. This leads to an increased burden on both the student and the teaching staff, as well as the administration. In this regard, it is logical to take into account the number of disciplines selected at the stage of submitting documents. All other things being equal, a student with a larger number of disciplines will have a higher chance of being selected for a limited number of places individually. Since the number of credits may vary depending on the fields of study students who have at least 18 credits in their individual plans (which is the average) will receive 1. Otherwise, 0.8.

The next step is to determine the weighting coefficients of each criterion. It is important to note that the sum of the weights of all criteria should be equal to 1. Thus, we get the following values:

1. For the first criterion (K1), the weighting factor (W1) will be 0.35.
2. For K2 − W2 = 0.3.
3. For K3 − W3 = 0.2.
4. For K4 − W4 = 0.15.

When checking, we make sure that the amount is indeed 1:

$$W_1 + W_2 + W_3 + W_4 = 0.35 + 0.3 + 0.2 + 0.15 = 1$$

You also need to enter a correction factor (P). It will take into account the student training program: for candidates from international educational programs, it will be equal to 1, that is, neutral. For students from other programs this coefficient will be 1.05. This coefficient is not intended to discriminate against the first group of candidates but rather to equalize the opportunities of those who do not have frequent access to language practice.

Thus, the mathematical model for calculating the final score (R) and assigning a rank will look like this:

$$R = (K_1 * W_1 + K_2 * W_2 + K_3 * W_3 + K_4 * W_4) * P$$

To test the model, let's look at an example. Let's say 5 students with the data shown in Table 1 apply to one university for an exchange program.

Table 1. Student data

Student's No.	Criteria				
	Average score	Language proficiency	Motivation and extracurricular activities	Compliance of the exchange program with the curriculum	International Educational Program
1	4,25	B2	+	18 ECTS	−
2	4,75	B2	+	17 ECTS	+
3	5	B2	+	21 ECTS	−
4	4,4	B2	−	18 ECTS	+
5	4,25	C1	+	18 ECTS	+

The next step is to assign points for each criterion. The results are shown in table 2.

Table 2. Assignment of points for each criterion

Student's No.	Criteria				
	Average score	Language proficiency	Motivation and extracurricular activities	Compliance of the exchange program with the curriculum	International Educational Program
1	4,25	1	1	1	1,05
2	4,75	1	1	0,8	1
3	5	1	1	1	1,05
4	4,4	1	0	1	1
5	4,25	1,1	1	1	1

Since a relatively small number of candidates participate in the selection process specialized software is not required. To calculate the results it will be enough to enter the results into a table, for example, MS Excel. The results are presented in table 3.

Table 3. Ranking of students

Student's No.	Criteria					Sum	Rank
	K_1	K2	K3	K4	P		
Weight factor (Wi)	0,35	0,3	0,2	0,15	Correction factor		
1	4,25	1	1	1	1,05	2,244375	3
2	4,75	1	1	0,8	1	2,2825	2
3	5	1	1	1	1,05	2,52	1
4	4,4	1	0	1	1	1,99	5
5	4,25	1,1	1	1	1	2,1675	4

Thus, thanks to the example, it was found that, all other things being equal, a student studying outside of an international educational program would have a slight advantage. Nevertheless, it is worth emphasizing once again that this is just an example of a model that can be used. In real life you will have to consider other criteria and conditions.

Thus, the development of a multi-criteria analysis model for the selection of students participating in the academic mobility program significantly simplifies the procedure itself and reduces the burden on staff.

The decomposition of the process "Organization of academic mobility of IIMET students" in the "as it should be" state would look as shown in Figure 6.

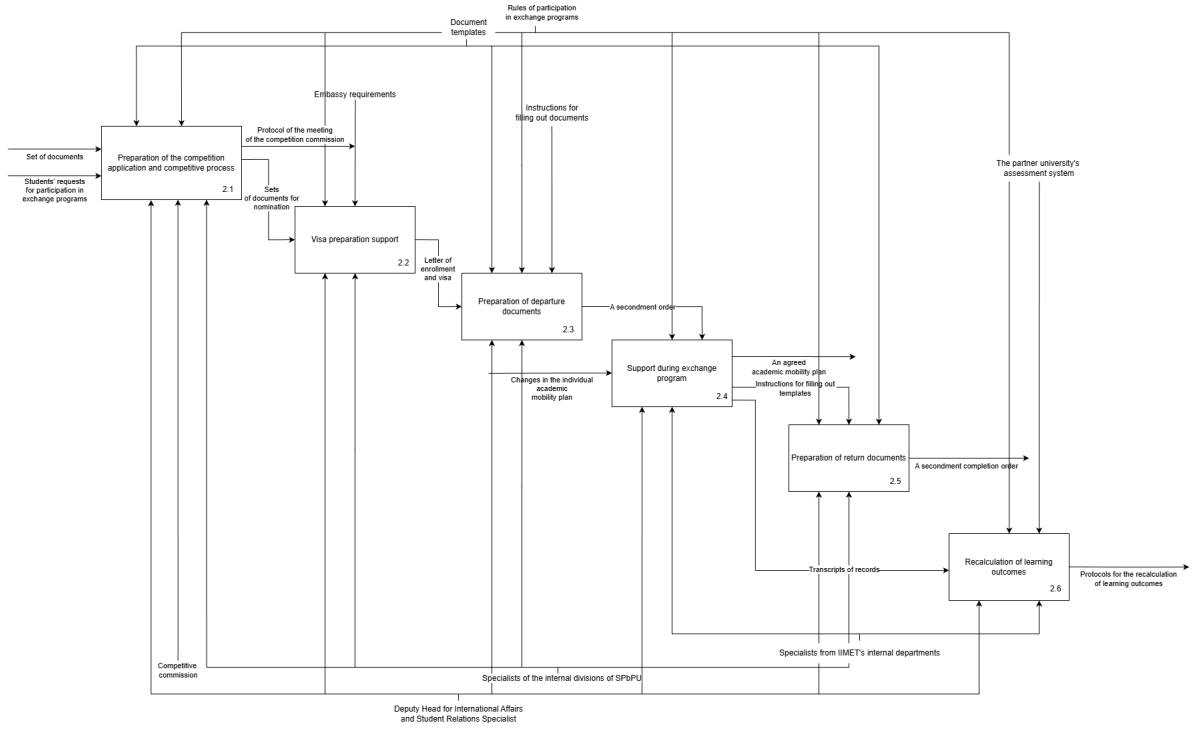


Fig. 6. Decomposition of the process "Organization of academic mobility of IPMEiT students" in the TO-BE state

As can be seen from the figure the processes of " Assistance in the preparation of the competition application " and "Competitive selection" were combined into one – "Preparation of the competition application and selection". Its decomposition is shown in Figure 7 below.

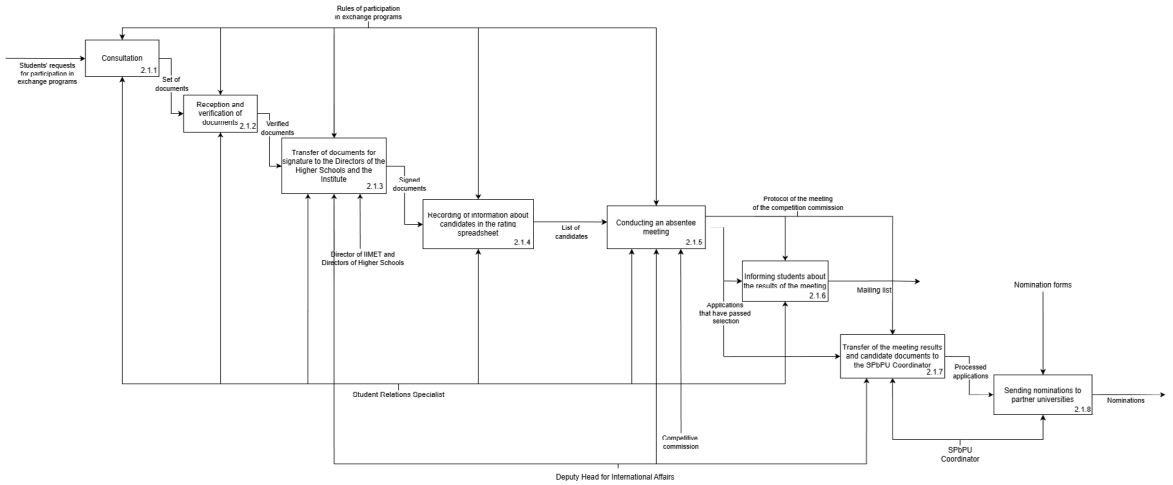


Fig. 7. Decomposition of the process "Preparation of the competition application and selection"

It can be noted that on the presented model there is still a subprocess of the meeting of the competition committee. This is justified by the fact that the decision on the nomination according to the regulations should be made collectively. Nevertheless, it is important to note that in this case the meeting will be held in absentia due to the introduction of a rating table which will calculate the points itself and offer a ready-made decision to the commission.

Now that the solution has been selected we can proceed to develop a model for multi-criteria analysis of alternatives which is a family of mathematical methods that make it possible to choose the optimal or closest to it based on the quantitative characteristics of the proposed options. In the framework of a multi-criteria analysis the alternative is considered as one of the many possible solutions. The criterion is a numerical characteristic describing a given alternative (Goncharov, 2023; Shcheneva, 2025).

Conclusion

During the writing of this article the processes taking place in the international office during the organization of academic mobility programs for students of the Institute were considered in detail. To do this, using the IDEF0 notation, a contextual diagram of the activity of the the object of research and a landscape of processes were created, as well as their decomposition. After analyzing the processes in the "as is" state, "bottlenecks" or problems were identified that significantly reduced the effectiveness of the office in the early stages of program organization. In particular, it was about the high workload of the office coordinator and the duplication of some functions.

As a solution, it was proposed to develop a multi-criteria analysis model that takes into account not only the formal characteristics of students, that is, their academic performance and language proficiency, but also other criteria and conditions. Thanks to this, models were created in the "as it should be" state. They clearly show that after the implementation of the multi-criteria analysis model it will be possible to get rid of several subprocesses thereby avoiding duplication of functions as well as reduce the burden on the coordinator of the institute and the members of the competition committee who will be involved only to resolve controversial issues.

It is worth noting that the multicriteria analysis model developed based on the results of the study really paid off. Taking into account the introduction of additional criteria and weighting factors, it will become relatively easier to select the most suitable candidates. Due to the correction factor the requirement of the director of the Institute to attract students from non-interna-

tional educational programs will be taken into account. The introduction of such a model will be a step towards the formation of a unified university identity and interdisciplinary enrichment.

In addition to all of the above, it is worth noting the huge potential for the implementation of this model. Although the paper considered a relatively simple and understandable example if we complicate the proposed model so that it is more objective and takes into account a larger number of criteria and conditions, it could become part of an entire system with the potential to scale. Thus, the methods discussed in this article can be used to optimize business processes not only of a single international office but also of other larger objects.

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INTELLIGENT AGENTS BASED ON LARGE LANGUAGE MODELS IN TRANSPORT MANAGEMENT: A COMPARATIVE ANALYSIS OF APPROACHES TO DEVELOPMENT AND IMPLEMENTATION

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Abstract. The paper addresses the "information gap" between objective telemetry data and primary documentation in logistics and road construction, which arises from the growing volume of unstructured information and a shortage of qualified personnel. Two projects aimed at creating intelligent agents to bridge this gap in transport management are examined. Based on a comparative analysis of two implemented solutions, the study identifies common architectural principles. The first project (technical proposal stage) develops an AI-powered dispatcher assistant that automatically collects and matches requests from external channels with an internal TMS system via deep API integration. The second project (working prototype) implements a workflow on the low-code n8n platform that extracts, normalises, and compares GLONASS PDF data with accounting records. Both agents share a unified five-stage cognitive agent model and a hybrid architecture combining a large language model with deterministic logic. The two solutions differ fundamentally in their integration paradigm: deep API integration versus low-code assembly. This difference determines development speed, total cost of ownership, and scalability. The low-code prototype achieves a payback period of less than one month, while deep integration offers greater customisation and ERP connectivity at significantly higher initial cost. Criteria for selecting an architectural approach are formulated based on the maturity of a company's IT landscape. These criteria enable a strategic choice between deep integration and low-code development depending on business priorities, infrastructure readiness, and available resources.

Keywords: intelligent agents, large language models, operational efficiency, logistics, road construction, low-code platforms, dispatch management, transportation auditing, digital divide

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ИНТЕЛЛЕКТУАЛЬНЫЕ АГЕНТЫ НА ОСНОВЕ БОЛЬШИХ ЯЗЫКОВЫХ МОДЕЛЕЙ В УПРАВЛЕНИИ ТРАНСПОРТОМ: СРАВНИТЕЛЬНЫЙ АНАЛИЗ ПОДХОДОВ К РАЗРАБОТКЕ И ВНЕДРЕНИЮ

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Аннотация. В статье рассматривается «информационный разрыв» между объективными телеметрическими данными и первичной документацией в логистике и дорожном строительстве, возникающий из-за растущего объема неструктурированной информации и нехватки квалифицированного персонала. Рассматриваются два проекта, направленные на создание интеллектуальных агентов для преодоления этого разрыва в управлении транспортом. На основе сравнительного анализа двух реализованных решений в исследовании определены общие архитектурные принципы. Первый проект (этап технического предложения) разрабатывает помощника диспетчера на базе ИИ, который автоматически собирает и сопоставляет запросы из внешних каналов с внутренней системой управления транспортом (TMS) посредством глубокой интеграции API. Второй проект (рабочий прототип) реализует рабочий процесс на платформе n8n с низким уровнем кодирования, который извлекает, нормализует и сравнивает данные PDF-файлов ГЛОНАСС с бухгалтерскими записями. Оба агента используют единую пятиступенчатую когнитивную модель агента и гибридную архитектуру, сочетающую большую языковую модель с детерминированной логикой. Два решения принципиально различаются по парадигме интеграции: глубокая интеграция API против сборки с низким уровнем кодирования. Это различие определяет скорость разработки, общую стоимость владения и масштабируемость. Прототип с использованием подхода low-code окупается менее чем за месяц, в то время как глубокая интеграция предлагает большую возможность индивидуальной настройки и подключения к ERP-системе, но со значительно более высокими первоначальными затратами. Критерии выбора архитектурного подхода формулируются на основе зрелости ИТ-инфраструктуры компании. Эти критерии позволяют сделать стратегический выбор между глубокой интеграцией и разработкой с использованием low-code в зависимости от приоритетов бизнеса, готовности инфраструктуры и имеющихся ресурсов.

Ключевые слова: интеллектуальные агенты, большие языковые модели, операционная эффективность, логистика, дорожное строительство, платформы с низким уровнем кодирования, управление диспетчеризацией, транспортный аудит, цифровое неравенство

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Introduction

Enterprises that intensively use transport and technical resources face a persistent contradiction. This contradiction is defined in this study as the “information gap” - the divergence between objective telemetry data and primary documentation. On one hand, physical processes: cargo movement, construction equipment operation, material consumption are tracked by

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high-precision satellite monitoring systems (Rassadkin, 2023), fuel level sensors, and video cameras. On the other hand, the document flow accompanying these processes remains predominantly paper-based or poorly structured electronic. On the other hand, the document flow accompanying these processes remains predominantly paper-based or poorly structured electronic. Data from satellite monitoring system reports arrive in disparate formats, requiring manual reconciliation with objective telematics readings. This "information gap" between instrumental monitoring and primary accounting results in losses amounting to millions (Ashurkina, 2025) due to undetected overbilling, suboptimal routing, and the diversion of qualified personnel to routine operations. As noted by Akishin and Chemeris (Akishin and Chemeris, 2026), the shortage of qualified personnel and technological import dependence are key factors that make the economic evaluation of AI agent deployment particularly critical for Russian logistics and construction companies.

Modern large language models and automation platforms have reached a level of maturity that allows for the creation of intelligent agents capable of processing unstructured documents, extracting meaningful information from them, and performing logically complex comparisons and calculations. Beyond logistics, similar agent based approaches have been applied to public health supply chains (Levina et al., 2024), demonstrating the cross industry potential of LLM enabled automation. However, the scientific literature does not sufficiently address the practical issues of selecting an architectural approach to creating such agents for real-world enterprises.

The purpose of this article is to present and compare the results of two completed AI agent development projects, both focused on solving similar transportation management tasks, but implemented using different technical paradigms: deep integration with a corporate TMS system and rapid low-code development on an independent platform. Based on a comparative analysis, common methodological principles and factors determining the choice of architectural solution are identified.

Materials and Methods

Each project under consideration, despite differences in subject areas, employs a unified conceptual model of an intelligent agent rooted in concepts of a rational agent from artificial intelligence theory. An agent is defined as a system capable of perceiving the environment through sensors and input channels and acting upon it via actuators and output interfaces to achieve its objectives (Xi et al., 2025).

As applied to transport control and dispatching tasks, the agent model is decomposed into five sequential stages that form a complete processing cycle for a unit of input information:

1. Perception. Monitoring target data repositories - network folders, cloud drives, and APIs - for the appearance of new documents or messages. Selectivity is ensured by maintaining a registry of processed files;

2. Semantic analysis. Extracting the text layer from PDF documents, performing OCR recognition if necessary, and feeding it into a large language model (LLM) along with a prompt containing a list of target attributes, such as date, license plate number, timestamps, and transaction type, after which the model returns a structured JSON array;

3. Transformation and normalization. Converting extracted values to a uniform format, cleaning them of artifacts, and applying the necessary business rules established in standard contracts with counterparties;

4. Matching and logical inference. Joining normalized data from heterogeneous sources by key fields and calculating discrepancies;

5. Interpretation and action. Generating a conclusion - a text comment, a recommendation to the dispatcher, or a claim report and transmitting it to the target system: Google Sheets, the

TMS interface, or a messenger.

A key architectural feature of the model is its hybrid nature (Bulaev and Burtsev, 2025; Ilin at al., 2018; Ilyin et al., 2015): fuzzy tasks requiring semantic understanding are delegated to the language model, while deterministic business logic, validation rules, and arithmetic calculations are implemented in imperative code (Akishin and Chemeris, 2026; Mehri, 2026), which minimizes the risk of LLM "hallucinations" and ensures the correct reproducibility of results.

This hybrid architecture is both domain-agnostic and scalable: adapting it to a new business context requires only modifying the LLM prompts and the set of normalizing functions, without restructuring the core data pipeline. This modularity aligns with the principles of data-driven process automation in digital organizations.

Results and Discussion

Case Study 1: AI Assistant Project for a Logistics Company Dispatcher.

Analysis of the Current State and Identified Bottlenecks.

The subject of the first study was logistics company "V" - one of Russia's leading operators with a fleet of 638 vehicles and over 5,000 daily deliveries, where the dispatch service, which processes freight transport requests from customers, serves as the central hub of operational management. The "as-is" dispatching process was modeled using observation, timing, and interviews with five dispatchers. The identification of systemic bottlenecks (multi-channel communication, incomplete utilization of AI modules, lack of a knowledge base) follows the content-analysis, based methodology for detecting problem zones in business processes proposed.

The average processing time for a single request, from receipt to vehicle assignment, was 2 hours and 45 minutes. The distribution of time across stages is presented in Table 1.

Table 1. Distribution of working time for a dispatcher at logistics company "V" (source: compiled by the authors based on time-motion study results)

Request processing stage	Share of total time, %	Average duration, min
Request registration and verification	15	25
Planning and routing	15	25
Finding and Engaging a Carrier	36	60
Negotiating and selecting a carrier	15	25
Assignment and documentation	19	30
Total	100	165

The analysis identified five systemic bottlenecks:

1. Multi-channel communication. The dispatcher is forced to simultaneously monitor the internal VEZUBR platform and other external freight exchanges, messaging apps where communication with counterparties and customers takes place, and phone calls. Up to 20% of offers from carriers go unanswered (Ashurkina, 2025) or are processed with a delay of more than an hour;

2. Incomplete utilization of the potential of existing AI modules. The VEZUBR TMS platform includes microservices for routing and contractor scoring, but these are not integrated with external data feeds and operate only within the system;

3. Lack of a systematic knowledge base on carriers. Information on reliability, history of failures, and personal agreements is stored exclusively in dispatchers' memories;

4. Lack of a formalized handover process between shifts, leading to duplication of work and loss of context with a 12-hour shift schedule;

5. Limited scalability. Productivity depends heavily on the individual experience and established connections of a specific specialist and does not increase linearly with an increase in staff.

Architectural Solution and Functional Requirements.

Based on the identified problems, the goal was formulated to develop an AI dispatcher assistant operating on a "human-in-the-loop" principle. The assistant does not replace the dispatcher but relieves them of the burden of monitoring multiple channels and performing initial processing of requests.

Architecturally, the assistant is a software module integrated with the VEZUBR TMS (Korus Consulting, 2025b) via an open API, as well as with the APIs of messengers and e-commerce platforms. The proposed technical stack includes Whisper for transcribing voice messages, models from the BERT (Zaykob and Ivanov, 2025) family for intent classification, the Natasha/SpaCy library for named entity extraction, and a large language model such as GPT-4 or LLaMA-3 for semantically matching proposals with requests.

The functional requirements for the assistant include:

— Automatic data collection from external channels (automatic data collection from work chats, exchanges, and email);

— Natural language processing: extracting parameters from messages and structuring them;

— Intelligent Matching: Automatic matching of incoming offers with open requests in VEZUBR based on route, date, and cargo type;

— Ranking of options and calculation of a comprehensive carrier rating based on price, score, and dispatchers' subjective evaluations;

— Proactive notification of the dispatcher in a unified interface about relevant offers with the ability to assign a carrier with a single click.

Expected Effectiveness.

The projected impact is based on benchmarks of similar systems and data from time-tracking studies. Expected results:

— A 30-40% reduction in average request processing time (to 1 hour 40 minutes);

— A 60-70% reduction in labor costs for monitoring communication channels;

— An increase in request conversion rates from 78% to 85-88%;

— The projected payback period for the development, estimated using the TCO methodology, is 4 to 7 months.

Case 2: Development and implementation of an AI agent for auditing construction equipment performance.

Issues and analysis of the audit process.

The subject of the second study was the "Monitoring of Rental Construction Equipment Operation" process at the road construction company "DSK." The company operates a fleet of over 400 units of rental equipment (Ovsyannikova, 2025). In accordance with the contracts, contractors provide GLONASS satellite monitoring reports upon request. The task of the financial and economic audit department is to verify the times indicated in the trip logs against the actual time the equipment spent in the project sites' geozones, identify overbilling, and initiate the recovery of overpaid funds.

An analysis of the AS-IS model showed that with a standard department staff of 3 people, the monthly labor costs for verifying just one piece of equipment (at 4 minutes and 20 seconds per machine-day) amount to 127.5 man-hours, which is equivalent to 0.74 full-time positions. During the peak construction season, due to strict contractual deadlines, only about 10% of equipment units undergo a full inspection. The total amount of funds identified and recovered per season is approximately 2 million rubles, which, according to management estimates, is only one-tenth of the potential volume of recoveries.

The key challenges of the process are: a lack of time for comprehensive inspections, the multi-step process of obtaining GLONASS reports through the logistics department and contractors, the high labor intensity of manually extracting data from PDF reports in various formats, and the lack of automated application of contractual time-rounding rules.

Implementation of the agent on the n8n low-code platform.

To drastically reduce labor costs, an AI agent was designed and deployed using a self-hosted version of the n8n low-code platform. The platform runs on a virtual private server with Ubuntu 22.04 inside a Docker container. The choice of platform was based on a comparative analysis of alternatives - Make, Zapier, LangFlow, and Flowise - using criteria of technical feasibility, economic viability, and compliance with corporate requirements (Stepik, 2026; Korus Consulting, 2025a) (Table 2).

Table 2. Comparative Analysis of Automation Platforms (Excerpt) (source: authors' analysis)

Criteria	n8n	Make	Zapier	LangFlow
Google Drive Trigger	+	+	+	+
LLM integration (native)	+	+	+	+
Self-hosting (free)	+	-	-	+
Customization (JS/Python)	+	-	-	+
Total cost over 3 years, thousand rubles	~60	from 200	From 250	~80

The agent's workflow implements a full processing cycle (Kazantsev, 2025) corresponding to the model described in Section 1. The process is initiated by the "Google Drive - On New File in Folder" trigger when a new PDF report appears in the designated folder. The sequence of nodes includes:

— "Get File," downloading the binary content;

— "Extract from File," extraction of the text layer;

— "JSON Parse", "Normalize & Round";

— "Comment Builder," a JS node that generates a text comment based on movement intervals;

— Subsequent validation (Sizov, 2025) and writing to a Google Sheet whose name matches the source file name.

The logic for rounding and duration calculation is completely moved from the LLM to deterministic JavaScript code, which guarantees its immutability and eliminates the risk of "LLM hallucinations" in operations critical to financial calculations. The system also includes a log of processed files and a notification module that sends alerts to the Telegram messenger upon completion of processing or in the event of an error.

Results of the experimental testing.

The validation was conducted on a representative sample of 300 anonymized GLONASS reports (Zaykov and Ivanov, 2025) covering the period from March 1 to May 10, 2026, of which 9 had non-standard structures, such as missing columns, manual edits, or continuous text. The reference values, which serve as examples, were prepared manually by an employee of the financial and economic audit department. The key results are summarized in Table 3.

Table 3. Results of the experimental processing of 300 reports (source: experimental results obtained by the authors)

Indicators	Values
Average processing time per report	3 min 12 sec
Date extraction precision	99.3%
License plate extraction precision	97.0%
Shift start time extraction precision	98.7%
Precision of shift end time extraction	98.3%
Completeness of day retrieval	100%
Percentage of errors correctable by post-validation	1.3%

All recorded hallucinations, namely 3% of cases, occurred in a separate sample of non-standard documents; for files with manual edits, the agent generated the recommendation “full manual review required.” The average processing time for a single report - 3 minutes and 12 seconds - stands in stark contrast to the 1 hour of manual labor required for similar work.

The economic effect is assessed based on two components. Direct savings from freeing up staff - 0.74 full-time equivalent of an audit specialist - amount to approximately 799,000 rubles per year. The main benefit stems from loss prevention: as the proportion of inspected equipment increases from 10% to 60% or higher, a conservative estimate of additional refunds for the construction season is 3.5-4.5 million rubles. Total cost of ownership for the system - including a VPS server, LLM API, and administration - over a 3-year period is estimated at 60,000 rubles, ensuring a return on investment within the first month of implementation.

Comparative analysis of approaches: deep integration vs. low-code development.

The case studies presented demonstrate two fundamentally different approaches to creating an AI agent, the choice between which is determined by the company’s strategy and the maturity of its IT landscape.

The project for Company "V," which involves deep integration, entails embedding an agent into the existing corporate ecosystem. Development is conducted at the API level using a wide range of technologies, such as Whisper, BERT, and LangGraph, and requires the involvement of a skilled development team. The advantages include: maximum reuse of existing TMS modules, a seamless user experience, a high degree of customization, and potential scalability. Among the disadvantages are: a long development cycle, high initial investment, and dependence on the internal IT team and the TMS vendor.

The project for DSK was implemented on the independent n8n platform using standard cloud services such as Google Drive, Google Sheets, and an external LLM provider. Development did not require programming skills, except for writing a few dozen lines of JavaScript code for data normalization. Key advantages: record-low total cost of ownership, rapid implementation, flexibility and ease of modifying logic, and the ability for an analyst to operate the system without IT department involvement. Limitations of the approach include the lack of direct integration with the 1C corporate ERP system, which necessitates manual transfer of final data, as well as dependence on the stability of Google and OpenRouter cloud APIs.

A comparative overview of the approaches is summarized in Table 4.

Table 4. Comparison of architectural approaches to creating an AI agent (source: compiled by the authors)

Comparison parameter	Deep integration	Low-code assembly
Implementation stage	Technical proposal, forecast	Working prototype, testing
Runtime environment	API integration with TMS VEZUBR	Self-hosted n8n on VPS
Technology stack	Whisper, BERT, LLM, Natasha/ SpaCy, LangGraph	n8n, Google Workspace API, DeepSeek (OpenRouter)
Required Qualifications	Data Scientist, ML Engineer, Developer	Analyst (low-code and basic JS)
Initial costs (CAPEX)	High (2.5 million rubles, according to an expert estimate)	Minimal (~10,000 rubles)
Payback period	4-7 months (forecast)	Less than 1 month (actual)
Integration with ERP	Deep, two-way	None (manual transfer to 1C)
Scalability	High within the TMS ecosystem	Horizontal via workflow replication
Vendor lock-in	Dependence on the TMS developer	Dependence on cloud APIs (Google, OpenRouter)

The economic consequences of choosing between integrated and low-code architectures are analyzed in detail by Chemeris, Borremans, and Tick (Chemeris et al., 2023), who conclude that the total cost of ownership for low-code solutions is often an order of magnitude lower for non-core processes. The comparative analysis indicates that the low-code approach is particularly suitable for rapid bottleneck resolution, pilot project implementation, and process automation under constrained IT budgets. Deep integration is justified when the process being automated is at the core of operational activities, requires maximum reliability, end-to-end integration with accounting systems, and long-term strategic development of the IT landscape (ZDM, 2025; Esphere, 2026). It is important to note that these approaches are not mutually exclusive: a low-code prototype can serve as a tool for validating hypotheses before making large-scale investments in deep integration (Bundle, 2026).

Conclusion

The two projects provide clear empirical evidence that modern AI technologies — especially large language models — have reached practical maturity for automating routine data-intensive tasks in transport and construction equipment management. Both successful solutions are based on a single methodology - a hybrid architecture that combines the semantic power of LLMs for analyzing unstructured data with deterministic logic (Paravyan, 2025), implemented in imperative code, to ensure the precision and reproducibility of business-critical calculations.

The practical significance of this research lies in demonstrating two effective, yet resource-intensive, approaches to achieving a single goal: bridging the “information gap” and improving operational efficiency. The choice between deep API integration into the existing TMS ecosystem and rapid solution development on a low-code platform should be determined by the company’s strategic priorities, the maturity of its IT infrastructure, and the availability of qualified personnel. As the second case study demonstrated, low-code tools already enable small and medium-sized businesses to achieve measurable economic benefits (Korus Consulting, 2025a) without significant upfront investment. Future research should focus on developing standard industry solutions that integrate low-code AI agents with enterprise accounting systems (e.g., 1C-class ERP platforms) and on creating unified dashboards with clear, executive-friendly reporting.

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ENDOGENOUS TOKEN SUPPLY STABILITY IN ALGORITHMIC BLOCKCHAIN PROTOCOLS

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Abstract. Three flows govern token supply in blockchain protocols: issuance, burning, and staking lock-ups. We study this supply adjustment mechanism in isolation from price dynamics, treating market returns and on-chain activity as predetermined observables. This design permits analytical examination of supply-side feedbacks without modeling price endogeneity. A representative staker's utility maximization problem yields an equilibrium staking function with a linearly decreasing dependence on market return. From this microeconomic foundation we derive a first-order ordinary differential equation (ODE) for circulating supply with endogenous feedbacks from all three supply channels. The direct Lyapunov method applied to the linearized system yields a closed-form sufficient condition for local asymptotic stability. The condition requires that deflationary absorption (burning plus staking outflow) grows faster with circulating supply than issuance does. The model is then extended to a stochastic differential equation (SDE) via Ito's Lemma, yielding a critical diffusion threshold σ_{crit} below which supply trajectories converge to equilibrium in mean-square. Calibration draws on 1,295 daily Ethereum observations (post-Merge, EIP-1559, 2022–2026). Four sequential OLS regressions are estimated, covering the issuance scale, burning sensitivity, equilibrium staking share, and mean-reversion speed, each with Newey–West HAC correction. The stability parameter $\lambda_{\min}$ is computed analytically from the estimated partial derivatives, and its 95% confidence interval is obtained via block bootstrap (B = 2,000 iterations, block length = 30 days). The stability condition is satisfied empirically: $\lambda_{\min}$ = 0.00274 day^{-1} (95% CI: [0.00175, 0.00373]; P($\lambda_{\min}$ > 0)= 100% by block bootstrap), with a characteristic supply half-life of approximately 253 days and a 13-fold stochastic safety margin ($\sigma_{emp} / \sigma_{crit} \approx 0.077$). Sub-period analysis confirms a structural break at the Shanghai upgrade (April 2023), after which $\lambda_{\min}$ rises to 0.00492 day^{-1}, consistent with the bidirectional mean-reversion mechanism. The stability parameter $\lambda_{\min}$ and the critical diffusion threshold σ_{crit} are proposed as standardized risk metrics for regulatory disclosure under EU Regulation 2023/1114 on Markets in Crypto-Assets (MiCA).

Keywords: tokenomics; blockchain; circulating supply; staking; stability analysis; Lyapunov function; stochastic differential equation; Ethereum; EIP-1559; algorithmic monetary policy

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ЭНДОГЕННАЯ УСТОЙЧИВОСТЬ ПРЕДЛОЖЕНИЯ ТОКЕНА В АЛГОРИТМИЧЕСКИХ БЛОКЧЕЙН-ПРОТОКОЛАХ

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Аннотация. В статье исследуется механизм изменения предложения токенов в блокчейн-протоколах, определяемый тремя эндогенными потоками: эмиссией, необратимым сжиганием токенов и стейкинговыми блокировками. Показатели рыночной доходности и сетевой активности трактуются как заданные наблюдаемые переменные. Анализ проводится без моделирования ценовой динамики, что позволяет изолированно исследовать механизмы обратного воздействия со стороны предложения. Из задачи максимизации полезности репрезентативного стейкера выводится равновесная функция стейкинга с линейной убывающей зависимостью от рыночной доходности. На этой микроэкономической основе строится обыкновенное дифференциальное уравнение (ОДУ) первого порядка для циркулирующего предложения токена с эндогенными обратными связями по всем трём каналам предложения. К линеаризованной системе применяется прямой метод Ляпунова, что даёт достаточное условие локальной асимптотической устойчивости в замкнутой форме. Условие требует, чтобы суммарные дефляционные потоки (сжигание и отток в стейкинг) нарастали по циркулирующему предложению быстрее, чем нарастает эмиссия. Далее модель расширяется до стохастического дифференциального уравнения (СДУ) с применением леммы Ито, что позволяет получить критический порог диффузии σ_{crit}, ниже которого траектории предложения сходятся к равновесию в среднеквадратичном смысле. Эмпирическая верификация выполнена на 1 295 ежедневных наблюдениях по сети Ethereum (пост-Merge, EIP-1559, 2022–2026). Оцениваются четыре регрессии МНК: по параметрам эмиссии, сжигания, равновесной доли стейкинга и скорости возврата к среднему. Все уравнения оцениваются с поправкой Newey–West на гетероскедастичность и автокорреляцию (HAC). Параметр устойчивости $\lambda_{\min}$ рассчитывается аналитически из оценённых частных производных; его 95%-й доверительный интервал (ДИ) получен методом блок-бутстрэп (B = 2 000 итераций, длина блока 30 суток). Полученные результаты подтверждают выполнение условия устойчивости: $\lambda_{\min}$ = 0,00274 сут$^{-1}$ при 95%-м ДИ [0,00175; 0,00373] и вероятности положительного значения 100% по блок-бутстрэп. Характерное время затухания отклонений составляет около 253 суток, запас стохастической устойчивости — 13-кратный ($\sigma_{emp} / \sigma_{crit} \approx 0.077$). Анализ подпериодов выявляет структурный сдвиг после Шанхайского апгрейда (апрель 2023 г.), по итогам которого $\lambda_{\min}$ возрастает до 0,00492 сут$^{-1}$, что соответствует двунаправленному механизму возврата к среднему. Параметр устойчивости $\lambda_{\min}$ критический порог диффузии σ_{crit} предложены в качестве стандартизированных индикаторов риска для раскрытия информации в рамках Регламента ЕС 2023/1114 о рынках криптоактивов (MiCA).

Ключевые слова: токеномика; блокчейн; циркулирующее предложение; стейкинг; анализ устойчивости; функция Ляпунова; стохастическое дифференциальное уравнение; Ethereum; EIP-1559; алгоритмическая монетарная политика

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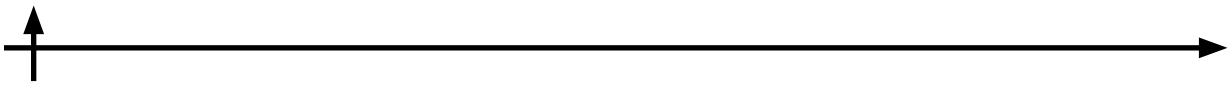


Introduction

Unlike a central bank, a blockchain protocol cannot adjust supply in response to conditions. The rules are fixed at deployment. Issuance schedules, burning triggered by transaction fees, and staking lockups are all driven by validator incentives. Discretionary intervention is not possible. This raises a natural theoretical question: under what design conditions does an algorithmic monetary architecture keep token supply locally stable? We answer this using nonlinear dynamical systems theory.

The question has practical implications. Terra/LUNA (May 2022) (Briola et al., 2023) showed what happens when the issuance loop is misdesigned. The system did not merely fluctuate; it collapsed irreversibly. In contrast, post-Merge Ethereum shows near-equilibrium supply dynamics sustained over four years, making it the primary case for empirical verification. A regulatory aspect reinforces the importance of this question. EU Regulation 2023/1114 on Markets in Crypto-Assets (MiCA) requires issuers of significant asset-referenced tokens to disclose supply management mechanisms. Meeting this requirement is much easier with an analytical criterion than with simulation outputs alone (Kochergin, 2021).

A note on scope: We treat market return *r(t)* and on-chain activity *A(t)* as predetermined observables throughout. We do not model price dynamics.

This is a deliberate choice that isolates supply-side feedback, allowing us to keep stability conditions analytically manageable. The model examines whether the supply mechanism is stable under given price conditions, not whether the entire monetary system is stable. This distinction has been formalized in the literature on DeFi protocols (Werner et al., 2022).

Literature review

Three paradigms mark the existing literature, and each of which has a structural limitation with respect to our task.

The largest research cluster focuses on price. Katsiampa (2017) established the GARCH framework for Bitcoin volatility; subsequent work extended to DCC-GARCH and GARCH-HAR specifications (Silva and Maciel, 2025). Stablecoin studies (Lyons and Viswanath-Natraj, 2023; Saito and Iwamura, 2019) center on price-peg maintenance. None treat $S_t(t)$ as an endogenous variable. It either vanishes from the model or is introduced as an exogenous scaling coefficient. Stability of the supply mechanism itself is simply not the object.

DSGE-based approaches broaden the scope but arrive at the same gap. Asimakopoulos et al. (2023), Schilling and Uhlig (2019), Cong et al. (2021), and Sockin and Xiong (2023) develop rich equilibrium models; Shin (2026) adds a network fragmentation dimension. In each case, token supply appears as an exogenous variable or an accounting identity. It is never the mechanism under study.

Dynamic systems methods are methodologically closest. Cong et al. (2025) model staking with endogenous quantity choice, and we adapt their staking function directly. Oderbolz et al. (2024) study the optimal staking reward design but do not establish an aggregate supply stability condition. Werner et al. (2022) examines Ethereum supply and staking dynamics in a DeFi SoK framework, focusing on pricing instead of an analytical stability threshold. Practical blockchain implementations outside finance, such as in power sector management (Chemeris et al., 2025), similarly require robust token supply mechanisms to ensure predictable operation. Leonardos et al. (2021) apply the Lyapunov method to EIP-1559, though their object is the base fee rather than the total circulating supply $S_t(t)$. Jermann and Xiang (2025), Dong et al. (2026), Zhang et al. (2020), and Caginalp (2018) round out the landscape; none provide a closed-form condition on S_t. The Bitcoin and Ethereum monetary architectures are defined in their foundational documents (Nakamoto, 2008; Roughgarden, 2020).

Research gap

Three things are simultaneously missing from all the above: $S_t(t)$ modeled as a dynamic variable with explicit endogenous feedback and correct staking–burning decomposition; a closed-form sufficient stability condition derived from agent optimization; and numerical verification on real on-chain data. Simulation-based methods cannot deliver the first two by construction.

Objectives

We tackle four tasks: (1) construct an endogenous ODE model for circulating supply with feedback grounded in agent optimization; (2) derive a closed-form sufficient stability condition; (3) extend the model to a stochastic framework and derive the critical volatility criterion; (4) verify all conditions on Ethereum on-chain data.

Section 2 covers model construction, microeconomic foundations, the stability theorem, and the stochastic extension. Section 3 reports calibration results and discusses their implications. Section 4 states the conclusions.

Materials and Methods

2.1 Variable System and Definitions

Four economically distinct supply concepts are required.

Definition 1 (Supply variable system). Total supply $S_{tot}(t)$ — the total quantity of tokens issued by time t per protocol rules. Circulating supply $S_t(t)$ — tokens actively traded in the market. Staked supply $S_l(t)$ — tokens temporarily immobilized in staking contracts; these tokens are not destroyed but are withdrawn from active circulation. Effective monetary supply is defined as follows:

$$S_{eff} = S_c + k * S_l, 0 \le k \le 1 \qquad (1)$$

where k is the staking liquidity coefficient ($k = 0$ in the base case, reflecting full lock-up). Accounting identity:

$$S_{tot}(t) = S_c(t) + S_l(t) \qquad (2)$$

From (2): $\frac{dS_{tot}}{dt} = E - B$. Staking flows redistribute tokens between S_t and S_l without affecting S_{tot}. This distinction matters: irreversible burning reduces S_{tot}, while staking outflow reduces S_t while S_{tot} remains unchanged.

2.2 Microeconomic Foundation of the Staking Function

Staking participation follows from a representative agent's optimization problem. The agent maximizes utility from staking rewards against a risk premium and opportunity cost of alternative investments — the standard tension between yield and forgone alternatives. Strict concavity of the objective in staking share θ guarantees existence and uniqueness of the interior equilibrium $\theta^*(r)$. Linearizing around steady-state return r^*:

$$\theta^*(r) = \delta_0 + \delta_1 * r, \delta_1 < 0 \qquad (3)$$

where $\delta_1 < 0$ reflects staking curve saturation: a higher market return r reduces the attractiveness of staking relative to outside alternatives. Equilibrium position: $S_l^* = \theta^*(r) * S_{tot}$. Since the actual share adjusts gradually, S_l dynamics follow a mean-reversion equation:

$$\frac{dS_l}{dt} = \omega \cdot [\theta^*(r) \cdot S_{tot} - S_l], \omega > 0 \ (day^{-1}) \qquad (4)$$

Linearizing (4) in S_t around equilibrium, with quasi-stationary $\gamma = S_l^* / S_{tot}^*$ so that $\frac{\partial S_l}{\partial S_t} = \frac{\gamma}{1-\gamma} \approx 0.322$, yields the reduced staking outflow:

$$L(S_c, r) \approx \omega \cdot \theta^*\left(\bar{r}\right) \cdot S_c \qquad (5)$$

Remark 1 (Stock-flow distinction). The parameter $\theta^*(r)$ is a dimensionless equilibrium share (stock), while $\omega \cdot \theta^*(r)$ in (5) is the corresponding adjustment flow with units' day^{-1}. Omitting the factor ω would overstate $\partial L / \partial S_t$ by a factor of $1/\omega \approx 89$ and distort the stability param-

eter by three orders of magnitude.

2.3 Model Assumptions

The model rests on five assumptions. (A) Flows E, B, L are twice differentiable in S (local dynamics between structural breaks). (B) Staking response is aggregated through the optimization in section 2.2. (C) Return r(t) and on-chain activity A(t) are predetermined observables; price feedback is absent. This assumption is most defensible in near-equilibrium regimes; at large price shocks, the price–supply feedback becomes material and requires the full three-dimensional extension outlined in Conclusion 6. (D) $\gamma(t) := S_l / S_{tot}$ is quasi-stationary for the one-dimensional reduction; the two-dimensional extension is in section 2.6. (E) All stability results hold locally in $B_\varepsilon(S_t^*)$; large deviations lie outside the linear approximation.

2.4 Baseline ODE for Circulating Supply

Circulating supply dynamics follow the first-order ODE:

$$\frac{dS_c}{dt} = E(S_l(t), A(t)) - B(A(t)) - L(S_c, r(t)) \quad (6)$$

In equation (6), $S_t(t)$ is fully endogenous. The three right-hand terms capture distinct supply mechanisms: issuance $E(S_l, A)$ driven by protocol rules and staking quantity; burning B(A) driven by transaction demand; and staking outflow $L(S_t, r)$ shaped by validator optimization. When the protocol creates more tokens than it absorbs, $dS_t / dt > 0$ — an inflationary regime. The equilibrium S_t^* is the supply level were creation and absorption balance exactly. A rise in S_t increases the absolute volume of L which exerts stabilizing negative feedback. Conversely, an increase in S_t raises S_l through the staking equilibrium, which amplifies issuance through the PoS formula and destabilizing positive feedback. Which mechanism wins determines system stability.

2.5 Functional Specifications

Ethereum (post-Merge, September 2022–present). Issuance under proof-of-stake grows as the square root of staked tokens — diminishing returns to validation, as specified in the Ethereum Beacon Chain protocol (Werner et al., 2022):

$$E_{ETH}(S_l) = \alpha \cdot \sqrt{S_l} \quad (7)$$

The EIP-1559 mechanism (Roughgarden, 2020) burns the base fee irreversibly:

$$B_{ETH}(A) = \beta_0 + \beta_1 \cdot A(t),\ \beta_1 < 0 \quad (8)$$

The negative sign of β_1 is an artifact of data reconstruction via the balance identity, not a reversal of the causal EIP-1559 mechanism; see Appendix A.2. Crucially, $(\partial B_{ETH}) / \partial S_t = 0$ – burning responds to demand, not to supply level directly. The staking outflow from (5):

$$L_{ETH}(S_c, r) = \omega \cdot \theta^*\left(\bar{r}\right) \cdot S_c = \omega \cdot \left(\delta_0 + \delta_1 \cdot \bar{r}\right) \cdot S_c$$

Bitcoin (limiting case). Fully deterministic exogenous architecture: $E_{BTC(t)} = R_0 \cdot 2^{-\left\lfloor \frac{t}{T_{halving}} \right\rfloor}$, $R_0 = 50$ BTC/block. Neither burning nor staking is structurally present; $\frac{\partial E}{\partial S_t} \equiv 0, \frac{\partial (B+L)}{\partial S_t} \equiv 0 \to \lambda_{\min} \equiv 0$. Bitcoin is a degenerate limiting case of neutral monetary architecture without active supply feedback. This is a deliberate design choice of the deterministic monetary rule rather than a structural weakness.

Solana. Gradually declining inflationary issuance $E_{SOL} = \varepsilon_0 \cdot (1-d)^t \cdot S_{tot}$ with partial transaction fee burning. The high staking share (~70%) provides a significant lock-up flow, but identification of ω is complicated by the deterministic historical staking trajectory; results are discussed in section 3.1. Token buyback pricing mechanisms for Solana have been studied from a market-microstructure perspective (Phinney Dominguez, 2025), providing a complementary demand-side view to the supply stability analysis developed here. Extension to Solana and Cosmos remains constrained by the identification challenge for ω under deterministic staking

trajectories; this is a priority for the companion empirical paper.

2.6 Equilibrium Point and Two-Dimensional Extension

The stationary point S_t^* is defined by the zero net-flow condition:

$$E(S_l^*, A^*) = B(A^*) + L(S_c^*, r^*) \quad (9)$$

For Ethereum, equation (9) is transcendental, and must be solved numerically. Uniqueness of the positive root follows from monotonicity: E grows as $\sqrt{S_l^*}(S_t^*)$, which is concave, while the right-hand side grows linearly in S_t^*. Under standard parameter values, they intersect exactly once.

Two-dimensional extension. Relaxing Assumption D by introducing S_l as an explicit second state variable gives:

$$dS_c / dt = E(S_l, A) - B(A) - \varphi_{in} \cdot S_c + \varphi_{out} \cdot S_l \quad (10a)$$

$$dS_l / dt = \varphi_{in} \cdot S_c - \varphi_{out} \cdot S_l \quad (10b)$$

where $\varphi_{in} = \omega \cdot \theta * \left(\bar{r}\right), \varphi_{out}$ is unstaking rate. The two-dimensional system (10) admits a saddle equilibrium: trace $tr(J_2) < 0$ but determinant $\det(J_2) < 0$ due to the destabilizing PoS issuance feedback $\frac{\partial E_{ETH}}{\partial S_l} = \frac{\alpha}{a\sqrt{S_l^*}} > 0$ (full Jacobian derivation: Appendix A.3). Practical quasi-stability is maintained while the system evolves along the stable manifold of the saddle under the empirically observed near-balance condition $E \approx B$. Violation of this condition as in Terra/LUNA (Briola et al., 2023) corresponds to $\det(J_2) < 0$ (source) or breakdown of Assumption D. The one-dimensional stability condition (11)–(12) derived in section 2.7 is therefore a sufficient condition for stability along the stable manifold under quasi-stationary γ (Assumption D).

2.7 Stability Theorem

The central economic question: are small deviations of S_t from S_t^* self-correcting? The Jacobian of the reduced one-dimensional system at $B_\varepsilon(S_t^*)$ under Assumption D:

$$J_1 = \frac{\partial E}{\partial S_c}\Big|_{S_c^*} - \frac{\partial B}{\partial S_c}\Big|_{S_c^*} - \frac{\partial L}{\partial S_c}\Big|_{S_c^*}$$

Theorem 1 (Sufficient Condition for Local Stability). Under Assumptions A–D, if

$$\frac{\partial (B + L)}{\partial S_c} > \frac{\partial E}{\partial S_c} \quad (11)$$

then the stationary point S_t^* of the one-dimensional reduced system is locally asymptotically stable in the Lyapunov sense: there exists a neighborhood $B_\varepsilon(S_t^*)$ such that every trajectory starting in $B_\varepsilon(S_t^*)$ converges to S_t^* as $t \to \infty$ $V(S_t) = \frac{(S_t - S_t^*)^2}{2} \geq 0$, with $V = 0$ if and only if $S_t = S_t^*$. Differentiating along trajectories of (6) and linearizing the drift near S_t^*:

$$\frac{dV}{dt} = (S_c - S_c^*) \cdot \frac{dS_c}{dt} \approx J_1 \cdot (S_c - S_c^*)^2$$

Condition $J_1 < 0$ under (11) ensures $\frac{dV}{dt} = -\lambda_{\min} \cdot (S_t - S_t^*)^2 < 0$ for all $S_t \neq S_t^*$ in $B_\varepsilon(S_t^*)$, where

$$\lambda_{\min} = \frac{\partial (B + L)}{\partial S_c} - \frac{\partial E}{\partial S_c} > 0 \quad (12)$$

By the Lyapunov stability theorem for nonlinear systems (Khasminskii, 2012), this is sufficient for local asymptotic stability.

Corollary 1 (Stochastic Safety Criterion). Under Theorem 1 conditions, extending (6) to the

SDE (14) below, the critical diffusion level preserving local mean-square stability is:

$$\sigma_{crit}(S_c) = \sqrt{2 \cdot \lambda_{\min}} \cdot \left| S_c - S_c^* \right| \quad (13)$$

(Derivation via Ito's Lemma — see section 2.8.)

Economic interpretation. Two competing feedback determine the sign of $\sigma_{crit}(S_c) = \sqrt{2 \cdot \lambda_{\min}} \cdot \left| S_c - S_c^* \right|$. When S_t rises, staking demand grows with it, expanding the staking pool S_1; through the PoS formula $E = \alpha\sqrt{S_l}$, this amplifies issuance — a positive feedback loop that pushes supply further from equilibrium. At the same time, rising S_t directly increases the staking outflow $L = \omega \cdot \theta^*\left(\bar{r}\right) \cdot S_t$. This is the stabilizing channel. Condition (11) requires the stabilizing channel to win. It is not guaranteed then the destabilizing feedback dominates. The characteristic half-life $\tau_{\frac{1}{2}} = \frac{\ln(2)}{\lambda_{\min}}$ assures "monetary inertia" — the time the supply mechanism needs to absorb a given deviation. At $\lambda_{\min} \to 0$, the restoring force disappears; at $\lambda_{\min} < 0$, deviations amplify without bound.

2.8 Stochastic Extension

The deterministic ODE (6) captures mean flows, not reality. Real dynamics are hit by structural stochastic shocks. Four matter most: (i) adoption shocks — unpredictable swings in blockspace demand; (ii) validator shocks — random entry and exit of validators that disrupt the continuous mean-reversion approximation; (iii) governance shocks — unexpected protocol changes such as the Shanghai upgrade of April 2023, which unlocked staking withdrawals overnight; (iv) fee volatility — base fee nonlinearity under high network load. The SDE in Ito form with additive noise:

$$dS_{\{c,t\}} = \left[E(S_l, A_t) - B(A_t) - L(S_{\{c,t\}}, r_t) \right] dt + \sigma \cdot dW_t \quad (14)$$

with $\sigma = const$ for analytical tractability. The drift satisfies local Lipschitz and linear growth conditions, ensuring existence and uniqueness of a strong solution (Khasminskii, 2012).

Proof of Corollary 1. Applying Ito's Lemma to $V = \frac{(S_t - S_t^*)^2}{2}$ along trajectories of (14):

$$\mathcal{L}V = J_1 \cdot (S_c - S_c^*)^2 + \frac{\sigma^2}{2} = -\lambda_{min} \cdot (S_c - S_c^*)^2 + \frac{\sigma^2}{2}$$

The condition $\mathcal{L}V < 0$ (mean-square decrease of V) reduces to:

$$\sigma^2 < 2 \cdot \lambda_{\min} \cdot (S_c - S_c^*)^2 \leftrightarrow \sigma < \sigma_{crit}(S_c) = \sqrt{2 \cdot \lambda_{min}} \cdot \left| S_c - S_c^* \right|$$

which is (13). When $\sigma < \sigma_{crit}$, trajectories $S_{\{c,t\}}$ are attracted to S_t^* in mean-square sense. At $\lambda_{\min} \to 0$, stochastic stability fails for arbitrarily small noise — a property critical for protocols near the boundary of deterministic stability.

2.9 Calibration Methodology

Data cover 15 September 2022 through 1 April 2026 — 1,295 daily Ethereum observations. S_{tot} and S_l were reconstructed from anchor points via Etherscan and the Everstake annual staking report (2026); issuance E_t followed directly from the protocol formula $E = \alpha \cdot \sqrt{S_l}$; B_t was recovered via the balance identity $B_t = E_t - \Delta S_{tot}$; and A_t was interpolated from eight anchor points (Etherscan, The Block).

Estimation uses OLS with Newey–West HAC correction ($n_{lag} \approx 7$; effective $n = 1294$ for first-difference equations). Four regressions are estimated in sequence:

(Reg. 1) $E_t = \alpha \cdot \sqrt{S_{\{l,t\}}}$

(Reg. 2) $B_t = \beta_0 + \beta_1 \cdot A_t$

(Reg. 3a) $\frac{S_{\{l,t\}}}{S_{\{tot,t\}}} = \delta_0 + \delta_1 \cdot r_t$

(Reg. 3b) $\Delta S_{\{l,t\}} = \omega \cdot (\theta^*(r_t) \cdot S_{\{tot,t-1\}} - S_{\{l,t-1\}}) + \varepsilon_t$

$\lambda_{\min}$ is then computed analytically from (12). For the bootstrap, a block length of 30 days was chosen: it exceeds the estimated autocorrelation decay horizon of approximately 7 lags, ensuring asymptotic validity of the percentile confidence interval. Statistical reliability is assessed by block bootstrap (B = 2000 iterations, block length = 30 days, seed = 42; 95% CI is the percentile interval of the bootstrap distribution of $\lambda_{\min}$).

Results and Discussion

3.1 Calibrated Parameters

At the calibrated equilibrium, the three partial derivatives in condition (11) take the following values.

Issuance sensitivity: $\left.\frac{\partial E_{ETH}}{\partial S_t}\right|_{S_t^*} = \left(\frac{\alpha}{2\sqrt{S_l^*}}\right) \cdot \left(\frac{\gamma}{1-\gamma}\right) \approx 2*10^{-6}\, day^{-1}$ — small, because the concave PoS formula carries strong diminishing returns.

Burning sensitivity: $\frac{\partial B_{ETH}}{\partial S_t} = 0$, since EIP-1559 burning tracks transaction demand, not supply level.

Staking outflow sensitivity: $\frac{\partial L_{ETH}}{\partial S_t} = \omega \cdot \theta^*\left(\bar{r}\right) = \lambda_{\min}$. Applying (12): $\lambda_{\min} = \omega \cdot \theta^*\left(\bar{r}\right) - \frac{\partial E}{\partial S_t}$, with the issuance term three orders of magnitude below the staking term — negligible in practice.

Table 1. Calibrated model parameters (Ethereum, post-Merge, 2022–2026)

Parameter	Economic meaning	Estimate	HAC s.e.	t-stat	R^2
α	PoS issuance scale ($ETH^{0.5} \cdot day^{-1}$)	0.01423	< 0.0001	14049508*	1.000
β_0	Base burning flow ($ETH \cdot day^{-1}$)	7769	1156	6.72	0.232
β_1	Burning sensitivity to A (ETH/tx)	—0.00500	0.000747	—6.70	—
δ_0	Baseline equilibrium staking share	0.6273	0.00492	127.4	0.980
δ_1	Sensitivity of θ^* to return r	—388.2	5.32	—73.0	—
ω	Mean-reversion speed of S_l (day^{-1})	0.01123	0.00206	10.21	0.559
$\theta^*\left(\bar{r}\right)$	Equilibrium staking share at mean $\bar{r}$	0.244	—	—	—
$\lambda_{\min}$	Stability parameter (day^{-1})	0.00274	—	—	—
$\lambda_{\min}$ % CI	HAC propagation + B = 2000 bootstrap	[0.00175; 0.00373]	—	—	—
σ_{emp}	Empirical diffusion coefficient ($ETH \cdot day^{-0.5}$)	4442	—	—	—
σ_{crit}	Critical diffusion level ($ETH \cdot day^{-0.5}$)	57520	—	—	—

*The extremely high t-value for α reflects the mechanical protocol formula $E_t \equiv \alpha\sqrt{S_l}$ (deterministic relationship). Newey–West HAC, 6–7 lags.

The critical regression is Reg. 3b: $\omega = 0.01123\, day^{-1} (t = 10.2, n = 1294)$. Each day, roughly 1.1% of the gap between actual and equilibrium staking share is closed. Slow, but persistent. The negative coefficient $\delta_1 = -388.2$ confirms the theoretical saturation condition derived in section 2.2. A moderate $R^2 = 0.559$ for ω is expected: staking adjusts discontinuously through validator queues and governance upgrades, not through smooth market clearing. The 95%

HAC confidence interval for $\lambda_{\min}$: $[0.00175, 0.00373]\, day^{-1}$, giving $\tau_{\frac{1}{2}} \in [186, 396]$ days. Block bootstrap (B = 2000, block = 30 days) yields $P(\lambda_{\min} > 0) = 100\%$. No parametric uncertainty reasonable to consider changes the sign of the stability condition.

3.2 Verification of the Stability Condition

Table 2. Verification of the sufficient local stability condition (11)

Protocol	$\frac{\partial E}{\partial S_c}(day^{-1})$	$\frac{\partial B}{\partial S_c}(day^{-1})$	$\frac{\partial L}{\partial S_c}(day^{-1})$	$\frac{\partial (B+L)}{\partial S_c}(day^{-1})$	$\lambda_{\min}(day^{-1})$	Verdict
ETH	$\sim 2*10^{-6}$	0	0.00274	0.00274	0.00274 > 0	Condition (11) satisfied
BTC	0	0	0	0	0	Neutral regime
SOL	$1.05*10^{-4}$	0	n/a	n/a	not identified	ω not identified

For Ethereum, $\lambda_{\min} = 0.00274\, day^{-1} > 0$: condition (11) is satisfied. The entire stabilizing contribution comes from staking mean-reversion ($\tau_{\frac{1}{2}} \in [186, 396]$); the issuance feedback ($\partial E / \partial S_t \approx 2*10^{-6}\, day^{-1}$) is three orders of magnitude smaller — effectively negligible. The characteristic half-life $\tau_{\frac{1}{2}} = \frac{\ln(2)}{\lambda_{\min}} \approx 253s$ gives a concrete sense of monetary inertia: most of a year for the supply mechanism to absorb a given deviation. Fig. 1 shows BTC and ETH supply dynamics over the full study period.

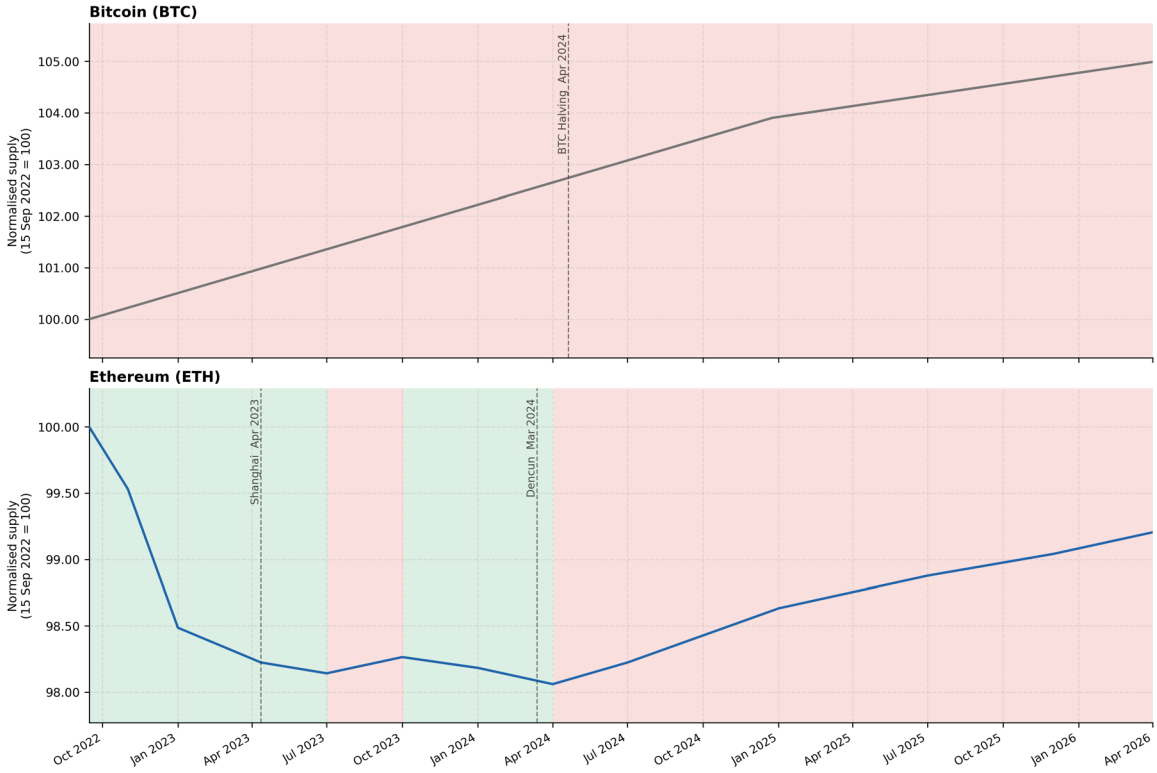


Fig. 1. Token supply dynamics and monetary regime — BTC and ETH, September 2022 – April 2026. Normalized supply S(t)/S(Sep 2022)*100; shaded area indicates deflationary (green) and inflationary (red) regimes classified by 7-day rolling $\Delta S(t)$. Key events: BTC Halving (Apr 2024); ETH Shanghai upgrade (Apr 2023), Dencun upgrade (Mar 2024).

3.3 Sub-period Analysis and Structural Break

Breaking the sample at the Shanghai upgrade (12 April 2023) exposes a structural shift that the theoretical model actually predicts (Table 3). Before Shanghai, the protocol enforced $dS_t / dt \geq 0$ — staking withdrawals were blocked. The bidirectional mean-reversion assumption in (4) simply did not hold. The pre-Shanghai estimate $\omega = -0.012\ day^{-1}$ is a data artefact of this one-directional structural constraint, not evidence of protocol instability. Assumption B from section 2.3 applies only to the post-Shanghai period. Once withdrawals were unlocked (April 2023 – March 2026), the stability parameter strengthened to $\lambda_{\min} = 0.00492\ day^{-1} (\tau_{1/2} \approx 141\ days)$, consistent with the fully bidirectional mean-reversion mechanism. The mechanism works faster when validators can actually exit. The temporal structure of monetary regimes is shown in Fig 2.

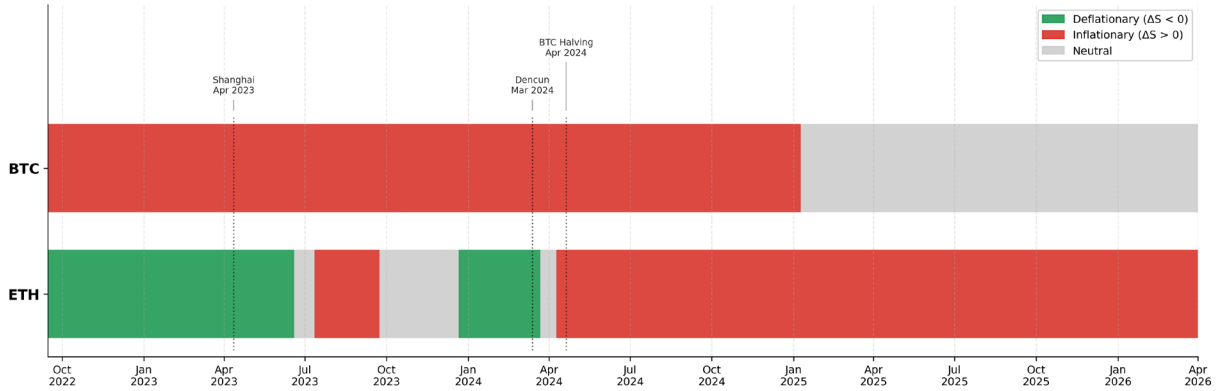


Fig. 2. Monetary regime timeline — BTC and ETH, September 2022 – April 2026.Horizontal bars colour-coded by 30-day rolling ΔS: green = deflationary ($\Delta S < 0$), red = inflationary ($\Delta S > 0$), grey = neutral.

Table 3. Sub-period analysis (ETH): structural break at Shanghai upgrade

Sub-period	n	$\omega (day^{-1})$	$\lambda_{\min}\ (day^{-1})$	$\tau_{1/2}$ (days)
Full sample	1,294**	0.01123	0.00274	253
Pre-Shanghai (before 12 Apr 2023)	209	—0.012*	—	—
Post-Shanghai (from 12 Apr 2023)	1085	0.0185	0.00492	141

** $n = 1294$ — effective sample for Reg. 3b (first differences $\Delta S_{\{l,t\}}$); raw series: 1295 daily observations.

* One-directional accumulation constraint; Assumption B does not hold for this sub-period.

Sensitivity analysis. Table 4 varies each parameter by ±20% analytically. $\lambda_{\min}$ remains positive in every scenario — Theorem 1 is robust across this range. The most sensitive parameter is δ_0, the baseline staking share: $\alpha \pm 20\%$ perturbation moves $\lambda_{\min}$ by roughly $\sigma_{crit}(S_t) = \sqrt{2 \cdot \lambda_{\min}} \cdot \left| S_t - S_t^* \right|$. The mean-reversion speed ω and saturation coefficient δ_1 have smaller effects but keep the system well within the stability region.

Table 4. Sensitivity of $\lambda_{\min}$ parameter variations (±20% from baseline)

Parameter	—20%	Baseline	+20%
ω	0.00220	0.00274	0.00330
δ_0	0.00133	0.00274	0.00416
δ_1	0.00361	0.00274	0.00188

3.4 Discussion

Position in the literature. Werner et al. (2022) described the staking mechanism as a supply stabilizer in qualitative terms. The magnitude $\lambda_{\min} = 0.00274\ day^{-1}$ quantifies this effect. What the present analysis adds is an operational criterion — something that can be monitored, updated quarterly on new on-chain data, and reported in regulatory filings. Leonardos et al. (2021) apply the Lyapunov method to EIP-1559 fee dynamics. Their object is the base fee; ours is aggregate circulating supply $S_t(t)$. These are different objects requiring different tools — a distinction the literature had not previously formalized.

The role of PoS versus deflation. EIP-1559 is not the supply stability mechanism — not in the sense measured here. Burning responds to transaction demand, not supply level; $\partial B / \partial S_t = 0$ by construction. The observed quasi-stability of ETH supply over the study period traces to PoS staking and its gradual mean-reversion property. For protocol designers, this has a direct implication: raising the base fee burn rate does not improve $\lambda_{\min}$ unless the burn scales with circulating supply.

Terra/LUNA contrast. Eight months to absorb a deviation might sound slow. But $\tau_{\frac{1}{2}} \approx 253$ days reflects a structural property of decentralized mechanisms: adaptation speed is bounded by $\omega \approx 0.011\ day^{-1}$ — the rate at which validators rebalance staking positions against market signals. This is genuinely slower than centralized monetary transmission, yet $\tau_{\frac{1}{2}} \approx 8$ months represents a realistic lower bound for decentralized mechanism speed — a property shared across PoS protocols (Werner et al., 2022). Terra/LUNA had a different problem entirely. The analog of condition (11) was violated at the design level: the feedback between UST issuance and LUNA burning amplified deviations rather than absorbing them - the equivalent of <<<Eqn071>>>. There was no half-life. Only runaway collapse. The framework proposed here would have flagged this vulnerability at the design stage, before deployment. Empirical supply deviation from equilibrium and theoretical convergence trajectories are illustrated in Fig. 3.

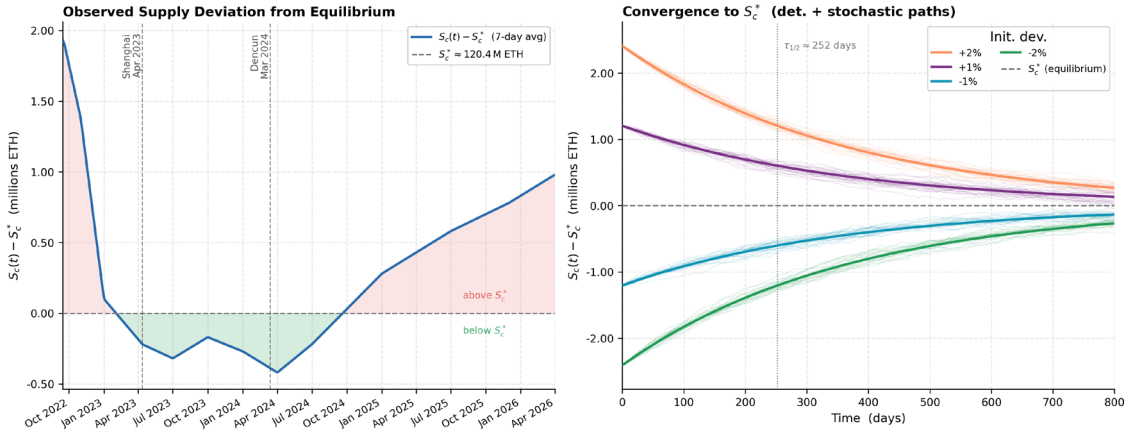
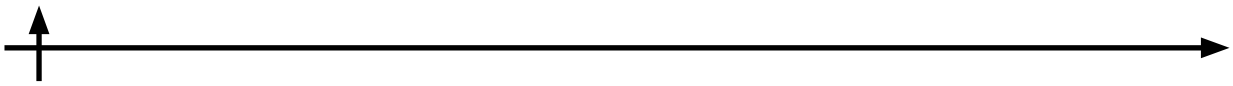


Fig. 2. Convergence of Ethereum circulating supply to equilibrium $S_c^* \approx 120.4M\ ETH$



Left panel: empirical deviation $S_c(t) - S_c^*$ (September 2022 – April 2026, 7-day moving average); green fill: supply below equilibrium; red fill: supply above equilibrium; dashed vertical lines mark the Shanghai upgrade (April 2023) and Dencun upgrade (March 2024). Right panel: theoretical convergence from ±1% and ±2% initial deviations; thin lines: 25 Euler–Maruyama realisations of $dX = -\lambda_{\min} X dt + \sigma dW$ ($\sigma = 4.442\ ETH\ day^{-1}$); thick lines: deterministic solution $X(t) = X_0 e^{\{-\lambda_{\min} * t\}}$; dotted vertical line: $\tau_{\frac{1}{2}} \approx 252$ days.

Regulatory implications. Observed ETH supply flow volatility sits roughly 13 times below the critical threshold ($\sigma_{emp} / \sigma_{crit} \approx 0.077$). The stochastic safety margin is comfortable. $\lambda_{\min}$ and σ_{crit} carry the natural properties of disclosure metrics: computable from public on-chain data, clear economic interpretation, and amenable to threshold-based regulatory criteria. Under MiCA requirements for significant asset-referenced tokens, these metrics could serve as standardized reserve stability indicators — a role currently filled by narrative description alone.

Conclusion

The paper derives a closed-form sufficient condition for local asymptotic stability of the token supply equilibrium — a result absent from the existing literature on blockchain monetary mechanisms. Condition (11), $\partial(B+L)/\partial S_t > \partial E / \partial S_t$, states that the marginal rate of deflationary absorption must exceed the marginal rate of issuance. The derivation proceeds from a representative agent's staking optimization problem, linearized around equilibrium, through the direct Lyapunov method. Crucially, the condition is structurally invariant to functional specifications: whether issuance follows a concave PoS formula or a linear rule, the criterion retains the same form — only the magnitudes of the partial derivatives change. Corollary 1 extends this into an operational stochastic safety criterion: $\sigma_{crit}(S_t) = \sqrt{2 \cdot \lambda_{\min}} \cdot \left| S_t - S_t^* \right|$. Below this threshold, stochastic supply trajectories converge to equilibrium in mean square. At $\lambda_{\min} \to 0$, stochastic stability fails for arbitrarily small noise — a property worth noting for protocols operating near the deterministic stability boundary.

Calibration on Ethereum on-chain data (post-Merge, EIP-1559, n = 1,295 daily observations, 2022–2026) confirms the condition holds in practice: $\lambda_{\min} = 0.00274\ day^{-1}$ (95% Newey–West HAC CI: [0.00175, 0.00373]; $P(\lambda_{\min} > 0) = 100\%$ by block bootstrap), with a characteristic half-life $\tau_{\frac{1}{2}} \approx 253$ days and a 13-fold stochastic safety margin ($\sigma_{emp} / \sigma_{crit} \approx 0.077$). Sub-period analysis adds resolution to this picture. Splitting the sample at the Shanghai upgrade (April 2023) reveals a structural break precisely where the model predicts one: before Shanghai, staking withdrawals were protocol-locked and the bidirectional mean-reversion assumption was structurally violated; after unlocking, $\lambda_{\min}$ rises to $0.00492\ day^{-1}$ ($\tau_{\frac{1}{2}} \approx 141$ days), consistent with the full two-directional adjustment mechanism. Pre-Shanghai estimates reflect an architectural constraint that the protocol itself later removed — not evidence of instability. Sensitivity analysis confirms $\lambda_{\min} > 0$ across all ±20% parameter variation scenarios, with maximum sensitivity to the baseline staking share $\delta_0 (\pm 52\%)$.

The most substantive finding concerns the actual driver of Ethereum's supply stability. EIP-1559 burning is widely discussed as the protocol's deflationary mechanism, however, according to the criterion developed here, it plays no direct role: burning responds to transaction demand, not supply level, so $\frac{\partial B}{\partial S_t} = 0$ by construction.

The stability of ETH circulating supply traces entirely to the PoS staking architecture and its gradual mean-reversion property ($\partial L / \partial S_t = \omega \cdot \theta^* = 0.00274\ day^{-1}$). For protocol designers, this has a direct consequence: increasing the base fee burn rate does not improve $\lambda_{\min}$ unless

the burn scales with S_t. The Terra/LUNA collapse is instructive in the opposite direction — in that system, the analog of condition (11) was violated at the design stage, with the feedback between UST issuance and LUNA burning amplifying deviations under stress rather than absorbing them. The framework proposed here would have quantified this vulnerability before deployment, translating qualitative risk assessment into a measurable threshold.

Finally, a regulatory and prospective dimension. The metrics $\lambda_{\min}$ and σ_{crit} carry the properties desirable for disclosure requirements under EU Regulation 2023/1114 (MiCA): they are computable from public on-chain data, carry clear economic interpretation, and admit threshold-based regulatory criteria — advantages over the narrative-description approach currently prevalent. Several extensions lie outside the scope of this paper and are reserved for future work: price feedback integration and the three-dimensional system (S_t, S_l, P); nonlinear Lyapunov analysis and bifurcation characterization near the stability boundary; a Markov-switching ODE for regime transitions; and cross-protocol verification on Cosmos and BNB Chain. The stochastic analysis and Monte Carlo verification are developed in a companion paper.

APPENDIX. Statistical Details

A.1 Calibration Pipeline

Parameters are estimated sequentially: (1) $E_t = \alpha \cdot \sqrt{S_{\{l,t\}}}$ — OLS-HAC, R^2 = 1.000 (mechanical protocol relationship); (2) <<<Eqn165>>> — OLS-HAC, R^2 = 0.232 (sign $\beta_1 < 0$ is a data reconstruction artifact via balance identity; the stability condition (11) is determined by $\frac{\partial B}{\partial S_t} = 0$ and holds regardless of the sign of β_1; see section 2.5); (3a) $\frac{S_{\{l,t\}}}{S_{\{tot,t\}}} = \delta_0 + \delta_1 \cdot r_t$ — OLS-HAC, R^2 = 0.980; (3b) $\Delta S_{\{l,t\}} = \omega \cdot (\theta^*(r_t) \cdot S_{\{tot,t-1\}} - S_{\{l,t-1\}}) + \varepsilon_t$ — OLS-HAC, R^2 = 0.559; (4) $\lambda_{\min} = \omega \cdot \theta^*\left(\bar{r}\right) - \frac{\partial E}{\partial S_t}$ computed analytically from (12). Full replication details are available from the author.

A.2 Statistical Verification Details

Block bootstrap: blocks of 30 days, B = 2000 iterations, seed = 42; 95% CI — percentile bootstrap distribution of $\lambda_{\min}$. HAC: n_lag = 6 − 7 (Newey–West); SE(ω) propagation gives $\Delta\lambda_{\min} \approx 0.00050$, CI = [0.00175, 0.00373]. For $n_{lag} \in \{5...8\}$, $\lambda_{\min}$ varies by less than 3%.

A.3 Two-Dimensional Extension: Jacobian Derivation

The Jacobian of the two-dimensional system (10) at the stationary point (S_t^*, S_l^*) with $\varphi_{in} = \omega \cdot \theta^*\left(\bar{r}\right)$ and φ_{out} — unstaking rate:

$$J_2 = \left(\begin{array}{cc} -\varphi_{in} & \frac{\partial E}{\partial S_l} \\ \varphi_{in} & -\varphi_{in} \end{array} \right)\Bigg|_{(S_c^*, S_l^*)}$$

Trace: $tr(J^2) = -(\varphi_{in} + \varphi_{out}) < 0$ (both rates are positive). Determinant: $\det(J^2) = \varphi_{in} \cdot \varphi_{out} - \varphi_{in} \cdot \left(\frac{\partial E}{\partial S_l} + \varphi_{out} \right) = -\varphi_{in} \cdot \frac{\partial E}{\partial S_l}$. For Ethereum $\frac{\partial E_{ETH}}{\partial S_l} = \frac{\alpha}{2\sqrt{S_l^*}} > 0$, hence $\det(J_2) = -\varphi_{in} \cdot \frac{\alpha}{2\sqrt{S_l^*}} < 0$. A negative determinant implies that the equilibrium (S_t^*, S_l^*) is a saddle point: one eigenvalue is positive, and one is negative. Trajectories starting off the stable manifold diverge; however, the system is attracted along the stable manifold direction, where the one-dimensional stability condition (11), (12) applies under Assumption D. This establishes the formal relationship between the one-dimensional reduced model and the full two-dimensional system.

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COMPARISON OF NIST CYBERSECURITY FRAMEWORK PATTERNS AND THE REQUIREMENTS OF FEDERAL SERVICE FOR TECHNICAL AND EXPORT CONTROL (FSTEC) ORDER NO. 31: COMPLIANCE MATRICES AND INTEGRATION METHODOLOGY

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Abstract. This study focuses on two of the most significant documents in the field of information security: the international standard NIST Cybersecurity Framework version 2.0 and the Russian regulatory act, FSTEC Order No. 31. The subject of the study is the conceptual and structural relationships between the NIST CSF functions and the groups of information security measures established by Order No. 31. The methodological basis consists of a comparative analysis of the original texts of the documents, Positive Technologies comparison tables, and the TOGAF architectural design methodology. The study resulted in the development of a correspondence matrix comparing 17 groups of measures from Order No. 31 with six functions of the NIST CSF 2.0 core. It was found that coverage of CSF functions by the Order's measures varies from 40-60% for class K3 to 95-100% for class K1, while the Govern function has no direct equivalent in the Russian document. A gap analysis methodology is proposed, allowing organizations to identify missing security measures when integrating the two approaches. Practical recommendations for prioritizing protective measures based on a risk-based approach have been developed. The results can be used in designing information security architectures for organizations working with critical information infrastructure and government information systems.

Keywords: NIST Cybersecurity Framework 2.0, FSTEC Order 31, information security risk management, standards integration, cybersecurity patterns, business architecture, critical information infrastructure, government information systems, information security

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СОПОСТАВЛЕНИЕ ПАТТЕРНОВ NIST CYBERSECURITY FRAMEWORK И ТРЕБОВАНИЙ 31 ПРИКАЗА ФСТЭК: МАТРИЦА СООТВЕТСТВИЯ И МЕТОДИКА ИНТЕГРАЦИИ

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Аннотация. Предметом исследования выступают два наиболее значимых документа в сфере информационной безопасности: международный стандарт NIST Cybersecurity Framework версии 2.0 и российский нормативный акт — приказ ФСТЭК №31. Предметом исследования являются концептуальные и структурные взаимосвязи между функциями NIST CSF и группами мер защиты информации, установленными 31 приказом. Методологическую основу составили сравнительный анализ оригинальных текстов документов, сопоставительные таблицы Positive Technologies, а также методология архитектурного проектирования TOGAF. В результате исследования разработана матрица соответствия, сопоставляющая 17 групп мер 31 приказа с шестью функциями ядра NIST CSF 2.0. Выявлено, что покрытие функций CSF мерами приказа варьируется от 40–60% для класса К3 до 95–100% для класса К1, при этом функция Govern не имеет прямого аналога в российском документе. Предложена методика гэп-анализа, позволяющая организациям выявлять недостающие меры защиты при интеграции двух подходов. Сформулированы практические рекомендации по приоритезации защитных мер на основе риск-ориентированного подхода. Результаты могут быть использованы при проектировании архитектуры информационной безопасности организаций, работающих с объектами критической информационной инфраструктуры и государственными информационными системами.

Ключевые слова: NIST Cybersecurity Framework 2.0, 31 приказ ФСТЭК, управление рисками информационной безопасности, интеграция стандартов, паттерны кибербезопасности, бизнес-архитектура, критическая информационная инфраструктура, государственные информационные системы, защита информации

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Introduction

The digitalization of the economy is accompanied by a steady increase in the number and sophistication of cyberattacks. According to the IBM Security 2024 report, the average cost of a data breach has reached $4.88 million, with 91% of companies raising cybersecurity issues to the board level (IBM Corporation, 2024). Under these circumstances, organizations are forced to build multi-layered security systems that meet the requirements of both international and national regulators.

In the Russian Federation, the primary regulatory body for technical information security is the Federal Service for Technical and Export Control (FSTEC of Russia). For government information systems (GIS), personal data information systems (PDIS), and critical information

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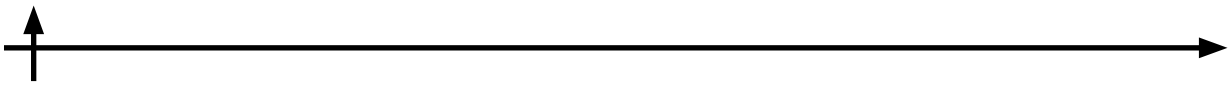


infrastructure (CII) facilities, the requirements of a number of regulatory acts are mandatory, including FSTEC Orders No. 17, No. 21, and No. 31 (FSTEC of Russia, 2014). The latter establishes strict rules for the creation of information security systems, regulating the classification of systems, the identification of threats, and the implementation of specific organizational and technical measures.

At the same time, the NIST Cybersecurity Framework, developed by the US National Institute of Standards and Technology, has gained widespread adoption internationally. Version 2.0 was published in February 2024, expanding its scope from critical infrastructure to all types of organizations and adding a new Governance feature to the framework, emphasizing the strategic importance of cybersecurity for management (NIST, 2024). Researchers note that Russian IEC 62443 series GOSTs, relevant for industrial systems, lag behind international versions by 10–15 years, according to expert estimates (INNER, 2025), making the NIST CSF an attractive benchmark for building modern security systems even when maintaining compliance with Russian regulators.

Experience shows that organizations integrated into international supply chains or using foreign practices face a dilemma. Adhering solely to the letter of Russian law can lead to the creation of a formal but inflexible security system. Using the flexible NIST CSF methodology does not automatically guarantee compliance with the strict requirements of the FSTEC. The lack of a systematic analysis of the interrelationships between these documents complicates their combined application and leads to duplication of effort and resources. Research in business engineering shows that the success of digital transformation and standards implementation depends not only on formal compliance with requirements but also on how well these requirements are integrated into the organization's business architecture and management processes (Van Looy A, 2021). The situation is exacerbated by tightened regulations in 2025: new fines for data leaks and the requirement to use exclusively domestic solutions for critical information infrastructure facilities necessitate careful planning of integration processes (INNER, 2025).

The purpose of this paper is to conduct a comparative analysis of NIST CSF patterns and the requirements of Order 31 of the FSTEC, as well as to develop recommendations for their integration. To achieve this goal, the following tasks are addressed: analysis of the theoretical foundations and structure of both documents; comparison of their key functions and requirements; identification of NIST CSF patterns applicable to optimizing compliance with the requirements of Order 31; and development of practical recommendations for integration, including a compliance matrix.

The theoretical basis of the study was formed by works on the application of NIST CSF in various industries (Brock et al., 2024; Gordon et al., 2023), analytical materials on the implementation of FSTEC requirements (Lukatsky, 2019). Of particular value are the comparative tables developed by Positive Technologies, which directly correlate the clauses of Order 31 with the requirements of international standards NERC CIP, ISA/IEC 62443, NIST SP 800-82 and NIST SP 800-53 (Positive Technologies, 2012). A number of authors consider the issues of integration of information security standards in the context of digital transformation of enterprises (Kitsios et al., 2024; Schmitt et al., 2025). However, as industry reviews show (Henshel et al., 2024), a comprehensive comparative analysis of NIST CSF and FSTEC Order 31 from the point of view of business architecture and management processes is presented fragmentarily. Existing studies either focus on the technical aspects of implementing security measures or consider the documents in isolation. This article aims to fill this gap by proposing an integrated approach that takes into account both the mandatory requirements of the Russian regulator and

the flexible methodologies of the international standard.

Materials and Methods

NIST Cybersecurity Framework 2.0: concept, structure and components

The NIST Cybersecurity Framework was developed in response to Executive Order 13636, "Strengthening Critical Infrastructure Cybersecurity," issued in February 2013. The first version of the document was published in February 2014. The framework's key idea was to unify approaches to security throughout the entire system lifecycle by building on existing standards and best practices (NIST, 2020). Researchers note that the CSF quickly gained the status of a de facto international standard due to its flexibility and adaptability to various organizational contexts (Shackelford, 2023).

In February 2024, the updated version of NIST CSF 2.0 was released. The changes affected not only the structure but also the scope of application—the standard is targeted at all types of organizations, from small non-profits to large corporations, regardless of their level of cybersecurity maturity (NIST, 2024). As noted in a Gartner analytical review, the inclusion of the Govern function was a response to business demand for the integration of cybersecurity into corporate governance (Gartner, 2024).

The central element of the framework is the Framework Core, a taxonomy of high-level cybersecurity outcomes. The core comprises six functions, 23 categories, and 108 subcategories. The Govern function defines the cybersecurity strategy, organizational context, roles and responsibilities, and supply chain risk management. The Identify function covers asset management, risk assessment, and process improvement. Protect encompasses identity and access management, awareness raising, data and platform security, and infrastructure resilience. Detect provides continuous monitoring and analysis of adverse events. Respond regulates incident management, analysis, reporting, and remediation. Recover defines the implementation of recovery plans and post-incident communication.

In addition to the core, the CSF includes two additional components. The Organizational Profile is a mechanism for describing the current and target state of an organization's cybersecurity in terms of the CSF core. CSF Tiers characterize the maturity of risk management processes: from Tier 1 "Partial" (one-time actions) to Tier 4 "Adaptive" (an organization-wide, risk-based approach).

An important feature of the CSF is its focus on interoperability with existing standards. NIST has conducted extensive work to align the proposed security controls with NIST 800-53, ISA/IEC 62443, ISO 27001, COBIT, and CIS Controls (NIST, 2020). NIST SP 800-82 specifically addresses the security of industrial control systems, and NIST SP 800-53 contains a detailed catalog of security controls for federal information systems (Positive Technologies, 2012).

FSTEC Order No. 31: Structure, Requirements, and Classification

In the Russian Federation, the Federal Service for Technical and Export Control (FSTEC) of Russia is responsible for implementing state policy in the area of technical information security. Order No. 31 "On Approval of Requirements for Ensuring Information Security in Automated Control Systems for Production and Technological Processes at Critical Facilities..." dated March 14, 2014 (as amended in 2017, 2018, and 2021) establishes mandatory requirements for the creation of information security systems (FSTEC of Russia, 2014). This document applies not only to automated process control systems but also to other automated systems at critical facilities. The methodology for classifying and selecting measures is largely similar to the approaches used for GIS and ISPDN (Orders No. 17 and No. 21).

The security class of an information system (K1, K2, K3) is determined in accordance with Appendix No. 1 to the order based on the significance (criticality) of the information being pro-

cessed. The significance level is calculated as a combination of the degrees of potential damage from a breach of the integrity, availability, and confidentiality of the information. The degree of damage can be high (federal or interregional emergency), medium (regional or intermunicipal emergency), or low (municipal or local emergency). Class I (K1) is the highest, and Class III (K3) is the lowest.

Appendix No. 2 to the order contains 17 groups of organizational and technical security measures, including identification and authentication (IAF); access control (AC); software environment restriction (SER); computer media protection (CMP); security audit (SEA); anti-virus protection (AV); intrusion prevention (IP); integrity assurance (IEC) and availability; protection of technical assets (PTA) and systems (PTS); incident response (IR); configuration management (CM) and update management (UM); planning (PLN) and actions in emergency situations (AES); personnel information and training (PIT). A basic set of measures is defined for each security class. The process of selecting measures includes defining the basic set according to the class, adapting it to the structural and functional characteristics, clarifying it according to the threat model, and supplementing it with other regulatory acts.

Requirements comparison results (Positive Technologies)

Positive Technologies specialists conducted a detailed comparison of the security measures established by FSTEC Order No. 31 with the requirements of international standards (Positive Technologies, 2012). The study showed that the order provides for a broader set of requirements than NERC CIP, ISA/IEC 62443, and NIST SP 800-82. The comparison results revealed a number of measures that can be added to the requirements of the order. Firstly, this is an explicit requirement to separate the corporate LAN and process networks at the network level (present in ISA-62443-2-1 and NIST SP800-82). The order does contain a requirement for segmentation; however, it would be advisable to explicitly note the need to separate process networks from corporate ones in methodological documents. Secondly, a detailed inventory of information system components is required, which includes storing additional information on their purpose and criticality. Thirdly, personnel verification is required before granting access to information systems (NERC CIP, ISA/IEC 62443). Fourth, activities related to the dismissal of personnel (blocking accounts, changing passwords), present in ISA-62443-2-1 and NERC-CIP.

Comparison of NIST CSF patterns and requirements of FSTEC Order no. 31

To identify potential integration opportunities between the two approaches, a comparison of their key functions and requirements was conducted. Table 1 presents a comparative analysis at the level of general document characteristics.

Table 1. Comparative Analysis of NIST CSF 2.0 and FSTEC Order 31.

Criteria	NIST CSF 2.0	FSTEC Order 31
Legal status	Advisory, voluntary	Mandatory, imperative
Main area of application	All types of organizations	Information systems at critical facilities, GIS, personal data information systems (through a common methodology)
Structure	6 functions, 23 categories, 108 subcategories	17 groups of measures, basic sets for classes K1-K3
Approach to risks	Risk-oriented, integrated into management	Classification based on damage, selection of measures according to class
Implementation tools	Best global practices, open standards	FSTEC-certified information security tools
Flexibility of adaptation	High, possibility of customization to suit the business context	Low, deterministic requirements for the composition of measures

NIST CSF Functions and Order 31 Group of Measure Correspondence Matrix

Based on an analysis of the measures in Order 31 and the functions of NIST CSF 2.0, as well as data from Positive Technologies (Positive Technologies, 2012) and analytical materials (SECURITM, n.d.), a correspondence matrix was developed, presented in Table 2. The matrix allows for establishing relationships between groups of measures of the Russian regulator and the functions of the international standard.

Table 2. Correspondence matrix of NIST CSF 2.0 functions and groups of measures in Order 31 of the FSTEC.

NIST CSF 2.0 Function	Function Description	Related groups of measures of Order 31	Notes
Govern (GV)	Managing strategy, policies, and risks in the supply chain	INT (information/training), PLN (planning), CM (configuration management), partially TA (threat analysis)	Policies and staff training are mandatory for all classes. The Govern function is not explicitly mentioned in Order 31; its elements are scattered across organizational measures.
Identify (ID)	Identification of assets, risks, threats	TA (threat analysis), IAF (identification/authentication), partially SP (system protection)	Mandatory threat analysis (TA.1) for all classes; device identification (IAF.2) – from level 2
Protect (PR)	Security: Access Management, Data Security, Technologies	AC (access control), SL (software limitation), SP (system protection), AV (antivirus), PTE (protection of technical equipment), MP (media protection)	AC.1-17, SP.1-30 mandatory for the corresponding classes; segmentation (SP.17) for K1-K2
Detect (DE)	Anomaly and intrusion detection	ER (event registration), ID (intrusion detection), SA (security analysis)	ER.1-7 for all classes; ID.1 for K1 and higher
Respond (RS)	Incident response	DR (detection/response), AES (actions in emergency situations)	DR.1-6 mandatory for all classes; development of response plans is required
Recover (RC)	Incident recovery	EA (ensuring accessibility), EI (ensuring integrity), AES.5 (recovery)	Redundancy (EA.2, EA.4) for all classes; ensuring the possibility of recovery

The developed matrix demonstrates a high degree of conceptual alignment between the two documents. Nearly all action groups in the 31 orders can be mapped to one or more NIST CSF functions. The exception is the Govern function, whose elements are distributed across several organizational action groups but are not identified as a separate strategic management category.

Comparison of security classes K1-K3 with CSF maturity levels

Security classes K1-K3 under Order 31 define the levels of information system protection based on the consequences of a breach. NIST CSF 2.0 uses generic functions without a strict hierarchy, but a parallel can be drawn between the classes and the required depth of CSF function coverage. Table 3 provides such a comparison.

Table 3. Comparison of classes K1-K3 and NIST CSF 2.0 functions.

FSTEC Order 31 Class	The nature of the consequences of the violation	Mandatory measures (examples)	Compliance with CSF 2.0 features	Coverage assessment, %
K1 (high)	Federal/interregional emergency, mass casualties, man-made disaster	All measure groups: IAF, AC, SP, ER, ID, DR, SA; segmentation, redundancy, strict access control	Full: Govern (policies), Identify (all assets), Protect (strict access and segmentation), Detect (SIEM, IDS), Respond/ Recover (plans, exercises)	95–100
K2 (medium)	Regional emergency, significant damage to health or the economy	IAF.1-3, AC.1-10, SP.1-15, ER.1-5, DR.1-4; without mandatory ID	Basic Govern and Identify, primary Protect, partial Detect and Respond	70–85
K3 (low)	Local emergency, minor negative consequences	IAF.1, AC.1-5, SP.1-5, ER.1-3	Identify (assets), basic Protect, minimal Detect	40–60

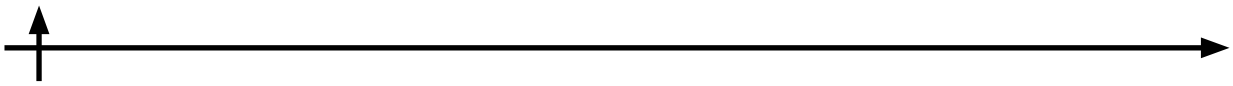
The data presented demonstrates that as the security level increases, not only does the number of mandatory measures increase, but also the required depth of coverage of cybersecurity management functions. Class K1 facilities must implement virtually the full range of capabilities provided by modern standards.

Analysis of key differences and adaptation opportunities

The Identify function in the NIST CSF focuses on understanding organizational context, asset management, and risk assessment. In Order 31, inventory and classification requirements are outlined in paragraphs 7 and 13.2. Both documents require a complete inventory of assets and their categorization based on their criticality to the organization. The difference is that the NIST CSF offers a more flexible approach, aligning asset categorization with business processes and the organization's mission, while Order 31 details the classification process into three security classes with clear criteria. The NIST Risk Assessment Framework (ID.RA) can be used to enrich the formal classification in Order 31. At the requirements generation stage (paragraph 13), it is advisable to supplement the expert damage assessment with an analysis of business processes, which will allow for a more precise determination of the security class and protection priorities.

The Protect function in the NIST CSF covers identity, authentication, and access management (PR.AC), awareness raising (PR.AT), data security (PR.DS), and platform security (PR.PS). In 31 orders, the corresponding measures are represented by the groups IAF, AC, SL, MP, PTE, and SP. Both documents require the implementation of basic security mechanisms: user and device identification, access control, protection from malicious code, and integrity control. The NIST CSF allows for implementation variability—for example, personal mobile devices with a temporary blocking mechanism and strong encryption can be used for authentication (NIST, 2020). The 31st order prescribes the use of certified information security tools, including cryptographic information protection tools of certain classes (paragraph 24). NIST's flexible approaches can be used during the adaptation phase of the basic set of measures (paragraph 19). When developing access control policies, it is advisable to apply the principles of assigning minimum necessary rights (AC.5) and separation of powers (AC.4), which are classic NIST patterns, with strict adherence to the requirements for certification of tools at the implementation stage.

The Detect and Respond functions in the NIST CSF include continuous monitoring (DE.CM), adverse event analysis (DE.AE), incident management (RS.MA), and incident analysis (RS.AN). In Order 31, these functions correspond to the SEA, ID, and DR groups. Section



16.6 details incident detection and response procedures, including detection, identification, analysis, and the adoption of measures to eliminate and prevent recurrence. Both documents require the creation of systems for monitoring security events, analyzing incidents, and taking measures to eliminate them. Order 31 prescribes the use of certified intrusion detection tools, while the NIST CSF emphasizes continuous process improvement based on incident analysis and the use of performance metrics (detection and response times). Continuous monitoring and threat analysis patterns can be used to customize processes on top of certified tools. The implementation of performance metrics (KPIs) for response processes allows one to evaluate actual security status and, if necessary, adapt procedures without changing the tools.

Practical Aspects of Implementation

Gap analysis technique based on a correspondence matrix

To simplify the integration of the two documents, it is proposed to use the developed correspondence matrix (Table 2) as the basis for gap analysis. The process involves the following sequential steps.

The first step is to create a current NIST CSF profile. The organization assesses the current state of implementation of each CSF subcategory. It is advisable to use a four-level scale, where 0 represents no implementation, 1 represents partial implementation, 2 represents full implementation, 3 represents process automation, and 4 represents optimization through continuous improvement.

The second step is comparison with the requirements of Order 31 using the developed matrix. For each group of measures in Order 31, the CSF subcategories that cover it are determined and the extent of coverage is assessed.

The third step is identifying gaps. The requirements of Order 31 that are not covered by the current CSF profile are identified, as well as CSF elements that could enhance compliance but are not directly required by the Russian regulator.

The fourth step is developing an action plan. Based on the identified gaps, an implementation plan is developed, taking into account their priority, budget constraints, and available resources.

Prioritization of protective measures

Given limited resources, it is advisable to use a risk-based approach to prioritizing protective measures. Based on international experience (ASD Essential Eight, CIS Controls) and expert assessments (Lukatsky, 2019), we can identify critical measures from 31 orders that should be implemented first, regardless of security class:

1. IAF.1, IAF.2 — Identification and authentication of users and devices (multifactor authentication).
2. AC.5 — Assignment of least necessary rights and privileges (least privilege).
3. SL.3 — Installation of only authorized software (application control).
4. SA.2 — Control over the installation of software updates (patch management).
5. AV.1, AV.4 — Antivirus protection and database updates.
6. SEA.4, SEA.7 — Security event logging and monitoring.
7. EA.4 — Periodic backups.
8. SP.17 — Information system segmentation.
9. ID.1 — Detection and prevention of computer attacks.
10. DR.1-DR.5 — Response to computer incidents.

This list can serve as a basis for establishing a baseline level of protection when integrating NIST CSF approaches and the requirements of Order 31. Research shows that implementing even these ten measures can reduce the risks of the most common attacks by 80–90% (Austral-

ian Signals Directorate, 2024).

Phased implementation strategy

Based on the analysis of best practices (Center for Internet Security, 2024), the following step-by-step integration strategy is proposed.

The assessment and classification phase takes 2–4 months. During this phase, the current state is assessed using the NIST CSF methodology, resulting in the creation of a current profile. Simultaneously, the system's security classification is determined according to Order 31, as per Appendix No. 1.

The gap analysis phase takes 1–2 months. The current NIST profile is compared with the requirements of Order 31 using a compliance matrix, and missing security measures are identified.

The policy development phase takes 2-3 months. Unified organizational and regulatory documents are created, taking into account the requirements of both standards. NIST patterns are used to describe the security goals and objectives, and the requirements of Order 31 are used to specify the technical measures.

The implementation phase takes 6-12 months. Technical security measures are implemented using certified tools required by Order 31. Tools are configured according to NIST best practices (for example, monitoring systems are configured to ensure continuous detection).

The effectiveness and improvement phase is ongoing. NIST-based effectiveness metrics (detection time, response time, and recovery completeness) are implemented. The threat model is periodically reviewed and security measures are adapted.

Practical examples of implementation

Real-life cases of implementing Order 31 at various facilities demonstrate the practical applicability of the integrated approach.

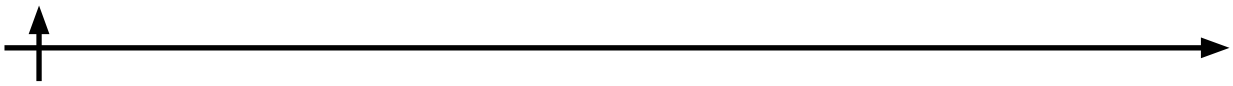
At the Severstal Steel Works (class K1-K2 critical information infrastructure facilities), infrastructure protection was implemented in accordance with Order 31: network segmentation (SP.17), antivirus protection (AV), event monitoring (ER/ID), and backup (EA) (ARPP Soft, n.d.). ARPP Soft acted as the integrator. The result was compliance with FSTEC requirements and a 60% reduction in the number of identified vulnerabilities. Additionally, elements of NIST-like threat modeling were implemented to improve protection effectiveness.

The project to implement the requirements of Orders No. 31 and No. 21, carried out by iTPROTECT, included automated vulnerability scanning (SA.1) and remediation planning (iTPROTECT, n.d.). Regular scanning using certified tools was organized for information systems at hazardous industrial facilities, identifying critical CVEs and promptly remediating them within scheduled windows. This resulted in confirmation of compliance with FSTEC requirements during annual audits.

The Jet CSIRT study focused on protecting information systems from advanced persistent threat (APT) attacks using measures from Order 31 (ISO, INC) (Jet CSIRT, 2025). Using a SCADA system as an example, it demonstrated how threat intelligence (TSI) combined with the implementation of a SIEM system for anomaly detection (DE.CM in NIST terms) enables the timely detection of suspicious activity. Integration with the NIST CSF was used to enhance cyber resilience and conduct penetration tests.

A role-based access control (RBAC) model was implemented at a company with a K2-class information system (SECURITM, n.d.). Multifactor authentication was implemented for all users in accordance with NIST CSF (PR.AC-01) and the requirements of Order 31 (AC.1, AC.3). The use of Active Directory and tokens allowed for the coverage of access audit requirements (ER.1). This resulted in a 40% reduction in incidents related to unauthorized access.

To monitor servers at a K1 enterprise, a Splunk-based security information and event management system (SIEM) and network intrusion detection sensors (NIDS) were deployed (SE-



CURITM, n.d.). This complies with the requirements of the Security Council (SOV.1) and the Security Council (ER.1-7) of the Order 31, as well as NIST CSF (DE.CM-01) recommendations. Event logs are stored for a specified period, allowing for retrospective analysis of incidents.

Problems and risks during integration

The main integration challenges stem from differences in terminology and approaches to describing security measures. As noted in Positive Technologies' comparative tables, some measures in Order 31 have no direct equivalents in international standards (for example, trusted boot requirements—UPD.17) (Positive Technologies, 2012).

Another challenge is the requirement to use certified security tools, which may limit the application of some NIST agile practices (such as the use of open-source monitoring solutions). This requires additional efforts to find certified alternatives that offer the required functionality.

The high cost of implementing a full set of measures for high security classes is also a deterrent. K1 class requires the implementation of over 100 measures, which is comparable in cost to the implementation of comprehensive security systems at large enterprises (Brock et al., 2024).

There is a risk of a formal approach, whereby the requirements of Order 31 are simply implemented "for show," without using NIST agile methodologies to truly improve efficiency. A critical risk is non-compliance with Order 31 requirements when using only the NIST CSF, especially when using non-certified security tools. To minimize this risk, it is necessary to clearly distinguish between the areas of application at the security system design stage: strategic planning and process management should be based on NIST methodology, while the implementation of technical measures should use certified tools in accordance with Order 31.

Conclusion

The analysis shows that the NIST Cybersecurity Framework and FSTEC Order 31 are not mutually exclusive documents, but rather have significant potential for complementarity. The NIST CSF offers a flexible, process-based methodology for integrating cybersecurity into an organization's business architecture and ensuring its continuous improvement. FSTEC Order 31 provides a rigorous framework of mandatory technical requirements that ensure compliance with legal regulations and the use of certified security tools.

The study yielded the following key findings. Both standards are based on a risk-based approach and require asset classification, access management, monitoring, and incident response. The key difference lies in their legal status: the NIST CSF is advisory, while Order 31 is mandatory in Russia for certain categories of systems (GIS, ISPDN, and critical infrastructure facilities). A comparison conducted by Positive Technologies shows that Order 31 provides a broader set of requirements than many international standards, but can be supplemented with a number of useful measures, such as explicitly requiring network segmentation and detailed inventory (Positive Technologies, 2012).

The developed compliance matrix (Table 2) and recommendations for prioritizing measures enable organizations to build an effective integration strategy, reducing duplication of effort and resources. Real-world implementation cases demonstrate the practical applicability of the integration approach and its effectiveness in protecting information systems of various classes.

The obtained results can form the basis for developing a detailed methodology for integrating the NIST CSF and Order 31 into the business architecture of organizations operating critical information infrastructure (CII) facilities, government information systems, and other automated systems. A promising area is research into the automation of compliance processes using specialized software solutions (such as Security Vision, SECURITM, and others) that enable the maintenance of a unified requirements database and the automatic generation of

questionnaires and action plans. Also relevant is an analysis of the application of NIST CSF 2.0 to risk management associated with the use of artificial intelligence technologies, in the context of Russian regulatory requirements.

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ARCHITECTURE AND MATHEMATICAL APPARATUS OF DECISION-SUPPORT SYSTEM FOR MARKETPLACE SELLERS

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Abstract. The growth of online marketplaces as multi-sided digital platforms has created a decision-making environment for sellers that differs fundamentally from traditional retail, combining a richer behavioral data trace with a narrower set of controllable parameters. This study addresses the resulting gap between the volume of available behavioral data and the absence of an integrated decision support architecture that connects this data to the several distinct types of decisions a seller must make. The aim of the study is to develop an enterprise-architecture model, in the ArchiMate notation, of a decision support system (DSS) for marketplace sellers, together with the mathematical models underlying its analytical and decision-support modules. The study applies methods of systematic literature analysis, enterprise architecture modeling, and mathematical modeling, including discrete-time hazard models and the Kolmogorov-Gabor polynomial. The resulting architecture comprises Business- and Application-layer ArchiMate models spanning four seller roles and four decision scenarios, supported by a shared analytical pipeline and explicit integration with the marketplace platform and external market-data providers. The proposed architecture and mathematical apparatus can be used as a reference design for information systems supporting marketplace sellers and as a basis for further empirical validation.

Keywords: decision support system, enterprise architecture, ArchiMate, marketplace, consumer behavior, Kolmogorov–Gabor polynomial, discrete-time hazard model, recommender system

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АРХИТЕКТУРА И МАТЕМАТИЧЕСКОЕ ОБЕСПЕЧЕНИЕ СИСТЕМЫ ПОДДЕРЖКИ ПРИНЯТИЯ РЕШЕНИЙ ПРОДАВЦОВ МАРКЕТПЛЕЙСОВ

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Аннотация. Рост маркетплейсов как многосторонних цифровых платформ сформировал для продавца среду принятия решений, принципиально отличную от традиционной розницы: более детализированный поведенческий след покупателя сочетается с более узким набором управляемых параметров. Исследование обращается к разрыву между объёмом доступных поведенческих данных и отсутствием целостной архитектуры поддержки принятия решений, связывающей эти данные с разными типами решений продавца. Цель статьи – разработка архитектурной модели (в нотации ArchiMate) системы поддержки принятия решений (СППР) продавца маркетплейса и математического обеспечения её аналитических и решающих модулей. Использованы методы систематизации научной литературы, архитектурного моделирования предприятия и математического моделирования, включая дискретно-временные модели риска и полином Колмогорова-Габора. Предложенная архитектура охватывает бизнес- и прикладной слои ArchiMate-модели для четырёх ролей продавца и четырёх сценариев решений – позиционирование, рекомендации, модификацию ассортимента и пополнение запасов, – опирающихся на единый аналитический конвейер и явную интеграцию с платформой маркетплейса и внешними поставщиками рыночных данных. Предложенные архитектура и математический аппарат могут служить эталонным решением для информационных систем поддержки продавцов на маркетплейсах и основой для дальнейшей эмпирической апробации.

Ключевые слова: система поддержки принятия решений, архитектура предприятия, ArchiMate, маркетплейс, поведение потребителей, полином Колмогорова-Габора, дискретно-временная модель риска, рекомендательная система

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Introduction

Online marketplaces have become one of the dominant formats of retail trade, but for an individual seller a marketplace is a fundamentally different operating environment than a conventional store or even a seller's own online shop. A marketplace is a multi-sided digital platform: the seller does not control the storefront, the search-ranking logic, or most of the points of contact with the buyer, and instead operates within rules set by the platform operator (The Open Group, 2022). At the same time, the platform records a far more detailed behavioral trace of the buyer than is available at a conventional point of sale – product-page views, transitions from search and recommendation blocks, cart additions without purchase, repeat visits, and reactions to price changes and promotions. This combination of reduced control and increased data availability is the central feature that distinguishes seller decision-making on a marketplace from decision-making in traditional retail (Dholakia and Zhao, 2019).

Research on consumer behavior in this environment is extensive. A systematic review by K.

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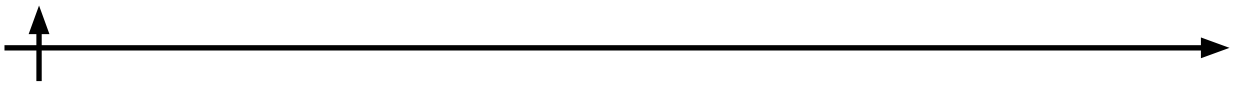


Singh and R. Basu, built on the TCCM (theory-context-characteristics-methodology) framework and covering 197 publications, shows that research on online shopping behavior has progressively shifted from describing isolated behavioral factors toward analyzing the platform context in which a purchase occurs (Singh and Basu, 2023). A more recent systematic review by Q. Liu and co-authors, covering 127 peer-reviewed studies published between 2012 and 2023, systematizes the data sources used in consumer-behavior research and the analytical methods applied to them, and observes that most studies are limited to a single data type or a single analytical task rather than an end-to-end processing architecture (Liu et al, 2026). This observation is directly relevant to the problem addressed in the present study: the volume of behavioral data available to a seller is growing, but the number of architectural solutions that connect this data to the seller's various managerial decisions is not growing proportionally.

A separate stream of research addresses the architecture of e-commerce information systems. K. Zong and co-authors propose an intelligent decision support system for e-commerce based on operations-research methods, oriented toward the seller's optimization problems (Zong et al, 2021). Y. Huang and co-authors describe the architecture of a next-generation e-commerce platform, distinguishing data, service, and user-interaction layers (Huang et al, 2019). T. Wulfert and E. Karger, on the basis of an analysis of several digital-platform architectures and expert interviews, propose a four-layer architecture framework for e-commerce platforms (Wulfert and Karger, 2022) – the work most closely related, in its logic, to the architecture developed below. However, all of these studies model the architecture from the standpoint of the platform or of e-commerce in general, rather than from the standpoint of the seller as an independent stakeholder of the marketplace. A narrower but closely related example is the decision support system for product recommendation proposed by S. Acharjee and co-authors, which shows how behavioral data can be decomposed into a single decision (a recommendation) but does not address the seller's other decision types (Acharjee et al, 2017).

Domestic studies of retail digitalization likewise document the growing importance of behavioral data for managerial decisions, primarily using data from traditional retail chains. N.A. Kalashnikov, comparing the digitalization practices of leading Russian and foreign retailers, shows that the most digitally mature companies use digital tools not only in buyer communication but also in assortment and category management (Kalashnikov, 2023). I.A. Katasonov, using an experiment on automating the management of assortment matrices, demonstrates that systematizing behavioral data at the category level increases margin without expanding the category-management staff (Katasonov, 2022). These studies confirm the practical importance of the problem, but the specific feature of a marketplace – the separation of the seller's and the platform operator's roles – remains outside their scope.

Two further branches of the literature inform the design of the seller-side analytical pipeline developed in this study. The first concerns the behavioral features used to characterize a customer: M. Platzer and T. Reutterer show that the regularity of purchase timing, not only its frequency, materially improves the prediction of future customer activity (Platzer and Reutterer, 2016), and Y. Zhang, E.T. Bradlow and D.S. Small show that a clumpiness measure of the purchase sequence adds predictive power beyond conventional recency–frequency–monetary (RFM) indicators (Zhang et al, 2015). The second concerns flexible non-linear modeling of consumer behavior: building on A.N. Kolmogorov's representation theorem (Kolmogorov, 1957) and on A.G. Ivakhnenko's polynomial theory of complex systems (Ivakhnenko, 1971), which together underlie the Group Method of Data Handling (GMDH), recent work continues to extend this family of models – for instance, M. Amiri and S. Soleimani propose a machine-learning-enhanced GMDH variant that improves on the conventional algorithm (Amiri and Soleimani, 2021). The authors' own prior work has examined the potential of the Kolmog-

orov-Gabor polynomial specifically for modeling consumer behavior (Lyovina and Liu, 2026) and, more generally, the assessment of the digital maturity of economic systems (Ilyin I.V. et al, 2015) and the practice of structured information-system design in business management (Ilyin et al, 2015; Bril et al, 2017), which together form the methodological lineage continued in the present study.

Taken together, the literature reveals a gap between three otherwise mature directions: systematic reviews of consumer behavior in digital environments (Dholakia and Zhao, 2019; Singh and Basu, 2023; Liu et al, 2026), architectural solutions for e-commerce oriented toward the platform or toward a single task (Zong et al, 2021; Huang et al, 2019; Wulfert and Karger, 2022; Acharjee et al, 2017), and studies of the digitalization of managerial decisions in retail conducted on traditional-retail data (Kalashnikov, 2023; Katasonov, 2022). None of these directions proposes a decision support architecture that is built from the standpoint of the marketplace seller and that connects a single stream of behavioral data to several heterogeneous types of decisions at once, nor do they specify the mathematical apparatus by which such an architecture's analytical modules would operate.

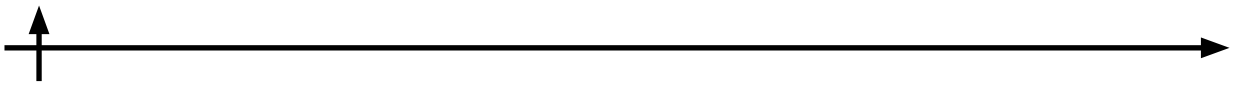
The aim of this study is to develop an enterprise-architecture model, in the ArchiMate notation, of a decision support system for a marketplace seller, together with the mathematical models underlying its analytical and decision-support modules. To achieve this aim, the following tasks are addressed: (1) to characterize the specifics of seller decision-making on a marketplace compared with traditional retail and to identify the corresponding decision-making roles; (2) to construct an ArchiMate model of the Business and Application layers of the decision support system, including its integration with the marketplace platform and external data providers; (3) to specify the mathematical models — behavioral feature construction, the discrete-time hazard and survival model, the Kolmogorov-Gabor polynomial extension, and the recommender and positioning scoring functions — that operationalize the architecture's analytical and decision-support modules.

Materials and Methods

The study is conceptual and methodological in character: it develops a reference architecture and its mathematical apparatus rather than validating them empirically on a specific marketplace dataset; empirical validation is identified as a direction for future work in Section 4. Three groups of methods were used to obtain the results presented in Section 3.

Literature analysis and systematization. The research gap underlying the study (Section 1) was established through a systematic review of four bodies of literature: systematic reviews of consumer behavior in digital environments, architectural solutions for e-commerce information systems, studies of retail digitalization, and the methodological literature on flexible non-linear modeling of consumer behavior. Sources were selected to cover both recent (predominantly 2015–2026) international publications and the relevant domestic literature, and were synthesized to identify which decision types and architectural layers had already been addressed and which had not.

Enterprise architecture modeling. The decision support system architecture is modeled using the ArchiMate enterprise-architecture notation (The Open Group, 2022), which distinguishes a Business layer (roles, processes, services, and interfaces) from an Application layer (components, services, and functions) and supports explicit modeling of external systems through dedicated relationship types (assignment, realization, serving, and flow). The Business layer was derived from the decision-making roles and decision types identified in Section 1; the Application layer was derived by decomposing the data-to-decision pipeline into four functional stages (data collection, data processing, behavioral analytics, and decision support) consistent with the



architecture proposed in the authors' companion study of the same decision-making process, and by further decomposing the decision-support stage into the parallel components needed to support several decision scenarios from a single analytical pipeline.

Mathematical and statistical modeling. The analytical modules of the architecture are formalized using four classes of methods: descriptive feature construction for recency, frequency-regularity, monetary value, and promotion exposure, following recency-frequency-monetary (RFM) and purchase-timing-regularity conventions established in the customer-base analysis literature (Platzer and Reutterer, 2016; Zhang et al, 2015); a discrete-time logistic hazard model and the corresponding survival function for churn and repeat-purchase forecasting; a Kolmogorov-Gabor polynomial extension of the hazard model's linear predictor, estimated in the manner of the Group Method of Data Handling through incremental, validation-driven combination of pairwise partial descriptors (Kolmogorov, 1957; Ivakhnenko, 1971; Amiri and Soleimani, 2021); and similarity- and segment-based scoring functions for the recommender-engine and product-positioning components. The exact specification, notation, and origin of each formula are given in Section 3.4.

Results and Discussion

3.1. Decision-Making Roles and the Architecture Design Approach

The proposed decision support system (DSS) is designed for a marketplace seller rather than for the marketplace platform itself. On the seller's side, decision-making is distributed across 4 roles that share the same underlying stream of behavioral data but act on it differently:

— a pricing manager, who sets the price and market positioning of a product;

— a promotion manager, who configures advertising campaigns and the personalisation logic shown to buyers;

— a category (assortment) manager, who decides which items to add to, remove from, or bundle within the product line;

— an inventory manager, who plans the volume and timing of stock replenishment.

All 4 roles share a common overarching objective — higher repeat-purchase rates and revenue at a sustained level of customer satisfaction — but this objective is operationalised differently for each role, which is the central design constraint behind the architecture presented below: the DSS must turn a single underlying analysis of buyer behaviour into several distinct, role-specific recommendations rather than a single generic output.

To make this requirement explicit and traceable, the architecture is modelled using the ArchiMate enterprise-architecture notation (The Open Group, 2022), which distinguishes a Business layer (the roles, processes, services and interfaces visible to the seller) from an Application layer (the software components, services and functions that realise them) and allows external systems — the marketplace platform itself and third-party market-data providers — to be modelled explicitly as integration points rather than left implicit. This separation makes clear which parts of the system concern what the seller needs (Business layer) and which concern how it is delivered (Application layer), and it allows the same application service to be reused across more than one business process — a property exploited extensively below and developed conceptually in our companion study of the same decision-making process (Dholakia and Zhao, 2019).

3.2. ArchiMate Model: Business and Application Layers

Figure 1 presents the ArchiMate model of the Business and Application layers of the seller DSS. In the Business layer, each of the four roles introduced above is assigned to a corresponding business process (Define Pricing and Positioning, Manage Recommendations, Manage Assortment, and Plan Replenishment) and each process realises a dedicated business service:

Product Positioning Service, Recommendation Service, Assortment Management Service, and Inventory Replenishment Service, respectively. All four roles access the system through a single business interface, the Seller Dashboard, which is the only point of contact a human role has with the DSS; this is a deliberate simplification, since in practice all four business processes could equally be triggered from the same dashboard rather than through four separate entry points.

In the Application layer, each business service is served by a dedicated application service (Positioning Recommendation Service, Recommendation Generation Service, Assortment Recommendation Service, and Replenishment Recommendation Service) and all four application services are realised by a single Application Component, the Decision Support Module. Modelling the four application services as realised by one shared component, rather than by four independent components, reflects the architectural decision discussed in (Dholakia and Zhao, 2019): the value of the architecture lies precisely in routing a single, shared analytical result to several different decision types, and a shared underlying component is the natural way to express this in ArchiMate.

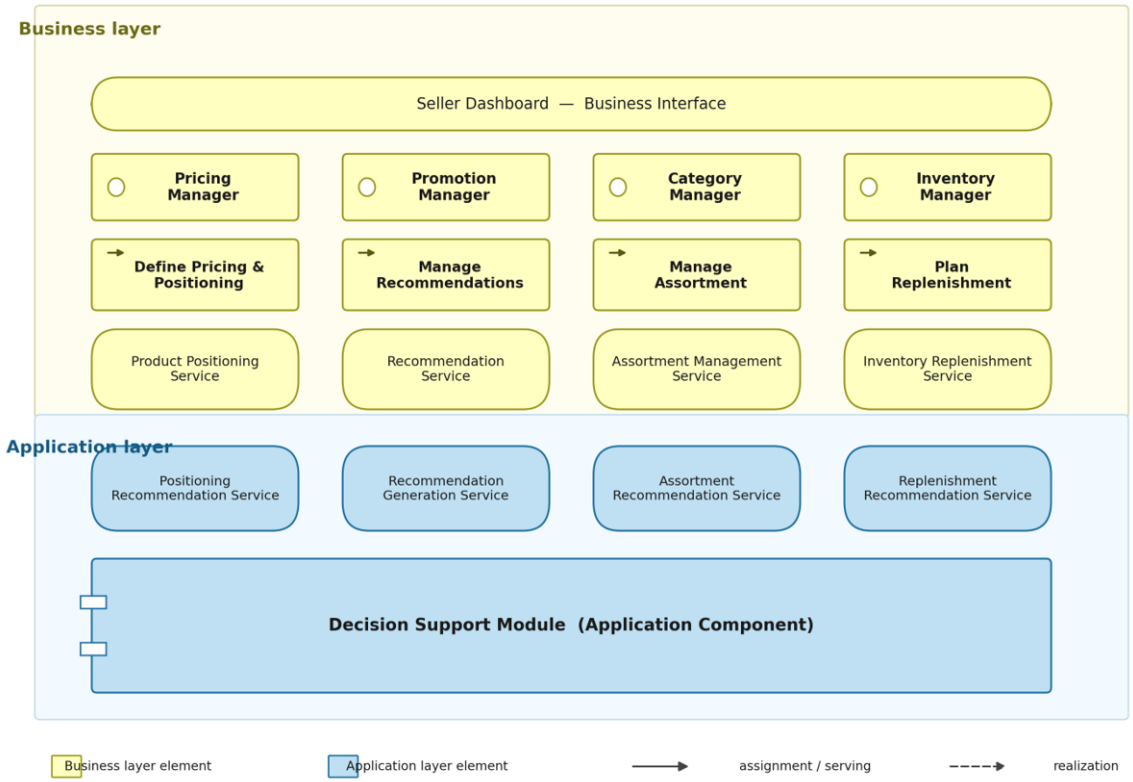


Fig. 1. ArchiMate model of the Business and Application layers of the seller DSS

3.3. Application Layer: Internal Structure and External Integration

Figure 2 details the internal structure of the Application layer that Figure 1 shows only at the level of services and a single aggregate component. Four application components form a left-to-right processing pipeline, corresponding to the four stages of data collection, processing, analysis and decision support introduced in (Dholakia and Zhao, 2019):

— The Data Collection Module connects to two external application components: the Marketplace Platform API, which provides the seller's own view, cart, order and promotion data through the seller and advertising accounts, and an external Competitor and Market Data Provider, which supplies competitor pricing, assortment and seasonality signals. Both are modelled

as external components connected through flow relationships, reflecting that neither is under the seller's control and both must be integrated through whatever interface the respective provider exposes.

— The Data Processing Module cleanses and integrates the incoming data streams and computes the recency-frequency-monetary-promotion (RFM-P) features described in Section 3.4.1, which serve as the common input representation for all downstream analytics.

— The Behavioral Analytics Module contains three internal functions: customer segmentation, descriptive and diagnostic analytics, and – the function carrying the heaviest mathematical content of the architecture – demand and repeat-purchase forecasting, which combines a discrete-time hazard model with a Kolmogorov-Gabor polynomial extension (Sections 3.4.2–3.4.3).

— The Decision Support Module contains five internal components, one per decision scenario plus the interface component: Positioning, Recommender Engine, Assortment Optimization, Replenishment Planning, and Seller Interface. The Seller Interface component is the one that realises the Seller Dashboard business interface shown in Figure 1, closing the loop between the Application layer detailed in Figure 2 and the Business layer shown in Figure 1.

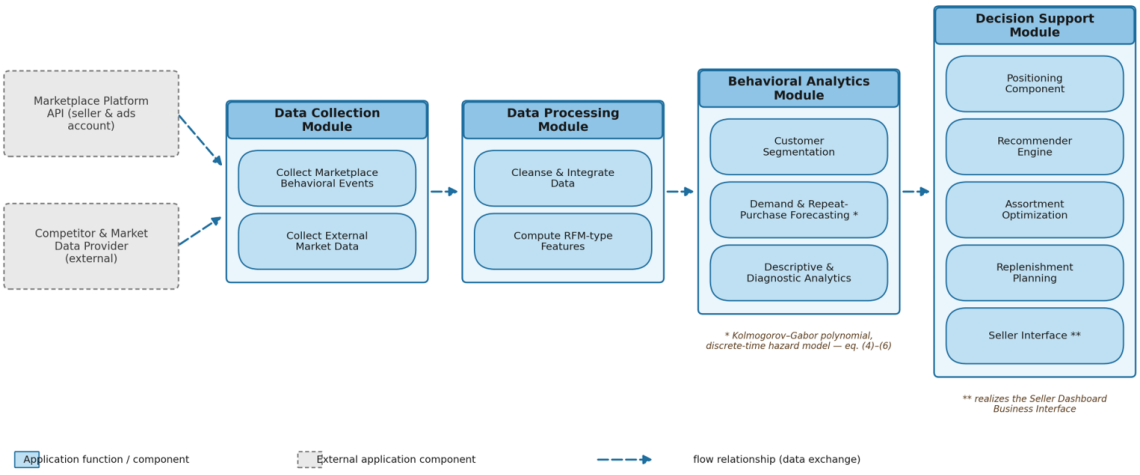


Fig. 2. Model of the Application layer internal structure and external system integration

This separation between a single shared analytical pipeline (Data Collection, Data Processing, Behavioral Analytics) and several parallel decision-specific components within the Decision Support Module is the architectural mechanism that allows one analytical result to support several scenarios, as discussed in Section 3.1.

3.4. Mathematical Models of the Analytics and Decision Support Modules

This section specifies the main formulas used inside the modules of Figure 2 that perform quantitative modelling, defines the notation of every variable, and indicates where each quantity originates in the data architecture described in Section 3.3.

3.4.1. Behavioral feature construction

For a customer i with purchase timestamps $t_{i,1},...,t_{i,n_i}$ and the order amounts and promotion flags recorded for each purchase, the Data Processing Module computes four behavioral features. Recency $R_i(t)$, equation (1), is the time elapsed, as of the current moment t, since the customer's most recent purchase $t_{i,last}$; it is recomputed every time a new event from the Marketplace Platform API arrives:

$$R_i(t) = t - t_{i,last} \qquad (1)$$

The mean inter-purchase interval $\Delta t_{i,avg}$ and its inverse, the frequency-regularity feature

F_i, equation (2), summarise how regularly the customer purchases, a property identified in the literature review [2] as more informative for retention than a simple purchase count:

$$\Delta t_{i,avg} = \frac{1}{n_1 - 1}\sum_{k=1}^{n_1-1}\Delta t_{i,k}, \quad F_i = \frac{1}{\Delta t_{i,avg}} \qquad (2)$$

The monetary feature M_i and the promotion-exposure share P_i, equations (3), are, respectively, the customer's mean order value and the share of the customer's purchases that took place during a promotional campaign:

$$M_i = \frac{1}{n_i}\sum_{k=1}^{n_i} A_{i,k}, \quad P_i = \frac{1}{n_i}\sum_{k=1}^{n_i} promo_{i,k} \qquad (3)$$

All four features are stored at the customer level in the data warehouse populated by the Data Processing Module and form the common input vector $x_i = (R_i, F_i, M_i, P_i)$ used by every downstream module.

3.4.2. Discrete-time hazard and survival model

The Demand and Repeat-Purchase Forecasting function inside the Behavioral Analytics Module estimates, for every discrete time period *t* (a day, at the granularity used by the architecture), the conditional probability $h_{i,t}$ that customer *i* churns in period *t* given that no churn has occurred before *t*. The baseline specification is a discrete-time logistic hazard model, in which the log-odds of the hazard, equation (4), are a linear function of the behavioral feature vector x_i, so that the hazard itself, equation (5), is a logistic transform of that linear predictor:

$$logit(h_{i,t}) = \beta_0 + \beta_1 R_i(t) + \beta_2 F_i + \beta_3 M_i + \beta_4 P_i \qquad (4)$$

$$h_{i,t} = \frac{1}{1 + \exp(-(\beta_0 + \beta_1 R_i(t) + \beta_2 F_i + \beta_3 M_i + \beta_4 P_i))} \qquad (5)$$

The coefficients $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4$ are estimated from historical churn outcomes recorded through the Marketplace Platform API (a customer is labelled as churned once the observed inter-purchase gap exceeds a chosen inactivity threshold, e.g. 180 days, as in our companion empirical analysis). The corresponding survival function $S_i(t)$ – the probability that customer i is still active after t periods – follows directly from the hazard sequence, equation (6), as the product of the period-by-period retention probabilities $(1 - h_{i,\tau})$, expressed here in logarithmic form for numerical stability.

$$\ln S_i(t) = \sum_{\tau=1}^{t} \ln(1 - h_{i,\tau}) \qquad (6)$$

3.4.3. Kolmogorov-Gabor polynomial extension

The linear specification (4) is interpretable, but it cannot represent interaction effects between behavioral features, for instance, the possibility that promotion exposure only affects churn risk for customers whose purchase interval has already become irregular. To capture such effects without abandoning interpretability, the linear predictor inside (4) can be replaced by a Kolmogorov-Gabor polynomial of the behavioral features, equation (7):

$$y_i = a_0 + \sum_{j=1}^{n} a_j x_{ij} + \sum_{j=1}^{n}\sum_{k=j}^{n} a_{jk} x_{ij} x_{ik} + \ldots \qquad (7)$$

Here $x_{i1}, \ldots, x_{in}$ denote the n input features of customer *i* ($n = 4$ for the baseline feature set $x_i = (R_i, F_i, M_i, P_i)$, extendable with category- or season-specific covariates), y_i is the modelled target (the hazard logit, or alternatively the expected repurchase time or a recommendation-relevance score, depending on which decision the model output feeds), and $a_0, a_j, a_{jk}, \ldots$ are polynomial coefficients: a_j capture the same linear effects as the β coefficients of model (4), the a_{jk} terms explicitly capture pairwise interactions between features, and higher-order terms (denoted by the ellipsis) capture progressively more complex non-linearities at the cost of additional coefficients to estimate.

The polynomial form (7) originates from A.N. Kolmogorov's representation theorem and D. Gabor's work on non-linear system identification through polynomial expansions, and was

later adopted by A.G. Ivakhnenko as the building block of the Group Method of Data Handling (GMDH) (Liu et al, 2026; Zong et al, 2021; Svetunkov, 2024). In the GMDH-style estimation procedure relevant to this module, the full polynomial (7) is not fitted directly; instead, the algorithm constructs partial second-degree descriptors, equation (8), for every candidate pair of input features (x_j, x_k), fits each one by ordinary least squares, and retains only the partial models that improve an external validation criterion (e.g. out-of-sample prediction error on a held-out set of customers), discarding the rest:

$$z_p = a_0 + a_1 x_j + a_2 x_k + a_3 x_j x_k + a_4 x_j^2 + a_5 x_k^2 \qquad (8)$$

Surviving partial descriptors are then combined into new intermediate variables and the procedure repeats, layer by layer, until the validation criterion stops improving. This incremental, validation-driven construction is what allows the Kolmogorov-Gabor specification to capture non-linear interactions among the behavioral features of Section 3.4.1 while controlling the overfitting risk that an unrestricted high-order polynomial would otherwise carry — and is the specific extension that our companion methodological study (Singh and Basu, 2023) identifies as the most promising direction for the predictive function of this architecture.

3.4.4. Recommender engine scoring

The Recommender Engine component of the Decision Support Module ranks candidate products p for customer i using a score, equation (9), that combines a behavioral-similarity term with a segment-affinity term:

$$Score(i, p) = w_1 \cos(v_1, v_p) + w_2 Aff(i, p) \qquad (9)$$

The similarity term is computed as the cosine similarity, equation (10), between the behavioral vectors v_1 and v_p — constructed, respectively, from customer *i*'s interaction history and from product p's co-occurrence pattern with other products in past purchases — and the affinity term *Aff (i,p)* reflects whether product p is typically purchased by customers in the same behavioral segment as *i*, where segments are produced by the customer-segmentation function of the Behavioral Analytics Module:

$$\cos(v_1, v_p) = \frac{v_i \cdot v_p}{\|v_i\| \|v_p\|} \qquad (10)$$

The weights w_1, w_2 are tuned so that the relative contribution of pure behavioral similarity versus segment-level affinity can be adjusted without retraining the underlying segmentation or similarity computation.

3.4.5. Positioning index

The Positioning component computes a positioning index for each product, equation (11), combining the product's price relative to the category's median competitor price — obtained through the external Competitor and Market Data Provider — with the customer segment's predicted price sensitivity $Sens_i$, obtained as one of the outputs of the hazard/polynomial model of Sections 3.4.2-3.4.3:

$$Pos_i = \gamma_1 \left(\frac{Price_i}{Price_{med}} \right) + \gamma_2 Sens_i \qquad (11)$$

The weights γ_1, γ_2 determine how strongly relative price standing versus predicted sensitivity drive the resulting recommendation that is surfaced to the pricing manager through the Seller Dashboard.

Conclusion

This study has developed an enterprise architecture model and a mathematical apparatus for a decision support system serving marketplace sellers, addressing the gap between the volume of behavioral data available on marketplaces and the absence of an architecture that connects this

data to the seller's several distinct decision types. The multi-sided nature of a marketplace gives the seller a fundamentally different set of behavioral data sources and controllable parameters than traditional retail, which means that architectural solutions developed for traditional retailers or for e-commerce platforms as a whole are not directly sufficient for the seller as an independent stakeholder (Dholakia and Zhao, 2019; Kalashnikov, 2023; Katasonov, 2022).

Modeling the decision support system in the ArchiMate notation, with a Business layer of seller roles, processes, and services and an Application layer of a shared analytical pipeline, makes it possible to route a single underlying analysis of buyer behavior to several role-specific business services rather than treating each decision type as a separate system. Decomposing the Application layer into a shared data-collection-processing-analytics pipeline and a set of parallel, decision-specific components within the Decision Support Module is the architectural mechanism that allows one analytical result to support several scenarios – positioning, recommendation, assortment modification, and inventory replenishment – simultaneously, which distinguishes the proposed architecture from the single-task or platform-oriented solutions identified in the literature review (Zong et al, 2021; Huang et al, 2019; Acharjee et al, 2017). Specifying the discrete-time hazard model and its Kolmogorov-Gabor polynomial extension alongside the architecture, with explicit notation for every variable and an explanation of the constructive (GMDH-style) estimation procedure, makes the analytics module's predictive function both interpretable and capable of representing non-linear interactions between behavioral features that a purely linear specification would miss (Kolmogorov, 1957; Ivakhnenko, 1971; Amiri and Soleimani, 2021; Svetunkov, 2024).

The study has a corresponding limitation: the proposed architecture and mathematical models have not been validated empirically on data from an operating marketplace. Future work by the authors will focus on such an empirical validation, including estimation of the Kolmogorov-Gabor polynomial's coefficients on real seller transaction data and a comparative assessment of its predictive performance against the linear hazard specification.

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PATIENT DATA MANAGEMENT IN A COMMERCIAL CLINIC: AUDIT, SEGMENTATION, AND DATA STRATEGY

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Abstract. This article examines data management methods in a commercial medical organization. Based on an audit of the information infrastructure of a multidisciplinary clinic, the study describes procedures for patient data profiling and deduplication, develops a KPI system using the Balanced Scorecard methodology, constructs an RFM segmentation model to identify patients at high risk of churn, and proposes a phased data strategy for transitioning toward data-driven management. The paper also provides a systematic review of Data Governance frameworks and digital transformation practices in healthcare, contextualizing the clinic-level findings within broader trends in health data management.

Keywords: data management, Data Governance, data audit, data profiling, deduplication, ETL, RFM segmentation, patient churn, KPI, Balanced Scorecard, digital transformation, healthcare analytics

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УПРАВЛЕНИЕ ДАННЫМИ О ПАЦИЕНТАХ В КОММЕРЧЕСКОЙ КЛИНИКЕ: АУДИТ, СЕГМЕНТАЦИЯ И СТРАТЕГИЯ ОБРАБОТКИ ДАННЫХ

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Аннотация. В данной статье всесторонне рассматриваются методы управления данными в современной коммерческой медицинской организации. На основе аудита информационной инфраструктуры многопрофильной клиники в исследовании описаны процедуры профилирования и дедупликации данных о пациентах, разработана комплексная и адаптируемая система ключевых показателей эффективности с использованием хорошо зарекомендовавшей себя методологии сбалансированной системы показателей, построена модель сегментации RFM для выявления пациентов с высоким риском оттока и предложена поэтапная стратегия обработки данных для перехода к управлению, основанному на данных. В статье также представлен систематический обзор систем управления данными и практик цифровой трансформации в здравоохранении, в котором результаты, полученные на уровне клиник, рассматриваются в контексте более широких тенденций в области управления медицинскими данными.

Ключевые слова: управление данными, пуководство данными, аудит данных, профилирование данных, дедупликация, ETL, сегментация RFM, отток пациентов, ключевые показатели эффективности, сбалансированная система показателей, цифровая трансформация, аналитика здравоохранения

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Introduction

Commercial healthcare organizations accumulate significant volumes of patient data, including demographic, clinical, financial, and behavioral information. However, the mere availability of data does not create managerial value; structured procedures for data collection, cleansing, storage, and analysis are required. The transition toward data-driven management in healthcare has been actively discussed in academic literature (Matyushok et al., 2023; Lamotkin et al., 2022), yet practical implementation methods for small and medium-sized clinics remain insufficiently described.

The growing availability of CRM platforms, cloud-based accounting systems, and integrated telephony solutions has lowered the technical barrier for data collection in private medical practice. Yet a persistent gap remains between data accumulation and analytical utilization. Studies examining health information systems in primary care settings consistently identify data fragmentation, poor interoperability, and inadequate governance structures as the principal obstacles to value creation from health data (Boonstra et al., 2014; Kruse et al., 2016).

This article addresses that gap by presenting the results of an audit and the design of a data

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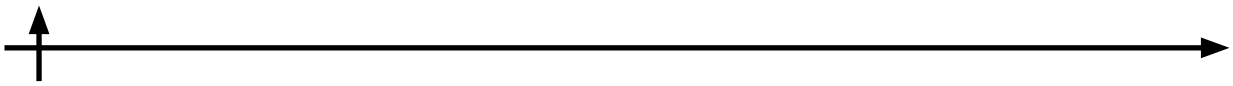


management system for a multidisciplinary commercial clinic specializing in plastic surgery, cosmetology, dentistry, and phlebology, with a database of approximately 40,000 patient records. The study covered the period from 2024 to 2025. Data sources included the organization's CRM system, accounting system, and IP telephony system.

The paper is structured as follows. Section 2 reviews the relevant literature on Data Governance frameworks, digital transformation in healthcare, and customer segmentation methodologies. Section 3 describes the data audit methodology and results. Section 4 presents the KPI system developed for the clinic. Section 5 details the RFM segmentation model and churn analysis. Section 6 outlines the phased data strategy. Section 7 discusses limitations and directions for further research, followed by concluding remarks.

Scientific novelty of this study lies in the following. First, an integrated multi-domain data quality assessment framework is proposed that combines four metrics (completeness, accuracy, timeliness, consistency) across five domain categories (demographic, clinical, operational, financial, reputational) and a two-stage exact-plus-fuzzy deduplication procedure adapted to the specific constraints of private outpatient CRM systems in the Russian market — an area not previously addressed in applied Data Governance literature. Second, a BSC-based KPI system is developed that explicitly links operational data quality indicators to the financial metric of patient Lifetime Value, establishing a quantifiable causal chain between data governance maturity and economic outcomes at the clinic level. Third, an RFM segmentation model calibrated for the commercial healthcare context is applied and its economic effect on churn reduction is formally estimated. Prior work applying data management tools to efficiency improvement in similar organizational contexts, such as Krokhina (Krokhina, 2024), has focused on biotechnology settings; the present study extends this methodological approach to the healthcare service sector and adds the economic quantification layer missing from earlier applications.

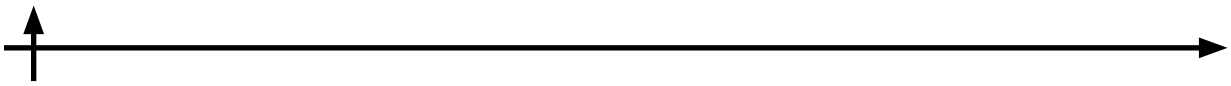
Literature Review

Data Governance: Conceptual Foundations

The concept of Data Governance emerged in corporate information management literature in the late 1990s and was systematically codified in the DAMA-DMBOK framework, first published in 2009 and substantially revised in 2017 (DAMA International, 2017). DAMA defines Data Governance as "the exercise of authority, control and shared decision-making over the management of data assets." The framework encompasses eleven knowledge areas, including data quality management, metadata management, master data management, and data security, which together define the organizational and technical conditions for treating data as a strategic asset.

Subsequent academic literature has elaborated the governance concept along several dimensions. Khatri and Brown (Khatri and Brown, 2010) proposed a five-domain decision framework for Data Governance, covering data principles, data quality, metadata, data access, and data lifecycle, arguing that governance effectiveness depends on the clarity of decision rights rather than the sophistication of technical infrastructure. Abraham et al. (Abraham et al., 2019) extended this perspective to cloud-based environments, showing that traditional governance architectures require substantial adaptation when data is distributed across multiple platforms — a condition highly relevant to small healthcare organizations relying on a combination of SaaS CRM, cloud accounting, and hosted telephony systems.

A recurrent finding in the empirical governance literature is the importance of organizational factors alongside technical ones. Otto (Otto, 2011) conducted a comparative analysis of Data Governance implementations across fifteen large enterprises and found that the appointment of data owners — individuals formally accountable for the quality and availability of a defined



data domain — was the single strongest predictor of governance maturity. This finding has direct implications for the clinic-level context, where informal data ownership (i.e., no one is explicitly responsible for the accuracy of patient records) is the default condition. The role of IT infrastructure reliability as a foundational precondition for data governance is further discussed in Gichko and Chemeris (Gichko and Chemeris, 2025), who analyze disaster recovery statistics with a focus on data preservation.

Digital Transformation in Healthcare: Evidence and Challenges

The digitalization of healthcare has been the subject of extensive policy attention and academic research, particularly following the accelerated adoption of telehealth and digital patient management systems during the COVID-19 pandemic. At the macro level, health data digitalization is associated with improvements in care coordination, reduction of diagnostic redundancy, and more precise population health management (Topol, 2019). At the organizational level, however, the evidence is more mixed.

Adler-Milstein et al. (Adler-Milstein et al., 2015) analyzed electronic health record (EHR) adoption patterns across US hospital systems and found that the mere implementation of EHR technology did not produce operational improvements in the absence of corresponding workflow redesign and data quality protocols. This finding — often summarized as "garbage in, garbage out" — has been replicated in numerous subsequent studies and underscores the centrality of data quality management as a precondition for digital transformation value realization.

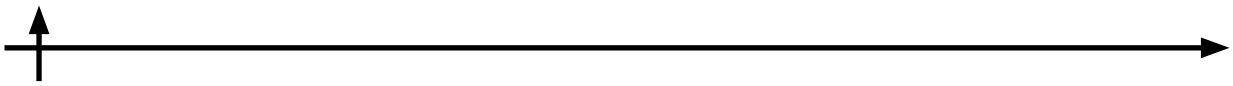
In the context of private and commercial healthcare, the literature identifies a specific set of challenges. Unlike public hospital systems, private clinics typically lack dedicated IT departments, operate under tighter resource constraints, and face stronger commercial pressure to demonstrate short-term returns on technology investments (Thimbleby, 2013). These conditions make comprehensive digital transformation programs difficult to sustain, and push organizations toward incremental, analytics-first approaches that prioritize rapid value realization over architectural completeness.

Bates et al. (Bates et al., 2014) identified five priority areas for data use in healthcare organizations: high-cost patient management, adverse event prevention, disease management, medication management, and population health monitoring. For commercial outpatient clinics, a sixth priority — patient retention and lifetime value management — is arguably of equal or greater strategic importance, as revenue sustainability depends directly on repeat visit rates and the ability to identify and reactivate at-risk patients.

Customer Segmentation in Healthcare: RFM and Beyond

The application of customer segmentation methodologies originating in retail and e-commerce to healthcare settings has gained traction over the past decade, driven by the increasing commercialization of medical services and the availability of CRM data at the patient level. The RFM framework — originally developed by Hughes (Hughes, 2000) for direct marketing — classifies customers according to the recency of their last purchase (R), the frequency of their transactions (F), and their total monetary value (M). Its appeal lies in its conceptual simplicity, low computational requirements, and strong empirical performance in identifying high-value and at-risk customer segments (Fader et al., 2005).

In healthcare applications, RFM has been used to segment patient populations for purposes ranging from chronic disease management outreach to commercial retention programs. Yeh and Chiu (Yeh and Chiu, 2009) applied RFM segmentation to a dental clinic database and demonstrated that segments defined by low recency and frequency scores showed significantly higher actual churn rates over a 12-month follow-up period, providing empirical validation for using these segments as proxies for churn risk. Similar results have been reported in ophthalmology (Wei et al., 2010) and cosmetic medicine (Moosavi et al., 2022) settings.



It is important, however, to maintain a clear terminological distinction between RFM-based risk identification and predictive churn modeling in the machine learning sense. RFM is a descriptive method: it segments the existing customer base by observed historical behavior without constructing a probabilistic model of future behavior. A predictive churn model, by contrast, estimates the probability that a given patient will not return within a defined time window, based on a feature set that may include RFM variables alongside demographic, clinical, and behavioral predictors, trained on a labeled historical dataset (Verbeke et al., 2012). The two approaches are complementary rather than interchangeable, and the appropriate choice depends on the volume and quality of available labeled data.

Data Quality Management: Metrics and Methods

Data quality management has been conceptualized along multiple dimensions in the literature. The most widely adopted framework, proposed by Wang and Strong (Wang and Strong, 1996), identifies four categories of data quality: intrinsic (accuracy, objectivity, believability), contextual (relevance, completeness, timeliness, consistency), representational (interpretability, ease of understanding, conciseness), and accessibility (accessibility, access security). For operational data management in a CRM context, the most practically significant dimensions are completeness, accuracy, timeliness, and consistency — the four metrics adopted in the present study. The importance of IT infrastructure reliability for data integrity is further highlighted in recent work on disaster recovery and data preservation (Gichko and Chemeris, 2025).

Deduplication, or the identification and resolution of duplicate records, is among the most resource-intensive data quality tasks in healthcare settings. The challenge is compounded by the absence of universal patient identifiers in many national healthcare systems, which means that the same patient may appear in a CRM database under different phone numbers, name spellings, or demographic combinations. Christen (Christen, 2012) provides a comprehensive taxonomy of record linkage methods, distinguishing between deterministic approaches (exact matching on a key combination), probabilistic approaches (weighted scoring across multiple fields), and machine learning approaches (classification models trained on manually labeled record pairs). For small to medium-sized healthcare databases, deterministic followed by fuzzy matching on name fields offers a cost-effective balance between recall and precision. A complementary content-analysis methodology for identifying business process weaknesses based on corporate reporting indicators (Ilyin and Chemeris, 2023) can be applied to healthcare settings for more granular audit procedures.

Balanced Scorecard in Healthcare Organizations

The Balanced Scorecard (BSC), introduced by Kaplan and Norton (Kaplan and Norton, 1996) as a strategic performance measurement framework, has been extensively adapted to healthcare settings since its original publication. The healthcare BSC literature generally retains the four original perspectives — financial, internal processes, customer/patient, and learning and growth — while adapting the specific metrics to reflect the dual accountability of healthcare organizations to both commercial and clinical outcomes (Zelman et al., 2003).

Inamdar and Kaplan (Inamdar and Kaplan, 2002) conducted a systematic review of BSC implementations in healthcare and identified several recurring patterns. First, financial metrics in healthcare BSC systems tend to emphasize sustainability indicators (cost per visit, payer mix, revenue per physician) rather than profitability alone. Second, patient experience metrics — particularly satisfaction scores and repeat visit rates — are consistently included as leading indicators of financial performance, reflecting the empirical finding that patient loyalty is a primary driver of revenue in outpatient settings. Third, staff performance metrics focused on clinical quality and conversion rates are included in organizations with a strong commercial orientation, consistent with the present study's inclusion of physician-level conversion metrics. An integral

assessment methodology for medical organizations under business process changes is developed in Chemeris et al. (Chemeris et al., 2023), which provides further validation of the causal link between operational metrics and financial outcomes.

Data Audit: Methodology and Results

Audit Design and ETL Process

The audit was conducted using the data profiling method — a systematic analysis of the content, structure, and quality of records across all source systems. Five data domains were evaluated: demographic, clinical, operational, financial, and reputational data. For each domain, four quality metrics were assessed: completeness (share of mandatory fields populated), accuracy (compliance with formatting constraints), timeliness (time elapsed since the last update), and consistency (alignment of identical attributes across different systems) (DAMA International, 2017).

Prior to profiling, an ETL (Extract, Transform, Load) process was applied to consolidate data from the three source systems — CRM, accounting platform, and IP telephony — into a unified analytical layer. The Extract stage involved API-based exports from each system in CSV format. The Transform stage standardized field formats across systems: date formats were unified to ISO 8601 (YYYY-MM-DD), phone numbers normalized to the E.164 standard, and patient name fields converted to a consistent capitalization convention. The Load stage populated a staging database used as the basis for profiling and deduplication procedures.

Deduplication

Deduplication was performed in two stages. The first stage used exact matching based on the combination of phone number and date of birth. The second stage applied fuzzy matching to the full name field with an 85% similarity threshold, enabling the identification of records containing typographical errors and alternative spellings of names.

The procedure revealed that duplicate records accounted for 9.4% of the total database (approximately 3,760 records out of 40,000), corresponding to the upper bound of the typical range for small-business CRM systems lacking regular data cleansing procedures (Christen, 2012). The majority of duplicates (71%) were resolved at the exact-matching stage; the remaining 29% required fuzzy name matching, indicating a substantial share of records where the same patient had provided different contact details across separate registration events.

Domain Quality Assessment

Table 1 summarizes the quality assessment results by domain and metric.

Table 1. Data Quality Assessment by Domain (compiled by the author based on data audit results)

Domain	Completeness	Accuracy	Timeliness	Consistency
Demographic	84%	91%	76%	78%
Clinical	37%	68%	52%	41%
Operational	79%	87%	83%	80%
Financial	98%	97%	96%	95%
Reputational	61%	74%	69%	72%

The lowest data quality was identified in the clinical domain: 63% of patient records lacked structured medical history data due to the partial preservation of paper-based documentation workflows. This finding is consistent with broader patterns in the Russian private healthcare sector, where EHR adoption in outpatient settings lags behind inpatient care (Lamotkin et al.,

2022; Lepekhin et al., 2022; Iliashenko et al., 2020; Ilin et al., 2022). Financial data demonstrated the highest completeness level, with 98% of key fields populated, largely because of accounting compliance requirements.

The reputational domain — encompassing patient satisfaction scores, NPS responses, and review platform data — showed moderate quality, with the primary gap being timeliness: NPS surveys were conducted episodically rather than systematically, resulting in long intervals between data updates for a significant share of the patient base.

KPI System Based on the Balanced Scorecard

Based on the audit results, a system of 12 performance indicators was developed and structured according to the four BSC perspectives (Kaplan and Norton, 1996).

Table 2. KPI System by BSC Perspective (compiled by the author)

Perspective	Indicator	Current / Target
Financial	Revenue per visit (RUB)	3,100 / 3,500
Financial	LTV (RUB)	15,600 / 25,000
Financial	LTV / CAC ratio	7.8 / 12.0
Operations	Schedule utilization (%)	68% / 85%
Operations	Appointment attendance rate (%)	74% / 88%
Operations	Average waiting time (days)	4.2 / 2.0
Customer	NPS score	42 / 65
Customer	Repeat visit rate (%)	63% / 75%
Customer	Annual churn rate (%)	37% / 22%
Customer	Reactivation rate (%)	11% / 25%
Staff	Primary-to-repeat conversion by physician (%)	48% / 65%
Staff	Avg. revenue per physician per month (RUB)	780K / 1.1M

Lifetime Value (LTV) was calculated using the formula: LTV = Average Check x Average Visits Per Year x Average Relationship Duration. Using current values (average check — 3,100 RUB; 1.8 visits per year; 2.8 years of average relationship duration), LTV amounted to approximately 15,600 RUB. Customer Acquisition Cost (CAC) was calculated as the ratio of total marketing expenditure during a period to the number of new patients acquired during the same period, yielding approximately 2,000 RUB. The resulting LTV/CAC ratio of 7.8 indicates economic sustainability of the acquisition model while also revealing substantial potential for growth through improved retention.

The gap between current and target LTV (15,600 vs. 25,000 RUB) reflects the combined effect of three addressable drivers: increasing average visit frequency from 1.8 to 2.5 per year, extending average relationship duration from 2.8 to 3.5 years through proactive retention, and growing the average check through service mix optimization. These drivers correspond directly to the operational and customer-facing KPIs in Table 2, establishing a clear causal logic connecting individual metrics to the financial outcome, as further supported by the integral assessment methodology for medical organizations developed in Chemeris et al. (Chemeris et al., 2023).

RFM Segmentation and Churn Risk Identification

Segmentation Methodology

Patient base segmentation was performed using the RFM methodology (Recency, Frequency, Monetary) — a descriptive approach that divides the customer base into groups according to three dimensions: time since the last visit (R), visit frequency (F), and total spending during the analyzed period (M) (Hughes, 2000). Each patient received a score from 1 to 5 for each dimension based on quintile ranking within the patient base. The final segment was determined by the combination of the three scores, yielding 125 possible cells, which were consolidated into five strategic segments for operational use (Table 3, Figure 1).

Table 2. RFM Strategic Segments and Communication Approach (compiled by the author)

Segment	RFM Profile	Share of Base	Communication Approach
Champions	R5 F5 M5	8%	Loyalty program, referral incentives
Loyal patients	R4-5 F3-5 M3-5	19%	Cross-sell new services, NPS survey
Promising	R3-4 F2-3 M2-3	24%	Activation offers, appointment reminders
At-risk	R2-3 F2-3 M2-4	28%	Reactivation campaign, satisfaction check
Lost	R1-2 F1-2 M1-3	21%	Win-back offer, feedback collection

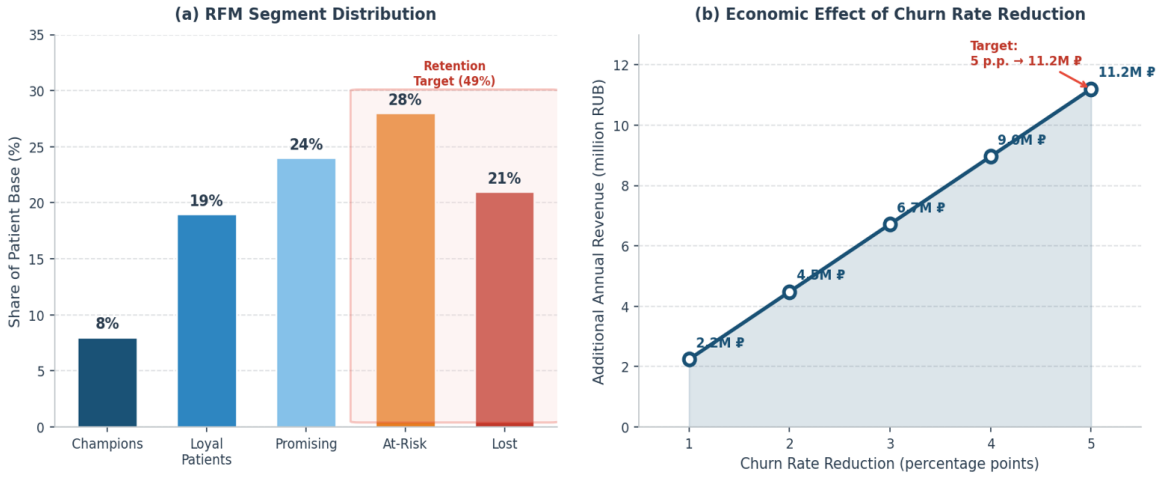
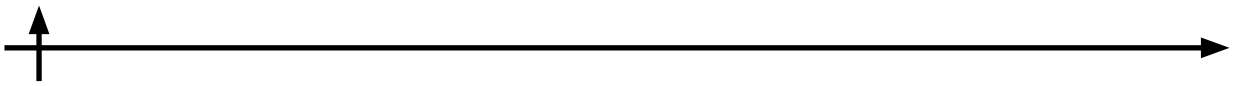


Fig. 1. RFM segmentation results: (a) distribution of patients across strategic segments; (b) estimated economic effect of churn rate reduction (compiled by the author)

Churn Analysis and Economic Effect

It is important to emphasize that RFM is a descriptive segmentation method rather than a predictive model in the strict sense: it does not calculate churn probability but instead identifies groups exhibiting signs of declining activity (Fader et al., 2005). Patients in the "At-risk" and "Lost" segments — defined by low Recency and Frequency scores — were interpreted as the primary target population for retention and reactivation interventions. The transition to a fully predictive churn model based on logistic regression or gradient boosting using labeled training data is planned for the next development phase, as discussed in Section 7.

The current annual churn rate is 37%, defined as the proportion of patients who did not return within 12 months of their last visit. The industry benchmark for multidisciplinary commercial clinics in the Russian private healthcare market is estimated at 20–25% (Lamotkin et al., 2022). The 12–17 percentage point gap represents a significant strategic risk, as each



percentage point of churn corresponds to the loss of approximately 400 patients annually from the active base.

The potential economic effect of churn reduction was estimated as follows. With baseline annual revenue of 24.7 million RUB and a repeat patient share of 63%, a 5 percentage point reduction in the churn rate corresponds to retaining approximately 2,000 additional patients per year. Each retained patient generates an average of 5,580 RUB annually (LTV of 15,600 RUB divided by average relationship duration of 2.8 years), producing an estimated cumulative effect of approximately 11.2 million RUB in additional annual revenue. The costs of communication scenarios (SMS, email, and outbound calls) are estimated at 150–200 RUB per targeted patient annually, yielding a retention program ROI of approximately 250–300% under conservative assumptions.

Data Strategy and Roadmap

Phased Implementation Plan

Based on the audit results and the analytical gaps identified, a phased data strategy was developed consisting of three implementation stages with defined deliverables and success criteria.

Phase 1 (months 1–4): Data Foundation. The primary objective is to establish a reliable, deduplicated single source of truth for patient data. Key deliverables include the introduction of a unified patient identifier enforced at the point of CRM registration, implementation of automated deduplication on a monthly cycle, deployment of a basic KPI dashboard covering the financial and operational metrics in Table 2, and assignment of data owners for each of the five data domains.

Phase 2 (months 5–10): Analytical Layer. Building on the data foundation established in Phase 1, the second phase introduces structured analytical capabilities. Key deliverables include the implementation of the RFM segmentation model with quarterly refresh cycles, configuration of automated communication workflows in the CRM system triggered by segment membership and behavioral events (e.g., appointment cancellation without rescheduling, NPS score below 6), and near-real-time calculation of LTV and CAC metrics integrated into the management dashboard.

Phase 3 (months 11–18): Predictive Layer. The third phase involves the transition to machine learning-based predictive capabilities, contingent on the availability of a sufficiently large labeled dataset (minimum 1,000 confirmed churn events recommended for logistic regression). Key deliverables include a predictive churn model with patient-level probability scores, personalized communication sequences based on predicted churn probability and patient value segment, and integration with a dedicated BI platform for advanced reporting.

Data Governance Principles

The following Data Governance principles are embedded in the strategy as binding organizational requirements:

— Single source of truth: each data domain has one authoritative system of record; all other systems consume data from it rather than maintaining independent copies.

— Data ownership: each domain has a named data owner responsible for quality monitoring, issue escalation, and access policy within their domain.

— Data quality policy: minimum quality thresholds (e.g., completeness > 90% for demographic fields) are defined for each domain, with automated validation checks at the point of data entry.

— Role-based access control: access to patient data is restricted based on job function, with audit logging of all data access events.

— Data lifecycle management: retention periods and archiving procedures are defined for

each data type in compliance with Federal Law No. 152-FZ on Personal Data (Russian Federation Federal Law No. 152-FZ, 2006).

For medical organizations, adherence to these principles is not only a management best practice but also a legal obligation. Federal Law No. 152-FZ requires explicit consent for personal data processing, documented data retention and deletion policies, and technical and organizational measures to protect data against unauthorized access. The data strategy described here is designed to satisfy these requirements as a baseline condition, with the additional governance measures representing value-adding enhancements beyond the minimum legal standard.

Discussion and Limitations

The methodology presented in this paper offers a structured, reproducible approach to data management in a small to medium-sized commercial healthcare organization. Several aspects merit further discussion.

First, the study is based on a single clinic, which limits the generalizability of specific quantitative findings (duplicate rates, churn rates, quality scores). The methodological framework — domain classification, four-metric quality assessment, RFM segmentation with strategic consolidation, and three-phase data strategy — is designed to be transferable, but calibration to specific organizational contexts will be required. Multi-site validation studies would strengthen the evidence base for the proposed approach.

Second, the economic estimates presented in Section 5.2 are necessarily approximate. The retention ROI calculation assumes that communication costs are the only incremental cost of the retention program, abstracting from implementation effort, staff time, and potential revenue cannibalization (e.g., discount offers reducing revenue per visit). A more rigorous financial model would account for these factors and present a range of scenarios under different assumptions.

Third, as noted throughout the paper, the RFM segmentation model is a descriptive tool rather than a predictive one. The transition to a machine learning-based churn model in Phase 3 of the data strategy is predicated on the accumulation of sufficient labeled data — a condition that cannot be guaranteed in advance. Organizations with smaller patient bases or shorter data histories may need to rely on RFM-based risk identification for a longer period, or supplement it with other leading indicators such as appointment cancellation patterns or NPS trends.

Fourth, the Data Governance framework proposed here reflects current Russian regulatory requirements under Federal Law No. 152-FZ. Organizations operating in jurisdictions subject to the General Data Protection Regulation (GDPR) or equivalent frameworks would need to adapt the governance principles accordingly, particularly with respect to data subject rights (access, rectification, erasure) and the legal basis for data processing.

Conclusion

This article presents a reproducible methodological approach to data management in a commercial clinic, ranging from profiling and deduplication of source data through KPI system design, RFM-based patient segmentation, and the development of a phased data strategy. The key contributions are as follows.

First, a structured data audit framework is proposed, applying four quality metrics across five data domains, combined with a two-stage deduplication procedure integrating exact and fuzzy matching. The audit revealed significant quality variation across domains, with clinical data showing the greatest deficits — a finding consistent with broader patterns in private outpatient care and pointing to paper-to-digital migration as a priority intervention.

Second, a 12-indicator BSC-based KPI system is developed, establishing a causal link be-

tween operational metrics (visit frequency, appointment attendance) and the financial outcome metric (LTV). The LTV/CAC analysis reveals that the current acquisition model is economically sustainable but that the primary value creation opportunity lies in retention rather than acquisition.

Third, RFM segmentation of the patient base is applied to identify five strategic segments, with the at-risk and lost segments (49% of the patient base combined) representing the primary target population for retention and reactivation interventions. The estimated annual revenue effect of a 5 percentage point churn rate reduction is approximately 11.2 million RUB, with a retention program ROI of 250–300%.

Fourth, a three-phase data strategy is formulated that progresses from data foundation (unified identifier, deduplication, basic dashboard) through analytical deployment (RFM automation, LTV/CAC in real time) to predictive modeling (ML-based churn prediction, BI integration). This phased approach is designed to deliver value at each stage while building the organizational and technical foundations for more advanced capabilities.

The study demonstrates that even without machine learning capabilities, descriptive segmentation methods can identify high-risk patient groups and support targeted communication campaigns with measurable economic impact. The scientific novelty of the proposed approach consists in combining, for the first time in the applied healthcare analytics literature, a multi-domain data quality audit with BSC-structured KPI design and an economically calibrated RFM segmentation model within a single phased governance roadmap applicable to small and medium-sized commercial medical organizations. Further development of the system will involve transitioning to full-scale predictive models as larger volumes of labeled data become available.

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