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СТРУКТУРНО-ФУНКЦИОНАЛЬНАЯ ОРГАНИЗАЦИЯ КЛЕТКИ КАК ОСНОВНОЙ ЕДИНИЦЫ ЖИВОГО ОРГАНИЗМА И ЕЁ РОЛЬ В ОБЕСПЕЧЕНИИ ЖИЗНЕДЕЯТЕЛЬНОСТИ

Аннотация: В данной статье рассматривается клетка как базовая структурная и функциональная единица всех живых организмов. Описывается происхождение термина «клетка», её основные компоненты, включая клеточную мембрану, цитоплазму и генетический материал. Подробно анализируются различия между прокариотическими и эукариотическими клетками, их структурные особенности, наличие или отсутствие ядра, а также органеллы, выполняющие ключевые функции жизнедеятельности. Отдельное внимание уделяется историческому аспекту открытия клетки Робертом Гуком (в 1665 году) и формированию клеточной теории Маттиаса Шлейдена и Теодора Шванна (1838–1839) Рассматриваются особенности одноклеточных и многоклеточных организмов, их классификация и эволюционное значение. Также описываются функциональные возможности клеток, такие как репликация, синтез белка, подвижность и энергетическое обеспечение. Приводятся примеры прокариотических организмов, включая бактерии и археи, а также упоминаются крупнейшие известные бактерии. Статья подчеркивает фундаментальную роль клетки в биологии и её значение как основы всех форм жизни на Земле.

Ключевые слова: Клетка, прокариоты, эукариоты, клеточная теория, органеллы, ядро, цитоплазма, мембрана, митохондрии, хлоропласты, биология клетки, бактерии, археи.

Клетка и её роль в живой природе

Клетка представляет собой базовую структурную и функциональную единицу всех живых организмов, независимо от уровня их организации [1, 2]. Она является минимальной системой, способной к осуществлению жизненно важных процессов, включая обмен веществ, синтез белков, репликацию и поддержание жизнедеятельности [1]. Сам термин «клетка» происходит от латинского слова cellula, что означает «маленькая комната», что отражает её ограниченную, но функционально сложную структуру [2]. С точки зрения морфологии и физиологии, клетка состоит из нескольких ключевых компонентов. Основой является клеточная мембрана, обладающая полупроницаемыми свойствами, которая отделяет внутреннюю среду клетки от внешней.

Внутри мембраны располагается цитоплазма, содержащая генетический материал, обеспечивающий передачу наследственной информации и контроль всех клеточных процессов [1]. Большинство клеток являются микроскопическими и могут быть изучены только с использованием увеличительных приборов [2]. Особое значение имеет способность большинства клеток к репликации и синтезу белка [1, 3]. Однако существуют специализированные высокодифференцированные клетки, такие как эритроциты и гаметы, которые утратили часть этих функций в процессе специализации.

Также выделяются клетки, обладающие способностью к движению, что расширяет функциональные возможности живых систем. Согласно представленным данным, возникновение клеточных форм жизни на Земле произошло приблизительно четыре миллиарда лет назад, что подчеркивает их эволюционную древность и фундаментальность [5]. Все организмы подразделяются на две основные группы — прокариоты и эукариоты, что отражает принципиальные различия в их клеточной организации [2, 5]. Прокариоты представлены одноклеточными организмами и включают бактерии и археи. Их характерной особенностью является отсутствие мембраносвязанного ядра, при этом генетический материал локализуется в области, называемой нуклеоидом [2]. Эукариоты, напротив, могут быть как одноклеточными, так и многоклеточными организмами [2, 5]. К ним относятся протисты, растения, животные, большинство грибов и некоторые виды водорослей. Основным отличительным признаком эукариот является наличие оформленного ядра, окружённого ядерной мембраной, что обеспечивает более высокий уровень регуляции генетической информации [1]. Внутренняя организация эукариотических клеток значительно сложнее по сравнению с прокариотическими. Они содержат мембранные органеллы, такие как митохондрии, выполняющие энергетическую функцию, и хлоропласты у растений, обеспечивающие процесс фотосинтеза и синтез органических веществ [1, 3]. Наряду с этим в клетках присутствуют немембранные структуры, включая рибосомы, которые участвуют в синтезе белка и встречаются как у прокариот, так и у эукариот, что указывает на их универсальность в биологических системах [1].

Особый интерес представляет обнаружение уникальной мембранной органеллы прокариот — магнитосомы, выявленной у магнитотактических бактерий, что расширяет представления о сложности прокариотических клеток [1]. Исторически важным этапом в развитии клеточной биологии стало открытие клетки Робертом Гуком в 1665 году [5]. Позднее, в 1839 году, Маттиас Якоб Шлейден и Теодор Шванн сформулировали клеточную теорию, которая стала основой современной биологии [5]. Согласно этой теории, все организмы состоят из одной или более клеток, клетка является основной единицей структуры и функции живых организмов, а новые клетки возникают только из уже существующих [5]. Организмы в целом подразделяются на прокариоты и эукариоты, что отражает фундаментальное различие в уровне клеточной организации [2]. Прокариоты являются исключительно одноклеточными организмами, тогда как эукариоты могут существовать как в одноклеточной, так и в многоклеточной форме.

Одноклеточные эукариоты представлены, например, микроводорослями, такими как диатомовые водоросли [2]. Многоклеточные эукариоты включают животных, растения, большинство грибов и некоторые виды водорослей. В таких организмах клетки приобретают специализацию и выполняют различные функции, обеспечивая целостность организма как единой биологической системы [2]. Прокариотические

клетки, вероятно, являются наиболее ранней формой жизни на Земле [5]. Они характеризуются наличием базовых биологических процессов, включая клеточную сигнализацию, несмотря на свою простую организацию. Их структура отличается меньшими размерами и отсутствием мембранных органелл [2]. Также прокариотические клетки способны выделять различные вещества через клеточную мембрану, включая экзоферменты и внеклеточные полимерные соединения, что играет важную роль во взаимодействии с окружающей средой [2]. Размер прокариотических организмов варьируется в пределах от 0,5 до 2,0 мкм, однако существуют исключения, такие как Thiomargarita magnifica, которая достигает длины до 1–2 см и может быть видима невооружённым глазом [5].

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NEUROBIOLOGICAL MECHANISMS OF ADDICTIVE BEHAVIOR FORMATION: THE ROLE OF THE DOPAMINE SYSTEM AND BRAIN NEUROPLASTICITY

Annotation: This article analyzes the neurobiological mechanisms underlying the development of addictive behavior, with particular emphasis on the role of the dopaminergic system and neuroplasticity of the brain. The relevance of the study is determined the growing prevalence of various forms of addiction among adolescents and young adults, including digital, behavioral, and substance-related dependencies. The article demonstrates that the dopaminergic system plays a central role in the regulation of reward and motivational processes in the brain, as dopamine release during pleasurable experiences reinforces behavioral patterns and increases the likelihood of their repetition. Furthermore, prolonged exposure to intense stimuli is shown to contribute to a decrease in sensitivity to natural sources of reward and satisfaction. Particular attention is paid to the phenomenon of neuroplasticity, which facilitates the formation and consolidation of stable neural pathways associated with habitual and addictive behaviors. In conclusion, addiction is considered as a multifactorial phenomenon resulting from the interaction of biological and behavioral factors accompanied by functional changes in the brain's reward system and the reorganization of neural networks.

Keywords: addictive behavior, dopaminergic system, neuroplasticity, brain reward system, motivation, pleasurable experiences, neural networks, synaptic plasticity, neuroscience

Introduction. Addictive behavior has become one of the most significant issues in contemporary society, particularly among adolescents and young adults. The rapid advancement of digital technologies, the extensive use of social media platforms, and the increased accessibility of various forms of stimulating content have contributed to the growing prevalence of behavioral, digital, and substance-related addictions. Addiction exerts a negative impact on mental health, social adaptation, academic achievement, and overall quality of life.

For many years, addiction was primarily regarded as a psychological or social phenomenon. However, recent advances in neuroscience have demonstrated that substantial neurobiological changes play a critical role in the development and maintenance of addictive behavior. In particular, the dopaminergic system, which regulates motivational and reward-related processes, as well as neuroplasticity, defined as the brain's capacity to reorganize and adapt in response to experience, are considered fundamental mechanisms underlying addiction formation.

Dopamine release occurs in response to pleasurable or rewarding stimuli and serves to reinforce specific patterns of behavior, thereby increasing the probability of their repetition. Prolonged and repeated exposure to highly stimulating experiences may lead to maladaptive alterations in the brain's reward circuitry, including reduced sensitivity to natural reinforcers. As a consequence, stable behavioral patterns associated with compulsive and addictive activities may emerge and become consolidated over time.

The study of the neurobiological mechanisms underlying addiction is of considerable importance for understanding the processes involved in the development and persistence of addictive behavior. Furthermore, such research contributes significantly to the development of effective preventive strategies and evidence-based approaches to early intervention.

Relevance of the study: The relevance of this research is aimed to increase prevalence of addictive behavior in contemporary society, particularly among adolescents and young adults. The accelerated development of digital technologies, the widespread use of social media platforms, and the increased accessibility of various reinforcing stimuli contribute to a higher risk of both behavioral and substance-related addictions. Addictive behavior exerts a substantial negative influence on mental health, social functioning, academic achievement, and overall quality of life. In this context, the investigation of the neurobiological foundations of addiction, with particular emphasis on the functioning of the dopaminergic system and mechanisms of neuroplasticity, represents a significant area of scientific inquiry. A comprehensive understanding of these mechanisms is essential for explaining the onset, maintenance, and progression of addictive disorders, as well as for designing evidence-based prevention strategies and effective early intervention approaches.

Aim of the study. The aim of this study is to investigate the neurobiological mechanisms underlying the development of addictive behavior, with particular emphasis on the role of the dopaminergic system and processes of brain neuroplasticity.

Objectives of the study:

- To conduct a comprehensive review of scientific literature concerning addictive behavior and its neurobiological foundations.
- To examine the functional role of the dopaminergic system in motivational processes and the neural reward circuitry.
- To analyze the contribution of dopamine-mediated mechanisms to the development and maintenance of addictive behavior.
- To explore the role of neuroplasticity in habit formation and the progression of addictive processes.
- To synthesize the research findings and formulate conclusions regarding the neurobiological mechanisms involved in addiction development.

The brain's dopaminergic system. The brain's dopaminergic system constitutes a complex neural network in which dopamine functions as a principal neurotransmitter involved in the regulation of motivation, reward processing, reinforcement learning, and hedonic experience. Dopamine release occurs in response to rewarding or behaviorally significant stimuli, including food consumption, social interaction, and goal attainment, thereby strengthening behavioral responses and increasing the probability of their future repetition.

The dopaminergic system primarily involves several interconnected brain structures, including the ventral tegmental area (VTA), the nucleus accumbens, and the prefrontal cortex. These neural regions collectively participate in the evaluation of environmental stimuli, the

regulation of motivational states, emotional processing, and executive functions related to decision-making and behavioral control.

Prolonged or repeated exposure to highly stimulating factors, such as psychoactive substances, gambling, or excessive engagement with digital technologies, may induce functional and structural alterations within the dopaminergic system. Such neuroadaptive changes can result in diminished responsiveness to natural rewards, impaired reward sensitivity, and an increased motivational drive toward stimuli associated with dopamine release. These processes are considered key neurobiological mechanisms contributing to the initiation, maintenance, and progression of addictive behavior.

Neuroplasticity and Habit Formation. Neuroplasticity refers to the brain's capacity to undergo structural and functional modifications in response to experience, learning processes, and repeated behavioral patterns. This adaptive property enables the formation of new neural connections, as well as the strengthening or weakening of existing synaptic pathways. Neuroplasticity constitutes a fundamental neurobiological mechanism underlying learning, memory consolidation, and habit formation.

Habit formation occurs through the repeated execution of specific behaviors, resulting in the reinforcement of corresponding neural circuits within the brain. Through continuous repetition, behavioral responses gradually become automated and require reduced levels of conscious cognitive control. This process enhances behavioral efficiency by enabling the brain to conserve cognitive resources and respond more effectively to familiar environmental contexts.

In the context of addictive behavior, neuroplasticity plays a critical role in the establishment and reinforcement of maladaptive behavioral patterns. Recurrent exposure to rewarding stimuli strengthens neural pathways associated with the brain's reward circuitry, thereby increasing the stability and persistence of addictive behaviors. Over time, these neuroadaptive changes may lead to the dominance of deeply ingrained neural networks over executive control mechanisms, contributing to compulsive behavioral patterns and the progression of addiction.

Consequences of Addictive Behavior. Addictive behavior exerts a substantial negative impact on multiple dimensions of an individual's functioning, including psychological, physical, and social well-being. From a psychological perspective, addiction is frequently associated with increased levels of anxiety, irritability, emotional dysregulation, and mood instability. Furthermore, addictive disorders may impair cognitive functioning, leading to deficits in attention, memory, executive functioning, and overall cognitive performance.

The physical consequences of addictive behavior vary according to the specific type and severity of addiction. Common physiological effects include sleep disturbances, compromised immune functioning, cardiovascular complications, and chronic fatigue or physical exhaustion. In cases involving substance dependence, prolonged exposure may result in significant damage to internal organs, alterations in neurological functioning, and long-term deterioration of overall physical health.

Addictive behavior also produces considerable social and occupational consequences. Individuals experiencing addiction often demonstrate difficulties in maintaining interpersonal relationships, reduced academic or professional performance, and diminished engagement in routine daily activities. Progressive social withdrawal and isolation are frequently observed, further reinforcing maladaptive behavioral patterns and creating additional barriers to recovery

and rehabilitation. Overall, the multifaceted consequences of addictive behavior contribute significantly to reduced quality of life and impaired psychosocial functioning.

Conclusion. This study examined the neurobiological mechanisms underlying the development of addictive behavior, with particular emphasis on the role of the dopaminergic system and brain neuroplasticity. The findings demonstrate that dopamine performs a central function within the brain's reward system by mediating pleasurable experiences and reinforcing the repetition of specific behavioral patterns. Prolonged exposure to highly stimulating factors induces functional alterations in neural processes, thereby contributing to the emergence, maintenance, and persistence of addictive behavior.

The analysis further indicates that neuroplasticity plays a crucial role in the formation and stabilization of neural networks associated with habitual and reward-driven behaviors. Through repeated behavioral engagement, specific actions gradually become automated and increasingly resistant to conscious regulation due to the strengthening of underlying neural pathways.

Therefore, addictive behavior should be understood as the outcome of a complex interaction among biological, psychological, and social determinants. A comprehensive understanding of the neurobiological foundations of addiction is essential for explaining the mechanisms of its development and progression, as well as for informing the design of effective prevention measures, early intervention approaches, and evidence-based therapeutic strategies.

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ТЕХНИКАЛЫҚ ҒЫЛЫМДАР - ТЕХНИЧЕСКИЕ НАУКИ - TECHNICAL SCIENCE

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GEOMETRY SHADER-BASED CORNER-POINT GRID RECONSTRUCTION FOR REAL-TIME PETROLEUM RESERVOIR VISUALIZATION ON CONSUMER GPUs

Abstract. The corner-point grid (CPG) format used by industrial reservoir simulators encodes subsurface geometry as irregular hexahedra whose eight corners are obtained by interpolation along inclined pillar lines. Faithful real-time visualization of CPG datasets is computationally demanding: a moderate-scale model such as the Norne ATW2013 benchmark contains tens of thousands of active cells, each requiring per-frame reconstruction. This paper presents a focused study of an OpenGL 3.3 geometry shader pipeline that performs full per-cell hexahedral reconstruction entirely on the GPU. The central contribution is a point-to-hexahedron expansion strategy in which the central processing unit submits a single GL_POINTS primitive per active cell and the geometry shader fetches eight corner depths from a texture buffer object, performs pillar interpolation, applies origin-shifted coordinates to eliminate float32 precision loss at universal transverse Mercator scale, and emits twelve triangles with correct winding order in a single shader invocation. Optional dual-axis slicing and interactive vertical exaggeration with on-the-fly normal recomputation are integrated into the same shader stage at negligible cost. On the Norne benchmark (forty-six by one-hundred-twelve by twenty-two grid; forty-four thousand four hundred thirty-one active cells) the pipeline sustains fifty-seven frames per second on a mobile NVIDIA GTX 1660 Ti Max-Q while consuming approximately five megabytes of video memory, representing a twenty-eight-fold reduction in graphics memory and an eleven-fold improvement in frame rate over a vertex-buffer baseline. The implementation requires only standard OpenGL Core Profile features and is therefore broadly portable.

Keywords: corner-point grid, OpenGL, geometry shader, GPU rendering, reservoir visualization, real-time graphics, ZCORN indexing, float32 precision.

Introduction. Three-dimensional visualization of subsurface reservoir models is a routine prerequisite for field development planning, well placement, and reservoir management. Industrial simulators such as Schlumberger ECLIPSE, CMG IMEX, and OPM Flow describe geological geometry through the GRDECL text format, in which the subsurface volume is discretized as a corner-point grid (CPG). Each grid cell in this representation is a general hexahedron whose eight corners lie on four inclined pillar lines, with depth values stored

separately in the ZCORN keyword. Unlike a Cartesian grid, a CPG faithfully encodes faulted horizons, pinch-outs, and dipping stratigraphic layers without geometric approximation, but the price is geometric irregularity: every active cell requires explicit per-corner reconstruction before it can be displayed.

At interactive frame rates this reconstruction step is non-trivial. Even the moderate-scale Norne ATW2013 benchmark, distributed publicly by the Open Porous Media initiative, contains a forty-six by one-hundred-twelve by twenty-two grid in which forty-four thousand four hundred thirty-one cells are active. A naive immediate-mode renderer that issues eight glVertex3f calls per cell submits more than one million per-frame vertex commands, a workload that saturates the central processing unit (CPU) bus while leaving the graphics processing unit (GPU) underutilized. Commercial workstation packages such as Petrel and tNavigator deliver high performance but require expensive licensing and hardware. General-purpose scientific visualization frameworks such as VTK and ParaView lack native CPG support, while ResInsight, the most widely used open-source reservoir viewer, depends on a heavy software stack that obscures the rendering core and resists customization on consumer-grade laptops.

The OpenGL geometry shader (GS) stage, available since version 3.2 of the OpenGL Core Profile, allows a single input primitive to be amplified into a controlled number of output primitives entirely on the GPU. This capability is uniquely well suited to CPG visualization, because each cell can be represented on the host as a single point and reconstructed into a complete six-faced hexahedron by the shader. The present work develops this idea into a fully optimized rendering pipeline and reports a focused technical analysis of the geometric, numerical, and memory aspects of the implementation. The contributions of this paper are summarized as follows. (1) A complete description of a point-to-hexahedron expansion algorithm in GLSL that performs ZCORN indexing, pillar interpolation, and per-face normal computation in a single geometry shader invocation. (2) A documented solution to the float32 precision problem that arises when CPG coordinates are expressed in the Universal Transverse Mercator (UTM) system, achieved through a CPU-side origin shift. (3) An on-shader implementation of vertical exaggeration that recomputes face normals in the deformed coordinate frame, preserving correct lighting under interactive depth scaling. (4) A quantitative evaluation on the Norne benchmark demonstrating a twenty-eight-fold reduction in graphics memory and an eleven-fold improvement in frame rate over a baseline vertex-buffer renderer.

The remainder of this paper is organized as follows. Section 2 reviews the structure of the GRDECL data and the geometry shader stage. Section 3 presents the three-stage architectural progression that motivated the proposed pipeline. Section 4 describes the GPU data layout, and Section 5 details the geometry shader algorithm itself. Section 6 reports experimental results on the Norne benchmark. Section 7 discusses limitations and applicability, and Section 8 concludes.

Background and related work. A GRDECL file describes a structured (i, j, k) grid through three principal keywords. SPECGRID specifies the grid dimensions nx, ny, and nz. COORD stores six floating-point numbers per pillar line, namely the (x, y, z) coordinates of the top and bottom endpoints of the line; for a grid of nx by ny cells in the lateral plane there are (nx+1) by (ny+1) such pillars. ZCORN stores the depth values of all eight corners of every cell in a one-dimensional array indexed by the standard ECLIPSE convention; the array length is eight times nx times ny times nz. Finally, ACTNUM is an integer mask that flags inactive cells, typically those falling outside the reservoir volume. Reconstructing a single cell therefore

requires reading eight depth values from ZCORN, evaluating four pillar interpolations to obtain (x, y) at the requested depths, and assembling the eight corners in the correct topological order.

Existing approaches to interactive CPG rendering fall into three broad categories. The first approximates each cell as an axis-aligned cube placed at the cell centroid. This representation is fast to render with hardware instancing but produces visible artifacts at faulted horizons, where adjacent cells should share corner points but instead expose gaps and overlaps. The second pre-computes the full set of triangular faces for every cell on the CPU and stores them in a vertex buffer object (VBO). This approach renders correctly but consumes large amounts of video memory: at twelve triangles per cell, three vertices per triangle, and ten floats per vertex, the Norne dataset alone requires more than fifty megabytes of GPU memory for static geometry. The third category, into which the present work falls, performs cell reconstruction on the GPU within the geometry shader stage. Earlier examples in geological visualization include the GPU isosurface and slice algorithms developed for seismic volumes, but a complete CPG implementation that addresses the float32 precision problem at UTM scale and supports interactive vertical exaggeration with correct lighting has not, to the authors knowledge, been described in detail in the open literature.

Three-stage architectural progression. The proposed pipeline was developed through three architectural iterations, each addressing a specific bottleneck encountered in the previous stage. Stage 1 used legacy fixed-function OpenGL with immediate mode glBegin/glEnd vertex submission. Although correct, this approach was incapable of sustaining interactive rates on the Norne dataset and was rejected. Stage 2 replaced immediate mode with hardware-instanced cube rendering. By submitting a single canonical cube and instancing it forty-four thousand four hundred thirty-one times, the per-frame draw-call cost was eliminated and frame rates above fifty-five frames per second were achieved. The geometric approximation, however, distorted faulted layers and was unsuitable for production interpretation. Stage 3, the focus of this paper, retains the single-draw-call performance characteristic of instancing but reconstructs the true CPG hexahedron geometry within the geometry shader. The result is correct geometry at instancing-level performance.

The Stage 3 pipeline is organized into four GPU stages. The vertex shader receives one seed vertex per active cell and forwards the cell index and a normalized scalar attribute (typically porosity or permeability) without modification. The geometry shader expands each input point into the six bounding faces of the cell, emitting twelve triangles arranged as triangle strips with counter-clockwise winding for correct hardware back-face culling. The fragment shader applies a three-point lighting model (ambient plus key plus fill) and maps the interpolated attribute through a rainbow transfer function. Finally, depth testing with polygon-offset bias is applied to suppress z-fighting artifacts on co-planar faces.

GPU data layout. The host-side data preparation is performed once at load time. The GRDECL parser reads COORD, ZCORN, ACTNUM, and one or more attribute arrays into NumPy arrays of explicit dtype. To circumvent the float32 precision limitation discussed in Section 5.3, an origin offset is computed as the centroid of the model bounding box and subtracted from all (x, y, z) coordinates before they are uploaded to the GPU. Three independent buffers are then constructed.

The seed VBO contains one record per active cell with a stride of twenty bytes. The first three floats encode the (i, j, k) cell index cast to single-precision floating point for shader compatibility; the fourth float carries the normalized scalar attribute in the range zero to one;

and the fifth float is reserved for future use. For the Norne benchmark this VBO occupies forty-four thousand four hundred thirty-one times twenty bytes, approximately 0.85 megabytes. The COORD data is uploaded into a texture buffer object (TBO) of dimension (nx+1) times (ny+1) times six floats, occupying about 0.13 megabytes. The ZCORN data is uploaded as a second TBO of dimension eight times nx times ny times nz floats, requiring about 3.5 megabytes for Norne. The total static GPU memory footprint, including small uniform buffers for the colormap and lighting parameters, is under five megabytes — to be contrasted with the more than fifty megabytes required by the precomputed-triangle baseline of the previous section. The compression factor is approximately twenty-eight, and is achieved without any algorithmic loss of geometric fidelity.

Table 1 — GPU memory footprint comparison on the Norne benchmark

Approach	VRAM (MB)	Draw calls	FPS
Stage 1: immediate mode	< 1	1.07 M	~ 5
Stage 2: instanced cubes	~ 50	1	~ 55
Stage 3: GS expansion (this work)	~ 5	1	57

Geometry shader algorithm.

5.1 ZCORN index resolution. The eight corners of cell (i, j, k) are addressed in the ZCORN array by an index function that treats the array as a three-dimensional grid of dimension (2nz, 2ny, 2nx). For a corner specified by half-cell flags (hk, hj, hi), each in the set zero, one, the linear index is given by

$$idx(i, j, k, hk, hj, hi) = (2k + hk)\cdot(4\ nx\ ny) + (2j + hj)\cdot(2\ nx) + (2i + hi).$$

Implemented in GLSL via the texelFetch operation against the ZCORN texture buffer, this lookup costs eight texture fetches per cell. The half-cell flag combinations enumerate the eight corners in a fixed topological order: (hk, hj, hi) = (0,0,0), (0,0,1), (0,1,0), (0,1,1), (1,0,0), (1,0,1), (1,1,0), (1,1,1), corresponding respectively to top-back-left, top-back-right, top-front-left, top-front-right, bottom-back-left, bottom-back-right, bottom-front-left, and bottom-front-right.

5.2 Pillar interpolation. Each ZCORN value provides only the depth z of a corner; the lateral coordinates (x, y) must be obtained by linear interpolation along the appropriate pillar line. For a pillar with top point (xt, yt, zt) and bottom point (xb, yb, zb), the interpolation parameter at depth z is t = (z − zt) / (zb − zt). The corresponding lateral coordinates are x = xt + t·(xb − xt) and y = yt + t·(yb − yt). When the pillar is exactly vertical, that is when zb equals zt, the parameter t is undefined; in this case the shader returns the top-point coordinates. The pillar identification for corner (hi, hj) of cell (i, j, k) follows the same regular pattern as the ZCORN flags: the pillar index is (i + hi, j + hj). Four pillar interpolations therefore suffice to reconstruct all eight corners of a cell.

5.3 Origin shift for float32 precision. Geological coordinates in industrial datasets are routinely stored in the Universal Transverse Mercator system. For the Norne field, situated in UTM Zone 32N, easting and northing values typically lie around four hundred fifty-six thousand and seven million three hundred twenty-one thousand metres respectively. A single-precision IEEE 754 float provides approximately seven significant decimal digits, which at this magnitude

corresponds to a least significant bit of about one metre. Since CPG cells in Norne have lateral extents of fifty to one hundred metres and vertical extents as small as one metre, direct float32 storage produces visible vertex jitter and discrete-step artifacts during camera motion. The pipeline addresses this through a CPU-side origin shift: the bounding-box centroid (x0, y0, z0) is subtracted from every coordinate before upload, so that the shader operates on values centred on the origin and bounded in magnitude by the grid extents. The shift is reversed in the projection matrix when an absolute coordinate display is required. The technique introduces no shader-side overhead and entirely eliminates the precision artifact.

5.4 Vertical exaggeration with normal recomputation. Reservoir engineers routinely apply a vertical exaggeration factor between five and twenty to highlight stratigraphic features that would otherwise be visually compressed by the large lateral-to-vertical aspect ratio of typical fields. In the proposed pipeline this scaling is applied within the geometry shader by multiplying the z-component of every reconstructed corner by a uniform variable verticalScale before primitive emission. A subtle but important consequence is that the surface normals of the cell faces, if precomputed in the unscaled frame, no longer correspond to the actual surface orientation after deformation, producing visibly incorrect lighting. The shader therefore recomputes normals after scaling using the cross product of two edge vectors of each face, ensuring that the lighting model receives the deformed-frame normal. This recomputation costs four cross products per cell and has no measurable impact on frame rate, but is essential for visual correctness under interactive scaling.

5.5 Dual-axis cross-section slicing. Cross-section slicing along the I and K grid axes is implemented as two early-exit tests at the start of the geometry shader. The shader receives two uniform integers, sliceI and sliceK, that specify the cut indices, and a third uniform that selects either include-below or include-above semantics. Cells failing the test return without emitting any primitives. Because the test occurs before any pillar interpolation, the entire cost of geometric reconstruction is avoided for clipped cells; for the Norne dataset, slicing typically discards forty to sixty per cent of the active cells and yields a measurable improvement in frame rate.

5.6 Face emission and winding order. Once the eight corners are reconstructed, the shader emits the six bounding faces as triangle strips. Each face is described by four corner indices in counter-clockwise order as seen from outside the cell; the geometry shader emits the four corresponding vertices and a primitive-end marker. The total per-cell output budget is fixed at twenty-four vertices (six faces times four corners) and twelve triangles. This count is below the conservative GS amplification limit on all consumer GPU architectures since OpenGL 3.2 and therefore does not trigger driver-level fallbacks. Hardware back-face culling, enabled by the consistent winding convention, eliminates approximately half of the resulting fragments before rasterization.

Experimental evaluation. All measurements were performed on a Dell G3 3590 laptop equipped with an Intel Core i7-9750H CPU, sixteen gigabytes of system memory, and an NVIDIA GeForce GTX 1660 Ti Max-Q discrete GPU. The operating system was Windows 10 with NVIDIA driver version 537.13. The benchmark dataset is the Norne ATW2013 model from the Open Porous Media initiative, containing a forty-six by one-hundred-twelve by twenty-two CPG (one hundred thirteen thousand three hundred forty-four total cells, of which forty-four thousand four hundred thirty-one are active per the ACTNUM mask). The implementation

uses Python 3.11, PyOpenGL, GLFW, and NumPy, and consists of approximately twenty-one hundred lines of Python and GLSL code in total.

Frame rates were measured by averaging over a one-thousand-frame test sequence with the camera orbiting the model at a fixed radius. Three configurations were evaluated. The legacy immediate-mode baseline (Stage 1) sustained approximately five frames per second; this rate is bounded by the CPU draw-submission rate rather than by GPU rasterization. The instanced-cube baseline (Stage 2), which approximates each cell as a unit cube, reached fifty-five frames per second but produces visibly incorrect geometry at faulted horizons. The proposed Stage 3 pipeline achieved fifty-seven frames per second with full corner-point reconstruction. Importantly, Stage 3 matches the performance of the geometrically incorrect Stage 2 baseline while delivering accurate geometry; the additional cost of pillar interpolation and ZCORN lookups in the geometry shader is masked by the reduction in primitive count that results from per-cell hexahedron emission rather than per-corner cube instancing. Table 1 summarizes the comparison.

GPU memory consumption was measured via the GL_NVX_gpu_memory_info extension. The Stage 3 pipeline reserved approximately five megabytes of GPU memory for the seed VBO, the COORD TBO, and the ZCORN TBO combined. A static-vertex-buffer baseline that pre-computes all twelve triangles per active cell on the CPU consumed approximately one hundred forty-four megabytes for the same dataset, a factor of twenty-eight higher. The memory advantage scales with the number of cells: for hypothetical models in the millions of cells the proposed pipeline remains within consumer-laptop GPU memory budgets, while the static-vertex-buffer baseline would exceed them by an order of magnitude.

Profiling under NVIDIA Nsight Graphics indicates that the geometry shader stage is the dominant cost in the Stage 3 pipeline, accounting for approximately sixty per cent of GPU time per frame, followed by fragment shading at thirty per cent and other stages at ten per cent. The geometry shader cost is dominated by texelFetch latency against the ZCORN TBO, suggesting that a future optimization could amortize this cost through a small per-cell on-shader cache or through reformulation as a compute-shader prepass that writes triangulated geometry to a buffer-object output. These directions are the subject of ongoing work.

Discussion. The geometry shader stage has historically been criticized as offering inferior throughput compared with hardware tessellation or compute shaders, particularly on certain mobile GPU architectures. The present results indicate that for the specific class of single-amplification CPG reconstruction (one input point producing twenty-four output vertices) the geometry shader remains competitive on consumer NVIDIA hardware, and provides the additional benefits of per-cell flow control (used here for slicing) and trivial integration with downstream fragment-stage features such as colormap lookups and lighting. Compute-shader-based alternatives that pre-compute the full triangle stream into a vertex buffer on demand would likely match or exceed Stage 3 performance for static models, but would forfeit the on-shader interactivity (slicing, vertical exaggeration, and per-cell culling) that the geometry shader formulation enables at zero additional CPU cost.

Limitations of the proposed pipeline are recognized. First, the geometry shader amplification limit, while comfortable on the studied dataset, would constrain extension to certain higher-order cell shapes. Second, the per-cell texelFetch pattern against the ZCORN TBO is not cache-friendly; on architectures without a unified texture cache (notably some

integrated GPUs) the pipeline may exhibit lower scaling efficiency. Third, the present implementation targets a single GPU and a single rendering thread. For multi-million-cell models, hierarchical level-of-detail strategies and out-of-core data streaming would become necessary; these directions are outside the scope of the present technical study.

Conclusion. This paper has presented a focused technical study of a geometry shader pipeline for real-time visualization of corner-point grid reservoir models. The pipeline combines a point-to-hexahedron expansion strategy, a CPU-side origin shift to circumvent float32 precision loss at UTM scale, and on-shader vertical exaggeration with normal recomputation. On the Norne ATW2013 benchmark the implementation sustains fifty-seven frames per second on a consumer mobile GPU while consuming under five megabytes of graphics memory, representing a twenty-eight-fold reduction in memory and an eleven-fold improvement in frame rate over a static-vertex-buffer baseline. The complete implementation uses only standard OpenGL Core Profile features and is therefore portable across desktop GPU vendors. Future work will investigate compute-shader alternatives, hierarchical level-of-detail strategies for million-cell models, and integration with stereoscopic virtual reality output.

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АНАЛИЗ И ПРОГНОЗ ПОТРЕБНОСТИ В ПРЕСНОЙ ВОДЕ В УСЛОВИЯХ РК НА ОСНОВЕ ПОГОДНЫХ ДАННЫХ И ПОКАЗАТЕЛЕЙ ПОТРЕБЛЕНИЯ

Аннотация: В условиях изменения климата и роста антропогенной нагрузки проблема рационального управления водными ресурсами приобретает стратегическое значение для Республики Казахстан. Целью настоящего исследования является разработка и сравнительный анализ моделей прогнозирования потребности в пресной воде на основе погодных данных и показателей потребления. В работе использованы методы эконометрического моделирования и алгоритмы машинного обучения, включая Ridge Regression, Random Forest, Support Vector Regression, Gaussian Process Regression и XGBoost. Результаты показали, что ансамблевые нелинейные методы обеспечивают наибольшую точность прогнозирования (R^2 до 0.97, MAPE < 9%). Построен прогноз совокупного водопотребления до 2030 года, подтверждающий устойчивый рост спроса на водные ресурсы. Полученные выводы могут быть использованы при формировании государственной политики в сфере водного управления и адаптации к климатическим изменениям.

Ключевые слова: водные ресурсы, Казахстан, водопотребление, машинное обучение, XGBoost, Random Forest, климатические данные, прогнозирование.

Введение. Водные ресурсы являются стратегически важным элементом устойчивого развития Казахстана, особенно в условиях изменения климата и роста потребностей различных отраслей экономики. Эффективное управление водными ресурсами требует точного анализа текущего состояния водопотребления и прогнозирования будущих потребностей, что является ключевой задачей для обеспечения водной безопасности страны.

По данным национальной статистики и международных организаций, объём возобновляемых водных ресурсов Казахстана составляет около 100–108 км³ в год, при этом до 45% формируется за пределами страны. Учитывая рост населения, расширение сельскохозяйственного производства и промышленного сектора, прогнозирование будущего спроса на воду становится необходимым инструментом стратегического планирования.

Настоящее исследование посвящено анализу и прогнозированию потребности в пресной воде в Республике Казахстан на основе климатических данных и показателей водопотребления. В работе рассматриваются методы прогнозирования водопотребления, включая статистические модели и алгоритмы машинного обучения.

Основной целью исследования является разработка модели прогнозирования потребности в пресной воде, учитывающей погодные данные и показатели потребления по регионам Казахстана. В рамках исследования решаются следующие задачи:

- Анализ существующих методов прогнозирования потребности в водных ресурсах
- Сбор и обработка данных по водопотреблению и климатическим изменениям в Казахстане
- Разработка прогнозной модели с использованием методов машинного обучения
- Сравнение различных моделей прогнозирования и оценка их точности

Ожидается, что результаты исследования будут полезны государственным органам, занимающимся управлением водными ресурсами, а также предприятиям аграрного и промышленного секторов, заинтересованным в эффективном планировании водопользования

Актуальность. Рост населения, развитие промышленности и изменение климата ведут к увеличению потребности в пресной воде, делая вопрос ее рационального использования все более значимым. Казахстан, обладая значительными, но неравномерно распределенными водными ресурсами, уже сталкивается с проблемами их дефицита. По данным Бюро национальной статистики, объем ежедневно потребляемой воды на одного жителя страны в 2023 году составил 3,5 тыс. литров. В то же время исследования Всемирного банка показывают, что если текущие тенденции сохранятся, объем доступных водных ресурсов Казахстана может сократиться с 100 до 70 кубических километров к 2050 году.

По прогнозам экспертов ПРООН, уже к 2040 году дефицит водных ресурсов в Казахстане может составить 50% от общей потребности. Это негативно скажется на всех секторах экономики, а в ряде регионов может привести к снижению ВВП на 6% к 2050 году.

Таким образом, необходимость исследования механизмов прогнозирования и оптимизации водопотребления становится очевидной. В данной работе особое внимание будет уделено комплексному анализу данных о потреблении воды, климатических изменениях и водном балансе. В Казахстане, где водные ресурсы ограничены и распределены неравномерно, особенно важно использовать современные методы прогнозирования, чтобы предотвратить кризисное развитие ситуации.

Современные модели машинного обучения, применяемые для анализа и прогноза водопотребления

В последние годы методы машинного обучения существенно расширили возможности прогнозирования водопотребления, обеспечивая более высокую точность по сравнению с традиционными подходами. В исследованиях, проведённых в Австрии, Китае и странах ЕС, активно применяются как интерпретируемые модели (Linear Regression, Decision Tree, KNN), так и более сложные алгоритмы (SVM, Random Forest, LSTM).

В работе Maußner et al. (2025) были сравнены шесть моделей для прогнозирования суточного водопотребления с учётом точности, интерпретируемости и устойчивости к климатическим сценариям[1]. Нелинейные модели, такие как LSTM и Random Forest, показали более высокую точность, однако оказались чувствительнее к качеству входных

данных. Более простые модели продемонстрировали большую устойчивость и прозрачность. Кроме того, Random Forest показал стабильные результаты и может быть дополнительно усилен бустинговыми алгоритмами, такими как XGBoost (Niazkar et al., 2024).

В исследовании Xia et al. (2024) предложена гибридная модель GA-BP-KDE, сочетающая точечный прогноз и оценку неопределённости. На первом этапе использовались нейронные сети и модели машинного обучения, оптимизированные метаэвристическими алгоритмами (GA, PSO, GWO), а на втором — метод Kernel Density Estimation для формирования доверительных интервалов[2]. Модель показала высокую точность и позволила учитывать асимметрию ошибок, что особенно важно при стратегическом планировании в условиях ограниченных водных ресурсов. Авторы подчёркивают значимость корректного выбора климатических переменных (температура, осадки, влажность), что повышает устойчивость прогноза. Возможность построения интервальных, а не только точечных оценок снижает неопределённость управленческих решений.

Таким образом, современные исследования подтверждают эффективность гибридных моделей машинного обучения и методов оценки неопределённости для прогнозирования водопотребления. Подобные подходы могут быть адаптированы к условиям Казахстана с учётом его климатических и социально-экономических особенностей.

Интеграция климатических данных в модели прогнозирования

Климатические переменные — температура, осадки и влажность — являются ключевыми факторами в моделях прогнозирования водопотребления. В исследовании X. Zhang et al. (2024) анализируется динамика водоснабжения в условиях полузасушливого климата на примере города Циньян (Китай), что близко по условиям к южным и западным регионам Казахстана[3]. Прогноз строился с использованием сценариев Shared Socioeconomic Pathways (SSP) и алгоритма Random Forest, который позволил учитывать сложные нелинейные связи между климатическими и социально-экономическими факторами.

Авторы выделили секторальную структуру спроса (сельское хозяйство, промышленность, бытовой и экологический сектор) и показали рост потребления прежде всего в аграрной сфере. Использование климатических сценариев SSP126, SSP245 и SSP585 позволило учесть влияние изменения климата на водный баланс. Подобный подход может быть применён в аграрных и энергетических регионах Казахстана для более устойчивого планирования распределения водных ресурсов.

Аналогичные выводы подтверждаются и другими исследованиями. В австрийской работе использовалась множественная линейная регрессия (MLR) с учётом климатических сценариев RCP, где прогнозируется рост пикового водопотребления на 14–19% к середине века, главным образом из-за демографических факторов. В ряде стран (Сербия, Эфиопия, Канада) установлено, что повышение температуры на 1°C может увеличить пиковое потребление воды на 1.8–2%.Помимо линейных моделей, широко применяются нейронные сети (ANN), SVR и Random Forest, повышающие точность прогнозов. Однако исследования показывают, что при корректном выборе переменных даже простые регрессионные модели могут обеспечивать сопоставимые результаты.

Для Казахстана, особенно в засушливых и резко континентальных регионах, перспективен комплексный подход к прогнозированию водопотребления, аналогичный австрийскому. Климатическая нестабильность, сокращение поверхностных и подземных вод, а также демографический рост требуют разработки адаптированных региональных моделей. Методологически такие модели должны опираться на исторические данные потребления и погоды, учитывать климатические индексы и демографические прогнозы, применять сценарный анализ и оцениваться с использованием MAPE, корреляции Пирсона и анализа пикового спроса. Важно также интегрировать прогнозы в систему управления водоснабжением для корректировки тарифной политики, планирования инфраструктуры и внедрения мер водосбережения.

Исследование Shu et al. (2024) сравнило пять моделей ИИ (GA-BP, ELM, GPR, SVR, Random Forest) для прогноза водопотребления в четырёх секторах[4]. Модели обучались на данных 2005–2020 гг., оценивались по R^2, RMSE и MAPE и использовались для прогноза до 2025 года. GPR показал наилучшие результаты для сельского, бытового и экологического сектора (R^2 до 0.98), тогда как GA-BP оказался наиболее эффективен для промышленности. Все алгоритмы продемонстрировали устойчивость к небольшим выборкам и пропускам данных, а прогнозы указали на рост потребления во всех секторах.

Для Казахстана такие методы особенно ценны с учётом региональных различий и климатической неопределённости. Модели GPR и SVR позволяют учитывать риски и демографические колебания, а секторный подход обеспечивает более точное распределение ресурсов, особенно в засушливых аграрных областях. Интеграция ИИ-моделей в государственную систему управления водными ресурсами может повысить точность прогнозирования и улучшить стратегическое планирование в условиях изменения климата.

Методология. Настоящее исследование основано на комплексном анализе климатических данных, собранных на территории Республики Казахстан за последние два десятилетия и показателей потребления. Для анализа были использована метеорологическая база данных РГП «Казгидромет», содержащая ежедневные наблюдения по 228 метеостанциям; Данные охватывают период с 2000 года по настоящее время[8].

В ходе работы были собраны ежедневные наблюдения с 2000 года по настоящее время по 228 метеостанциям, расположенным на территории всех регионов Республики Казахстан. Для каждой станции были выгружены следующие ключевые климатические показатели: среднесуточная температура воздуха (°C), Суточное количество атмосферных осадков (мм), относительная суточная влажность воздуха (%)

Все данные были получены в ежедневном разрезе и объединены в единый формат, включающий название станции, регион, дату наблюдения и значения измеряемых параметров.

Помимо метеорологических наблюдений был выполнен сбор данных по потреблению воды были получены из закрытого источника Бюро национальной статистики Агентства по стратегическому планированию и реформам Республики Казахстан (портал открытых данных data.egov.kz): https://data.egov.kz/datasets/view?index=water_dispensed_to_consumers[13].

Набор данных содержит статистическую информацию о распределении воды потребителям в разрезе территорий и временных периодов. Структура датасета

представлена следующими атрибутами: наименование территории, период, объем потребления воды, вид местности (сельская/городская), категория потребления.

После завершения этапа парсинга климатические данные представляли собой разрозненные таблицы, выгруженные по годам и по станциям наблюдений. Была выполнена комплексная предобработка набора данных с целью приведения информации к единому стандарту и подготовки к последующему анализу и построению моделей прогнозирования. В процессе очистки данные значительно сократились за счёт удаления пустых, некорректных и дублирующих наблюдений.

После выполнения всех этапов предобработки был сформирован единый очищенный массив данных, включающий:

- период наблюдений: с 2000 года по настоящее время (более 25 лет);
- количество станций: 228 meteorological and hydrological stations;
- параметры: суточная температура воздуха, суточные атмосферные осадки, суточная относительная влажность воздуха, суточный уровень воды в реках, объем потребления, регион, тип местности(сельская,городская), код КАТО (Классификатор административно-территориальных объектов);
- общий объём: около 2,7 миллиона строк наблюдений.

Эконометрическое моделирование и базовая оценка зависимостей

Первым этапом моделирования стало построение эконометрической модели панельной регрессии с фиксированными эффектами. Использование данной модели обусловлено необходимостью выявления устойчивых зависимостей между климатическими факторами и уровнем водопотребления с учётом региональной специфики и временных трендов. Включение фиксированных эффектов регионов позволило учесть неизменяемые во времени особенности территорий, такие как уровень инфраструктуры водоснабжения, структура экономики и демографические характеристики. Введение фиксированных эффектов года позволило учесть макроэкономические и климатические тенденции, оказывающие влияние на водопотребление на национальном уровне.

PanelOLS Estimation Summary

Dep. Variable:	consumption	R-squared:	0.1762
Estimator:	PanelOLS	R-squared (Between):	0.0273
No. Observations:	180	R-squared (Within):	0.0674
Date:	Tue, Feb 17 2026	R-squared (Overall):	0.0102
Time:	01:34:57	Log-likelihood	-3516.5
Cov. Estimator:	Clustered		
		F-statistic:	3.8237
Entities:	21	P-value	0.0004
Avg Obs:	8.5714	Distribution:	F(8,143)
Min Obs:	2.0000		
Max Obs:	9.0000	F-statistic (robust):	16.350
		P-value	0.0000
Time periods:	9	Distribution:	F(8,143)
Avg Obs:	20.000		
Min Obs:	20.000		
Max Obs:	20.000		

Parameter Estimates

	Parameter	Std. Err.	T-stat	P-value	Lower CI	Upper CI
rain_year	-2.761e+04	1.198e+04	-2.3042	0.0227	-5.13e+04	-3924.4
hum_mean	4.267e+06	8.895e+06	0.4797	0.6322	-1.332e+07	2.185e+07
hum_min	2.036e+07	1.181e+07	1.7244	0.0868	-2.979e+06	4.37e+07
temp_mean	-1.326e+07	1.873e+07	-0.7076	0.4803	-5.029e+07	2.378e+07
temp_max	-4.079e+06	7.01e+06	-0.5818	0.5616	-1.793e+07	9.778e+06
temp_min	9.389e+05	5.05e+06	0.1859	0.8528	-9.044e+06	1.092e+07
days_obs	1.804e+05	1.372e+05	1.3143	0.1908	-9.089e+04	4.516e+05
allowance_mean	5.294e+08	7.326e+07	7.2264	0.0000	3.846e+08	6.742e+08

Рисунок 1. Результаты оценки панельной регрессии (PanelOLS) для модели водопотребления

Результаты панельной регрессии (Рисунок 1) подтвердили наличие статистически значимой зависимости между погодными параметрами и уровнем водопотребления. В частности, наблюдалась положительная связь между ростом температуры воздуха и увеличением объёмов потребляемой воды, что согласуется с теоретическими предположениями о влиянии испарения и роста бытового спроса в тёплые периоды. Количество осадков, напротив, демонстрировало отрицательную зависимость с водопотреблением, что объясняется снижением потребности в ирригации при повышенном естественном увлажнении.

Несмотря на интерпретируемость результатов, эконометрическая модель показала ограниченную способность учитывать сложные нелинейные зависимости, что обусловило переход к методам машинного обучения.

Логарифмическая регрессионная модель Ridge Regression

Следующим этапом исследования стало построение линейной модели Ridge Regression, применённой к логарифмированным значениям водопотребления. Использование логарифмического преобразования позволило стабилизировать дисперсию временного ряда и уменьшить влияние экстремальных значений, характерных для гидрологических данных.

Регуляризация, применяемая в модели Ridge, позволила уменьшить эффект мультиколлинеарности между климатическими переменными и повысить устойчивость модели к переобучению. По сравнению с базовой эконометрической моделью наблюдалось заметное улучшение качества прогнозирования, что подтвердило целесообразность перехода к более сложным алгоритмам.

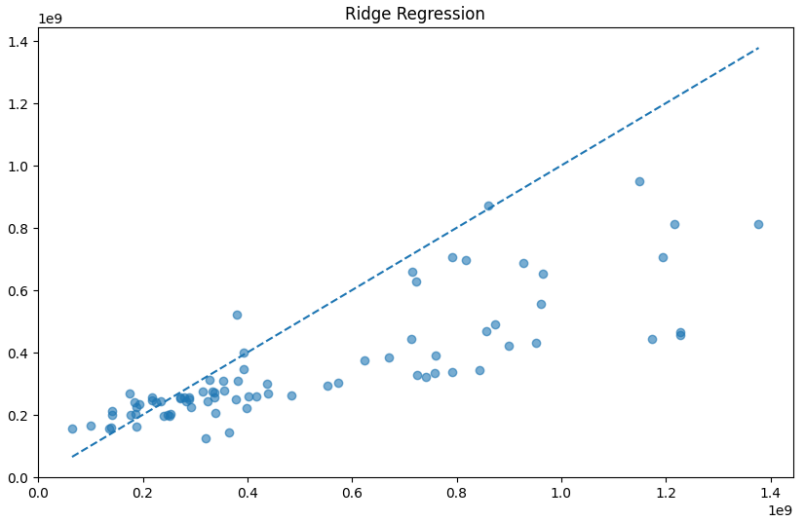


Рисунок 2. График сравнения фактических и прогнозных значений водопотребления (модель Ridge Regression)

На графике наблюдается способность модели корректно воспроизводить общий тренд водопотребления, однако в периоды резких изменений наблюдаются отклонения прогнозных значений.

Применение нелинейных алгоритмов машинного обучения

Основной этап моделирования был связан с применением алгоритмов машинного обучения, способных учитывать нелинейные зависимости и сложные взаимодействия факторов. В рамках исследования были реализованы модели Random Forest, Support

Vector Regression, Gaussian Process Regression (GPR) и XGBoost, что позволило провести сравнительный анализ эффективности различных подходов.

Ансамблевые методы продемонстрировали существенное повышение точности прогнозирования по сравнению с линейными моделями. Это объясняется их способностью выявлять сложные закономерности в многомерных данных и устойчивостью к шуму и пропущенным значениям.

Модель Random Forest Regression стала первым нелинейным алгоритмом, использованным в работе. Random Forest представляет собой ансамбль деревьев решений, обучаемых на случайных подвыборках данных, что обеспечивает высокую устойчивость модели и способность учитывать сложные зависимости между переменными.

Результаты показали значительное повышение точности прогнозирования по сравнению с линейными моделями. Модель Random Forest продемонстрировала наилучшие результаты по всем ключевым метрикам. Значение MAPE составило 8.33%, что соответствует точности прогноза 91.67%. Коэффициент детерминации R^2 равен 0.9549, что свидетельствует о высокой степени объяснения вариации зависимой переменной. Минимальное значение RMSE также подтверждает устойчивость модели и ее способность формировать прогнозы с наименьшим среднеквадратичным отклонением.

Высокие показатели объясняются ансамблевой природой алгоритма. Random Forest строит множество деревьев решений и агрегирует их результаты, что позволяет эффективно моделировать сложные нелинейные зависимости и снижать влияние выбросов и шумов в данных.

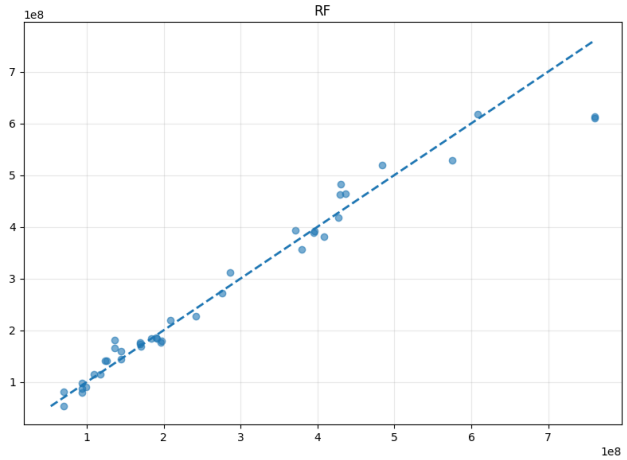


Рисунок 3. График сравнения фактических и прогнозных значений водопотребления (модель Random Forest)

Наиболее значимыми факторами прогнозирования оказались лаговые переменные водопотребления, температура воздуха и норматив водопотребления.

Метод Support Vector Regression (SVR) был использован для моделирования сложных нелинейных зависимостей между переменными. Использование ядровых функций позволило аппроксимировать нелинейную зависимость водопотребления от климатических факторов.

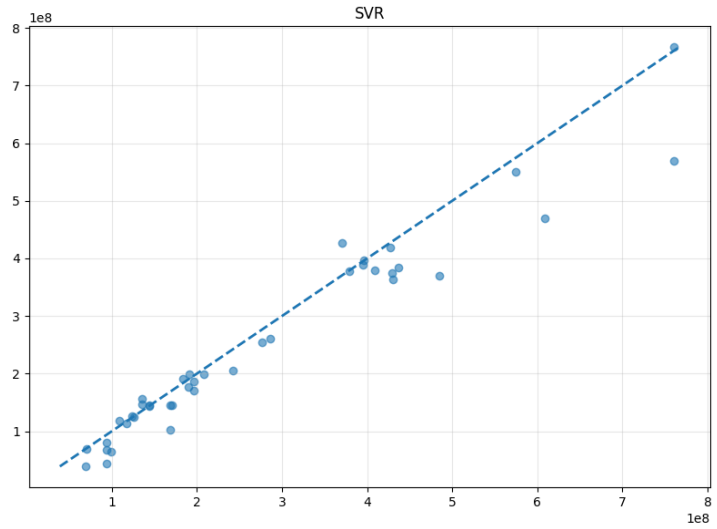


Рисунок 4. График сравнения фактических и прогнозных значений водопотребления (модель Support Vector Regression)

Модель SVR показала умеренные результаты. Средняя абсолютная процентная ошибка составила 12.41%, что заметно выше по сравнению с Random Forest. Коэффициент детерминации R^2 равен 0.9259, что указывает на достаточно хорошую, но менее высокую объясняющую способность.

SVR чувствителен к выбору ядра и настройке гиперпараметров. При большом масштабе данных и значительной вариативности целевой переменной модель может демонстрировать менее стабильные результаты без тщательной калибровки параметров.

Модель GPR показала более высокие значения RMSE и более низкий коэффициент детерминации (0.9000). Несмотря на теоретическую способность точно моделировать нелинейные процессы и учитывать неопределенность прогноза, на практике при работе с большими значениями целевой переменной наблюдается увеличение дисперсии предсказаний.

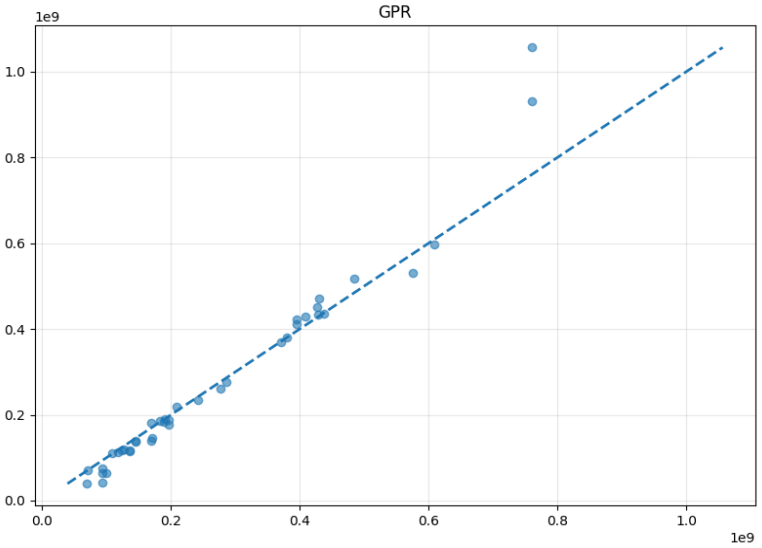


Рисунок 5. График сравнения фактических и прогнозных значений водопотребления (модель Gaussian Process Regression)

Дополнительным ограничением GPR является вычислительная сложность, которая возрастает при увеличении объема выборки.

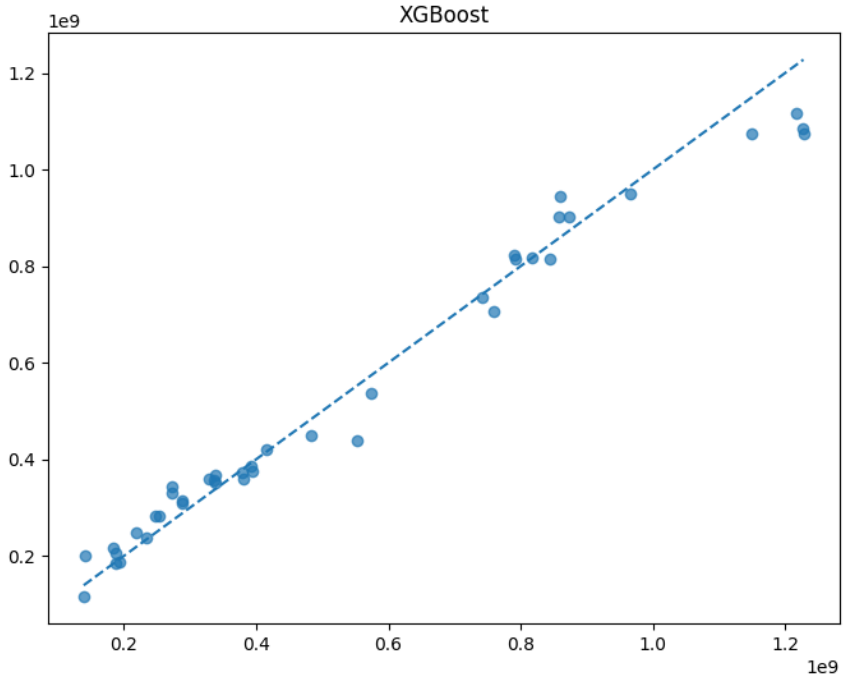


Рисунок 6. График сравнения фактических и прогнозных значений водопотребления (модель XGBoost)

Далее для прогнозирования потребности в пресной воде использовался алгоритм градиентного бустинга XGBoost (Extreme Gradient Boosting). Выбор данного метода обусловлен его высокой эффективностью при работе с табличными данными и способностью учитывать сложные нелинейные зависимости между признаками. В отличие от линейных моделей и простых ансамблевых методов, XGBoost реализует последовательное построение ансамбля деревьев решений, где каждая новая модель обучается на ошибках предыдущих. Такой подход позволяет минимизировать функцию потерь и постепенно повышать точность прогнозирования.

Для задач прогнозирования водопотребления данный алгоритм особенно актуален, поскольку рассматриваемая система характеризуется:

- нелинейным влиянием климатических факторов
- сильной автокорреляцией временных рядов
- взаимодействием погодных и социально-экономических переменных
- наличием шумов и пропущенных значений.

По результатам модель XGBoost продемонстрировала высокое качество прогнозирования потребности в пресной воде, обеспечив значение MAPE на уровне 8.77%, что означает среднюю относительную ошибку менее 9% и подтверждает высокую точность модели, при этом показатель Accuracy составил 91.23%, указывая на способность алгоритма воспроизводить более 90% фактической величины потребления, а значение RMSE, равное 53 013 131.94, отражает умеренное среднеквадратичное отклонение в абсолютных величинах с учетом крупного масштаба целевой переменной, тогда как коэффициент детерминации $R^2 = 0.9743$ свидетельствует о том, что модель объясняет более 97% вариации потребления воды, что является очень высоким результатом для социально-экономических данных и подтверждает эффективность XGBoost в выявлении сложных нелинейных зависимостей и воспроизведении динамики временного ряда.

Сравнительный анализ моделей прогнозирования водопотребления

Сравнительный анализ моделей прогнозирования водопотребления выявил значительные различия в их эффективности. Линейная модель Ridge Regression показала ограниченную объясняющую способность: коэффициент детерминации составил 0.3718, а средняя абсолютная процентная ошибка превысила 30%, что подтверждает нелинейный характер зависимости водопотребления от климатических и социально-экономических факторов. Переход к нелинейным алгоритмам существенно улучшил результаты: Random Forest продемонстрировал высокую точность (R^2 = 0.9549; MAPE = 8.33%) и наименьшее значение RMSE среди базовых моделей, а Support Vector Regression и Gaussian Process Regression также обеспечили устойчивые прогнозы, хотя уступили ансамблевым методам при высоких значениях потребления.

Наилучшие результаты были достигнуты с помощью XGBoost, который обеспечил максимальный коэффициент детерминации (R^2 = 0.9743) при низкой средней процентной ошибке (MAPE = 8.77%). Улучшение качества прогнозирования стало возможным благодаря использованию лаговых переменных и скользящих средних, что позволило учесть автокорреляцию временного ряда и инерционность спроса на воду. Визуальное сопоставление фактических и прогнозных значений подтвердило преимущество ансамблевых методов: Random Forest и XGBoost наиболее точно отражают структуру данных и региональные особенности. В целом анализ показал, что именно эти модели являются наиболее сбалансированными и устойчивыми для задач долгосрочного прогнозирования водопотребления.

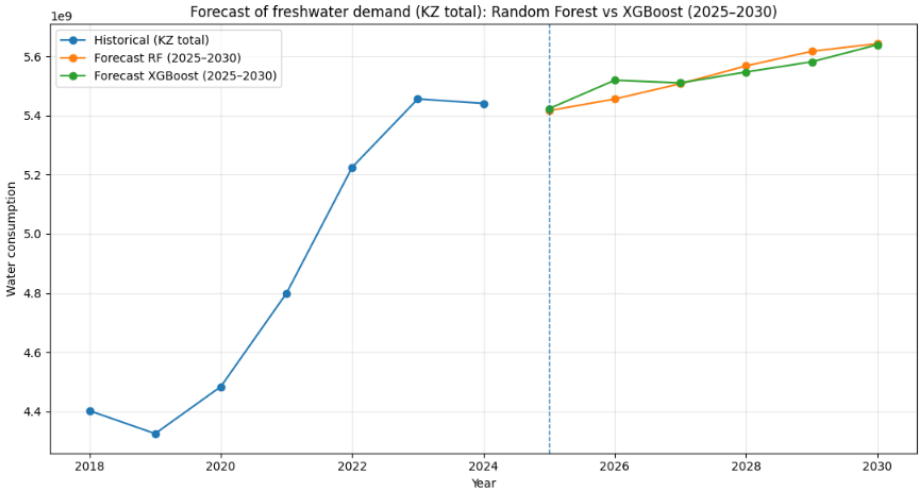
Таблица 1 - Сравнительный анализ моделей прогнозирования водопотребления

Model	MAPE	Accuracy	RMSE	R^2
Ridge Regression	31.72%	68.28%	262,037,957	0.3718
Random Forest	8.33%	91.67%	38,838,488	0.9549
Support Vector Regression	12.41%	87.59	49,788,311	0.9259
Gaussian Process Regression	10.75%	89.25%	57,812,878	0.9000
XGBoost	8.77%	91.23	53,013,131	0.9743

Прогноз водопотребления до 2030 года

На основе сравнительного анализа двух наиболее эффективных моделей - XGBoost и Random Forest - было выполнено прогнозирование совокупного потребления воды в Республике Казахстан на период до 2030 года. На представленном графике отображены три ключевых элемента: фактическая динамика водопотребления за 2018–2024 гг., прогнозные значения на 2025–2030 гг., рассчитанные моделью Random Forest, а также прогноз, полученный с использованием алгоритма XGBoost. Вертикальная пунктирная линия отделяет исторический период наблюдений от прогнозного интервала, что

позволяет наглядно сопоставить фактические данные с модельными оценками будущей динамики.



Анализ исторических данных демонстрирует устойчивую тенденцию роста потребления воды, особенно начиная с 2020 года. Наиболее интенсивное увеличение объёмов зафиксировано в 2021–2023 гг., что может быть связано с климатическими факторами, ростом сельскохозяйственной активности, демографическими изменениями и увеличением промышленного потребления. В 2024 году динамика несколько стабилизируется, однако уровень потребления остаётся существенно выше значений начала анализируемого периода.

Прогнозный интервал 2025–2030 гг. характеризуется сохранением восходящего тренда. Обе модели демонстрируют близкие траектории роста, что подтверждает устойчивость полученных оценок. Модель Random Forest формирует более сглаженную и линейную динамику увеличения потребления, отражая усреднённый характер ансамблевого метода бэггинга. В свою очередь, XGBoost демонстрирует более гибкую траекторию, несколько чувствительнее реагируя на структуру данных и взаимодействие признаков, однако к концу прогнозного периода значения двух моделей практически совпадают.

К 2030 году прогнозируется дальнейшее увеличение совокупного водопотребления по сравнению с уровнем 2024 года, что указывает на сохранение структурного спроса на водные ресурсы. Отсутствие резких колебаний в прогнозной части графика свидетельствует о стабильности модели и подтверждает инерционный характер динамики потребления.

Визуализация позволяет сделать несколько ключевых выводов:

- Рост водопотребления носит устойчивый и долгосрочный характер.
- Прогнозные значения двух независимых моделей демонстрируют высокую согласованность.
- Структура временного ряда сохраняет плавную динамику без признаков резкого снижения или экстремальных скачков.

Заключение. Проведённый сравнительный анализ различных подходов к прогнозированию потребности в пресной воде показал, что классические линейные и эконометрические модели обладают ограниченной способностью описывать сложную структуру данных. Несмотря на их интерпретируемость и теоретическую обоснованность, такие модели демонстрируют снижение точности при наличии

выраженных нелинейных зависимостей, региональной неоднородности и взаимодействия климатических факторов с лаговыми значениями потребления.

Переход к ансамблевым методам машинного обучения позволил существенно повысить качество прогнозирования. Использование алгоритмов, основанных на деревьях решений, обеспечило автоматическое выявление сложных нелинейных зависимостей между температурой, осадками, влажностью, нормативными показателями и историческими значениями потребления воды. Это позволило значительно снизить среднюю процентную ошибку и увеличить коэффициент детерминации по сравнению с традиционными моделями.

Наиболее эффективными алгоритмами по итогам тестирования оказались Random Forest и XGBoost. Обе модели продемонстрировали высокие значения коэффициента детерминации (R^2 свыше 0.95 для Random Forest и свыше 0.97 для XGBoost), что свидетельствует о способности объяснять практически всю вариацию целевой переменной. При этом значения средней абсолютной процентной ошибки (MAPE) находились ниже 10%, что соответствует высокому уровню точности для задач макроэкономического и ресурсного прогнозирования.

Random Forest продемонстрировал минимальные абсолютные ошибки и устойчивую сглаженную динамику прогноза, что подтверждает его стабильность и надёжность. В свою очередь, XGBoost показал более высокую объясняющую способность и лучшую адаптацию к сложной структуре данных, что делает его предпочтительным инструментом для долгосрочного прогнозирования и сценарного анализа.

Прогноз до 2030 года, построенный на основе данных моделей, указывает на сохранение устойчивого восходящего тренда водопотребления в Республике Казахстан. Полученные результаты подтверждают наличие инерционного характера динамики спроса и влияние климатических факторов на формирование потребности в водных ресурсах.

В целом результаты исследования демонстрируют высокую эффективность методов машинного обучения при решении задач прогнозирования водопотребления и подтверждают их практическую применимость для поддержки принятия решений в сфере стратегического управления водными ресурсами Республики Казахстан, разработки программ устойчивого водоснабжения и оценки рисков водного дефицита в условиях изменения климата.

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MULTI-VIEW ПРЕДСТАВЛЕНИЯ БИНАРНЫХ ФАЙЛОВ ДЛЯ КЛАССИФИКАЦИИ СЕМЕЙСТВ ВРЕДОНОСНОГО ПО В ПАРАДИГМЕ MALWARE-AS-IMAGE

Аннотация: Обеспечение надёжной классификации вредоносного ПО семейства malware остаётся актуальной задачей в области кибербезопасности. Один из современных методов -представление бинарного файла как изображения (malware-as-image) с последующим применением сверточных нейронных сетей (CNN). Наиболее известный датасет -**Malimg** (2011) с 9 339 образцами и 25 семействами , где была продемонстрирована высокая (до 98%) точность при использовании признаков текстуры изображения. В большинстве работ входной канал ограничивался одной матрицей («grayscale»), при этом улучшения достигались за счёт более глубоких сетей, transfer learning или генеративных моделей. В данной работе мы рассматриваем альтернативный подход: *multi-view* представление, добавляющее к исходному изображению канал местных переходов (фильтр Sobel), не меняя существенно архитектуру CNN. Мы конструируем оба варианта (baseline vs multi-view) с одинаковыми блоками и оцениваем их на Malimg. Для оценки используются метрики accuracy, macro-F1, weighted-F1, сбалансированная точность, топ-3 точность, а также анализ матрицы ошибок и Grad-CAM. Результаты показывают, что двухканальный ввод повышает точность классификации без существенного роста параметров сети, но при этом выявляет ограничение: очень редкий класс сохраняет низкую распознаваемость. Наши выводы показывают, что предложенный multi-view подход служит эффективным «легковесным» усилением malware-as-image метода, а не полной заменой более сложных архитектур.

Введение. Классификация malware-семейств является важной задачей статического анализа вредоносного ПО, так как традиционные сигнатурные и эвристические методы часто хуже работают при обфускации и появлении новых вариантов. В последние годы активно используется подход **malware-as-image**, где бинарный файл преобразуется в grayscale-изображение, а CNN извлекает визуальные признаки семейства без запуска файла. Такой подход позволяет анализировать

устойчивые структурные паттерны кода и данных, поскольку варианты одного семейства часто имеют схожую визуальную текстуру.

В данной работе проверяется, улучшает ли качество классификации дополнительное структурное представление входных данных. Для этого к исходному grayscale-изображению добавляется второй канал- **Sobel-view**, отражающий локальные границы и перепады интенсивности. Архитектура CNN при этом практически не изменяется, поэтому сравнение позволяет оценить именно вклад входного представления, а не увеличение сложности модели.

Эксперименты на датасете Malimg показали, что grayscale baseline достиг accuracy **0.9035** и balanced accuracy **0.9346**, тогда как multi-view модель повысила accuracy до **0.9821** при увеличении всего на **288 параметров**. Однако подход не решил полностью проблему редких классов: например, класс **Autorun.K** с 12 тестовыми образцами не был распознан моделью. Это показывает, что multi-view представление существенно улучшает общие метрики, но не устраняет ограничения, связанные с дисбалансом и визуальной близостью отдельных семейств.

Дальше в статье рассматриваются датасет и предобработка, архитектура baseline и multi-view CNN, экспериментальная настройка, сравнительные метрики, матрицы ошибок, per-class recall и интерпретация Grad-CAM. В заключении обсуждаются ограничения метода и возможные направления дальнейшего улучшения.

Связанные исследования

Важной основой для направления **malware-as-image** является работа Nataraj et al. (2011), где бинарные файлы вредоносного ПО были впервые представлены как grayscale-изображения. Авторы показали, что образцы одного malware-семейства имеют схожую визуальную текстуру, а классификация по таким признакам может достигать около 98% точности без дизассемблирования файла. Позднее эта идея была развита в работах с применением CNN: например, Polsani (2020) предложил модель DeepGray для классификации grayscale malware-изображений, а Bensaoud et al. (2020) показали применимость CNN к malware-картинкам и отметили устойчивость такого подхода к упаковке и обфускации.

Более сложные архитектуры также применялись для повышения качества классификации. Dao et al. (2022) объединили CNN, вариационный автоэнкодер и механизм внимания, подтвердив эффективность image-based подхода на датасете Malimg. При этом авторы также указывали на сильный дисбаланс классов, где одни семейства представлены тысячами образцов, а другие — значительно меньшим числом. Это делает задачу классификации сложнее, особенно для редких классов.

Отдельное направление связано с **multi-view learning**. Seeland and Mäder (2021) показали, что объединение нескольких визуальных представлений одного объекта может повысить точность классификации по сравнению с использованием одного вида. Подобная идея также применяется в медицинских изображениях и системах обнаружения вторжений, где разные «виды» данных дают дополнительную информацию о классифицируемом объекте. Для задач malware-классификации также актуальны методы transfer learning: например, система DEFENDIFY использует предварительно обученные CNN-архитектуры и показывает высокие F1-результаты как на обычных, так и на обфусцированных malware-образцах (Silva et al., 2025).

Наш подход объединяет идеи malware visualization и multi-view learning. В отличие от работ, где улучшение достигается за счет более сложной архитектуры, transfer learning или VAE/attention-механизмов, мы сохраняем CNN почти неизменной и проверяем вклад дополнительного представления входа. Multi-view вход строится из двух каналов: исходного grayscale-изображения и Sobel-карты границ. Таким образом, модель получает не только информацию об интенсивности пикселей, но и сведения о локальных переходах и структурных границах. Это позволяет проверить, помогает ли простое расширение входного представления улучшить классификацию malware-семейств без существенного увеличения сложности модели.

Датасет и экспериментальная настройка

Эксперименты проводились на **Malimg**. Мы использовали 128×128 пикселей, подгоняя размер каждого malware-изображения линейной интерполяцией. Изначальный Malimg не сбалансирован: семьи Allaple.A и Allaple.L составляют большую часть выборки, поэтому важна стратифицированная разбивка данных. Данные разделены на обучающую, валидационную и тестовую части в пропорции 70/15/15 с сохранением распределения классов (stratify по меткам). Для борьбы с дисбалансом в *train* наборе вычислены веса классов (class_weight="balanced"). Мы не использовали Data Augmentation, чтобы сравнение фокусировалось на представлении, а не на объёме данных.

Метрики оценки: accuracy, macro-F1, weighted-F1, сбалансированная точность (balanced accuracy) и Top-3 accuracy (попадание истинного класса в 3 наиболее вероятных). Также анализируются *confusion matrix* и *recall* по классам. Для интерпретации дополнительно применялся Grad-CAM. В качестве baselines использован канал [grayscale] и та же CNN-структура.

Гиперпараметры: оптимизатор Adam (learning rate = 1e-3), batch size = 16, эпохи = 30. Использовались слои BatchNorm, ReLU, Dropout (0.1 в Conv-блоках, 0.3 после Dense). Loss -sparse categorical crossentropy. Самодельные callback'и для отслеживания top-3 accuracy.

Архитектуры CNN

В эксперименте использовались две версии сверточной нейронной сети: базовая grayscale CNN и предложенная multi-view CNN. Главная идея сравнения заключалась в том, чтобы не менять существенно архитектуру модели, а проверить, дает ли улучшение именно дополнительное представление входного изображения.

Baseline-модель получает на вход одно grayscale-изображение размером 128 × 128 × 1. Это изображение представляет бинарный malware-файл, где значения байтов интерпретируются как интенсивности пикселей. Multi-view модель использует почти такую же архитектуру, но вход имеет размер 128 × 128 × 2. Первый канал соответствует исходному grayscale-изображению, а второй канал содержит Sobel-view, то есть карту локальных границ и переходов интенсивности.

Архитектура обеих моделей состоит из четырех сверточных блоков. Каждый блок включает Conv2D, BatchNormalization, ReLU, MaxPooling2D и Dropout. Количество фильтров последовательно увеличивается: 32, 64, 128 и 256. После последнего сверточного блока используется GlobalAveragePooling2D, затем Dense-слой на 128 нейронов, Dropout и итоговый softmax-слой на 25 классов malware-семейств.

Важный момент заключается в том, что multi-view модель почти не увеличивает сложность сети. Baseline CNN содержит 425 401 параметр, а multi-view CNN — 425 689 параметров. Разница составляет всего 288 параметров, так как изменение затрагивает только первый сверточный слой: вместо одного входного канала модель принимает два. Поэтому улучшение качества нельзя объяснить тем, что модель стала значительно больше; основной вклад связан именно с более информативным входным представлением.

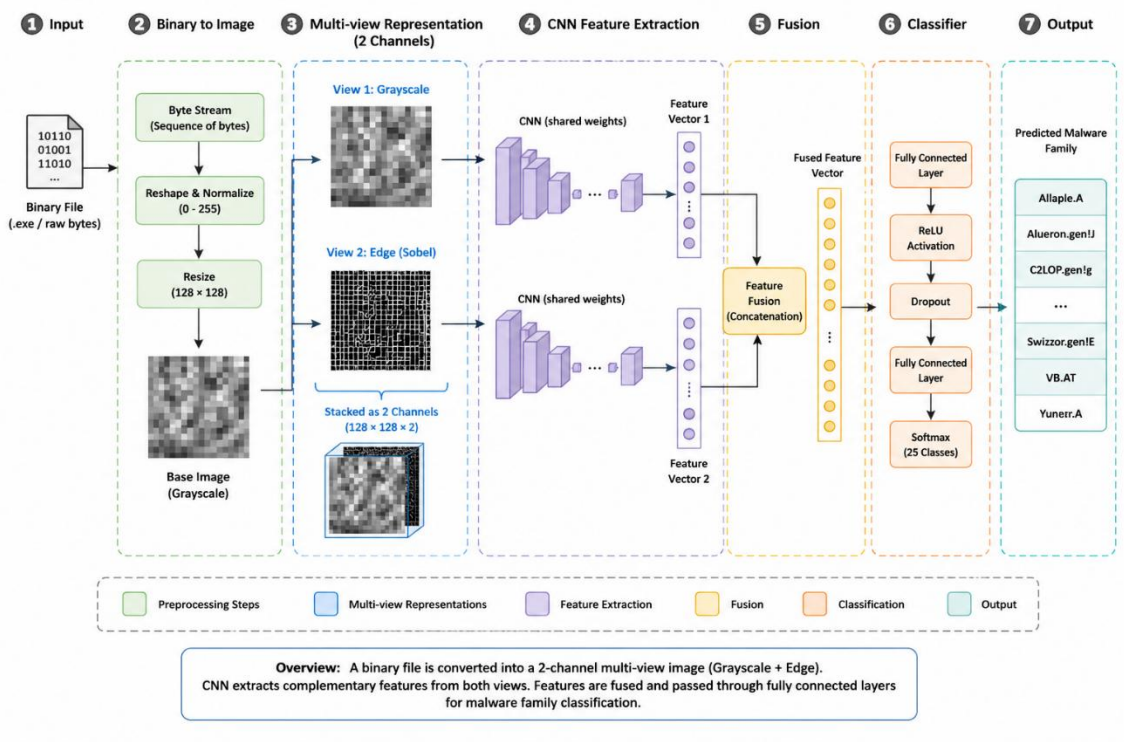


Рисунок 1 – Общая архитектура baseline и multi-view CNN

Результаты

Результаты эксперимента показывают, что добавление второго Sobel-канала значительно улучшило качество классификации malware-семейств. Grayscale baseline достиг accuracy 0.9035, macro-F1 0.9012 и weighted-F1 0.8945. Multi-view модель показала accuracy 0.9821, macro-F1 0.9413 и weighted-F1 0.9771. Также balanced accuracy увеличилась с 0.9346 до 0.9437. При этом top-3 accuracy в обеих моделях осталась равной 1.0000, что означает: правильный класс всегда находился среди трех наиболее вероятных предсказаний.

Таблица 1- Сравнение baseline и multi-view модели

Показатель	Baseline CNN	Multi-view CNN	Изменение
Входное представление	Grayscale	Grayscale + Sobel	—
Размер входа	128×128×1	128×128×2	+1 канал
Количество классов	25	25	0
Количество параметров	425 401	425 689	+288
Accuracy	0.9035	0.9821	+0.0786
Macro-F1	0.9012	0.9413	+0.0401
Weighted-F1	0.8945	0.9771	+0.0826
Balanced accuracy	0.9346	0.9437	+0.0091
Top-3 accuracy	1.0000	1.0000	0.0000

Полученные результаты показывают, что multi-view подход заметно повысил общую точность классификации. Особенно важно, что рост accuracy составил почти 7.9 процентных пункта, а число параметров увеличилось менее чем на 0.1%. Это подтверждает, что дополнительный Sobel-view действительно помогает модели лучше различать визуальные структуры malware-изображений.

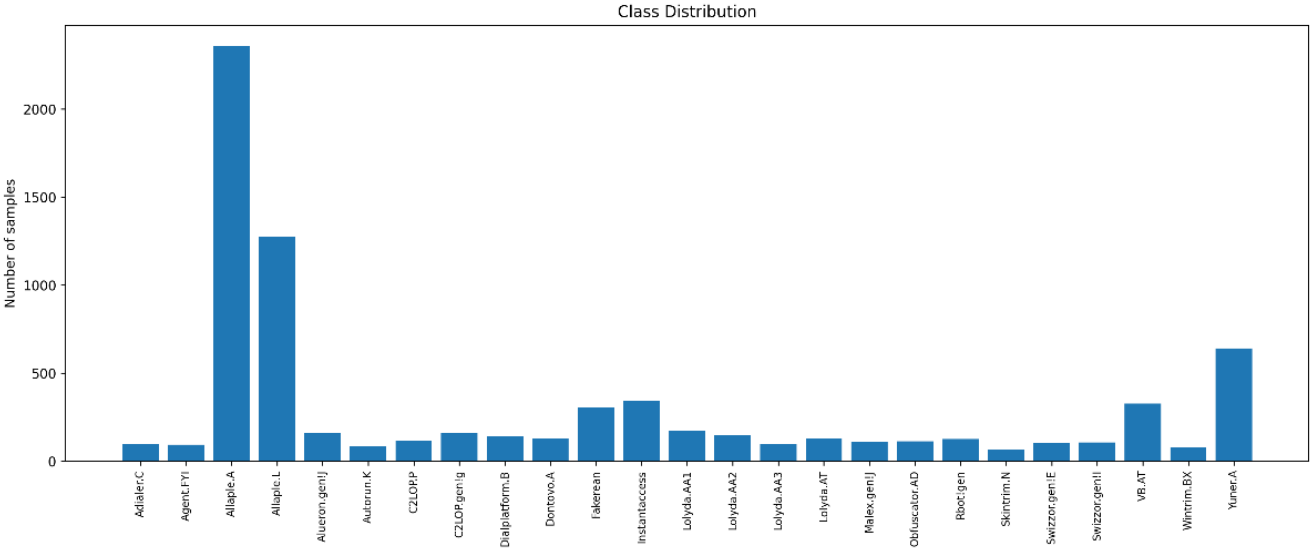


Рисунок 2 – Распределение классов в датасете

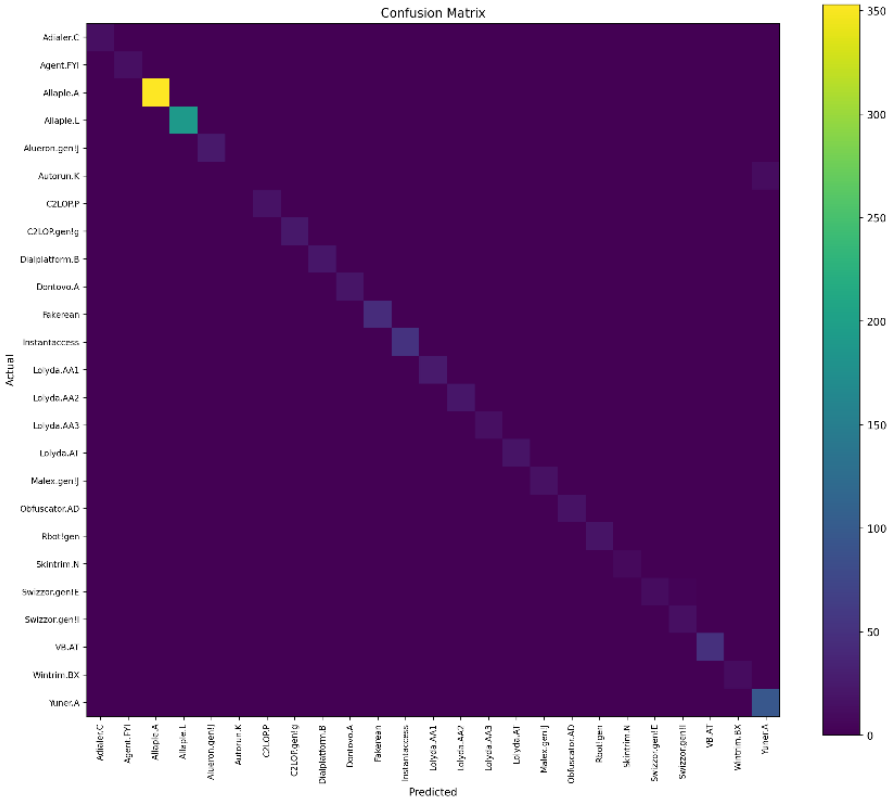


Рисунок 3 – Confusion matrix multi-view модели

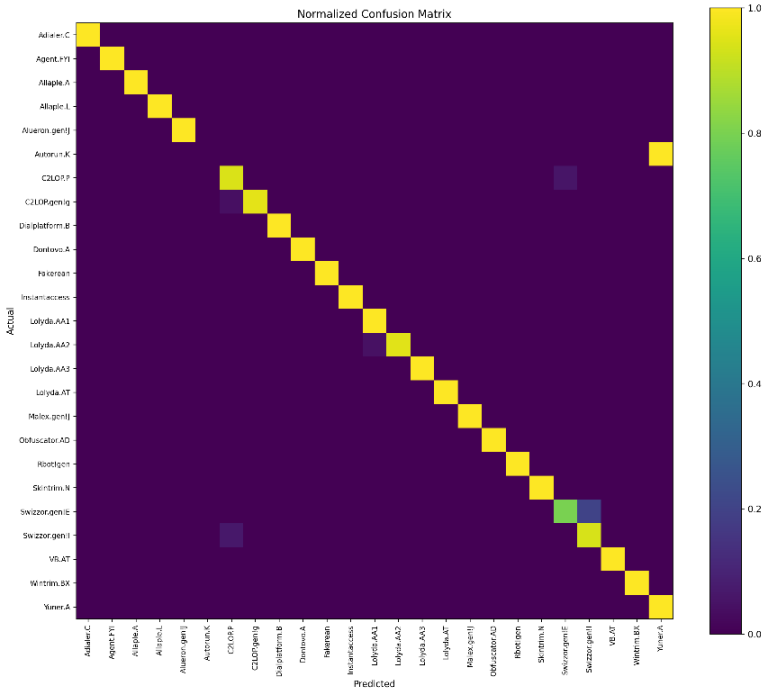


Рисунок 4 – Normalized confusion matrix multi-view модели

По confusion matrix видно, что большинство классов сосредоточены на главной диагонали, то есть модель правильно классифицирует основную часть malware-семейств. Однако ошибки не исчезли полностью. Главная проблема связана с классом Autorun.K: в classification report для него precision, recall и F1-score равны 0.0000 при support = 12. Это означает, что все 12 тестовых образцов этого класса были отнесены к другим семействам.

При этом многие другие классы были распознаны идеально или почти идеально. Например, Adialer.C, Agent.FYI, Alueron.gen!J, Dialplatform.B, Dontovo.A, Fakerean, Instantaccess, Malex.gen!J, Obfuscator.AD, Rbot!gen, Skintrim.N, VB.AT, Wintrim.BX и Yuner.A получили recall = 1.0000. Это показывает, что multi-view модель значительно усилила общую классификацию, но проблема редких и визуально близких классов все еще остается.

Отдельно стоит отметить классы Swizzor.gen!E и Swizzor.gen!I. Для них сохраняется частичная путаница: Swizzor.gen!E имеет recall 0.8000, а Swizzor.gen!I — 0.9375. Это говорит о том, что Sobel-view помогает выделять структурные границы, но не всегда полностью разделяет семейства с похожей визуальной текстурой.

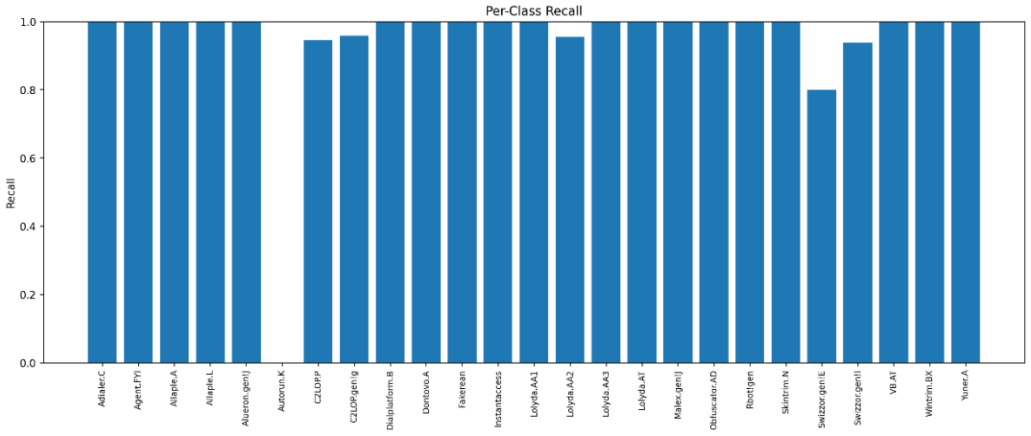


Рисунок 5 – Per-class recall multi-view модели

Графики обучения показывают, что модель достаточно быстро достигает высокой точности. Accuracy на обучающей и валидационной выборках растет в течение первых эпох, после чего стабилизируется. Loss снижается, что указывает на успешную сходимость модели. Top-3 accuracy быстро выходит на значение, близкое к 1.0, что согласуется с итоговой top-3 accuracy на тестовой выборке.

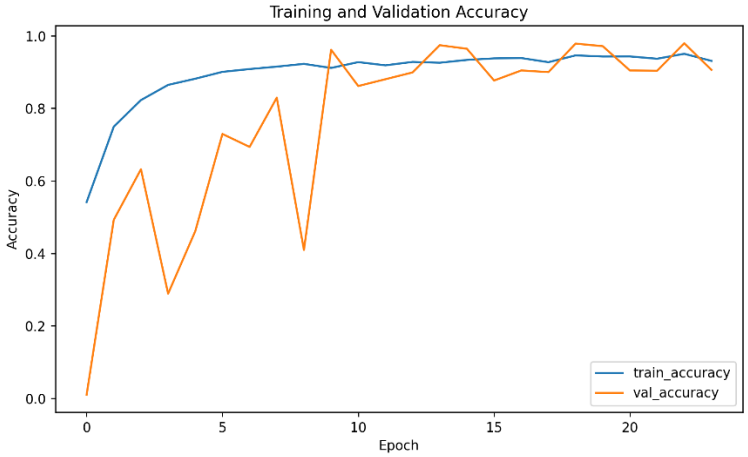


Рисунок 6 – График accuracy по эпохам

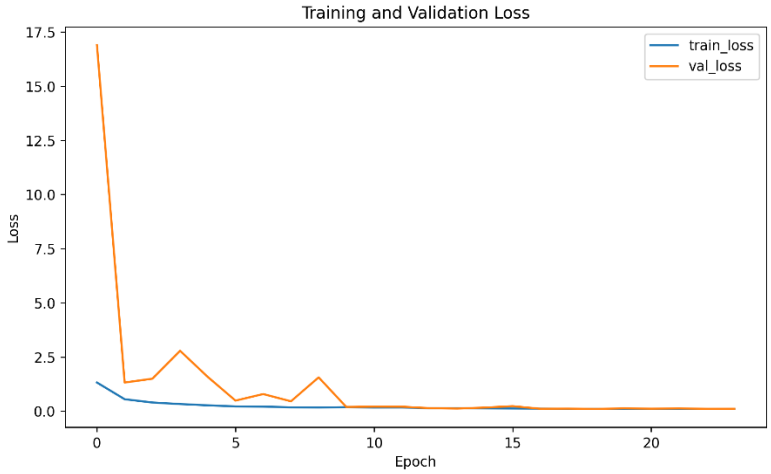


Рисунок 7 – График loss по эпохам

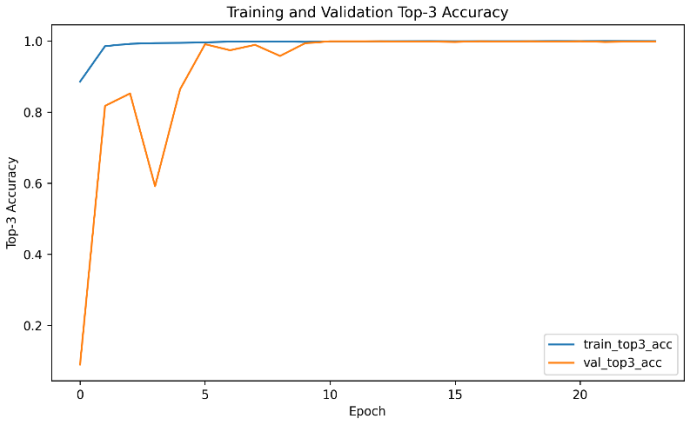


Рисунок 8 – График top-3 accuracy по эпохам

Дополнительно Grad-CAM визуализации показывают, что CNN обращает внимание не на случайный шум, а на структурные зоны изображения: горизонтальные полосы, переходы интенсивности и локальные границы. Это поддерживает идею multi-view подхода: если модель действительно использует структурные переходы, то Sobel-канал может усиливать полезные признаки для классификации.

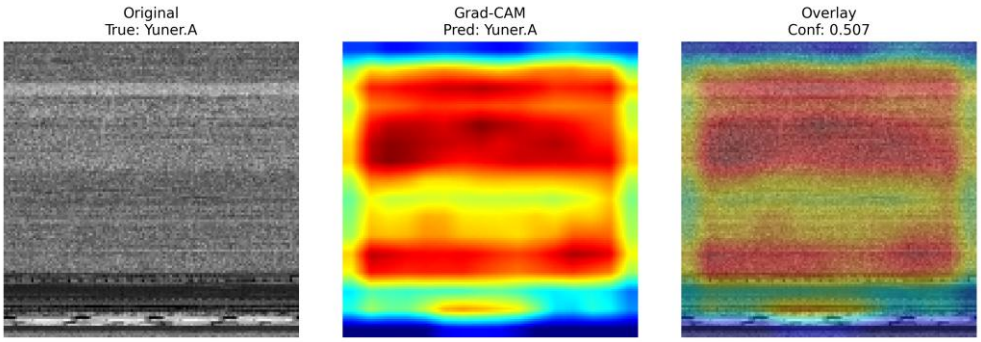


Рисунок 9 – Grad-CAM визуализация

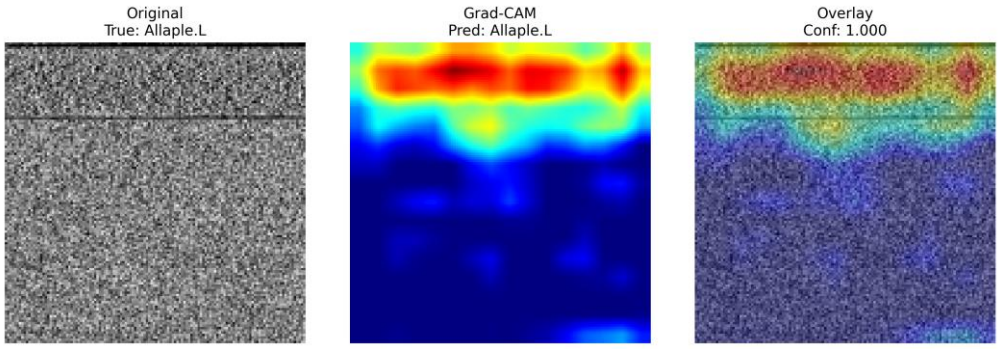


Рисунок 10 – Grad-CAM визуализация 2

Таким образом, результаты показывают, что предложенная multi-view CNN заметно превосходит grayscale baseline по основным метрикам, почти не увеличивая размер модели. Однако модель не решает полностью проблему редких классов, что особенно видно на примере Autorun.K. Поэтому multi-view подход следует рассматривать как эффективное улучшение входного представления, а не как полное решение всех проблем malware classification.

Обсуждение

Улучшение vs компромиссы. Результаты ясно показывают, что предложенное двухканальное представление существенно повышает точность классификации. Без значительного роста параметров (+288 из ~425k) мы повысили accuracy на +7.86% и weighted-F1 на +0.0826. Это демонстрирует, что доп.информация о локальных переходах (границы объектов) эффективно дополняет глобальную яркостную информацию из одного канала. Важный нюанс: *Top-3 accuracy* оставалась 100% в обоих случаях, т.е. baseline уже почти всегда помещал правильный класс в топ-3. Multi-view устранил часть спутанных ситуаций, двигая верный класс в топ-1 чаще.

Однако мы не добились идеального распознавания всех классов. Как видно из Табл. 5-6 и матрицы ошибок, ошибки после multi-view остаются локальными. Они сосредоточены на нескольких редких или схожих классах: главная проблема - класс **Autorun.K** (12 образцов) - не распознаётся вовсе. Это означает, что для этого

семейства добавленный Sobel-канал не дал модель новой информации, возможно потому, что граничные паттерны класса совпадают с другими (см. Родственность с Yuner.A). Аналогично, **Swizzor.gen!E** потерял часть recall, хотя **Swizzor.gen!I** наоборот улучшился. Эти случаи указывают на так называемое *trade-off*: multi-view перестраивает фичи, подчеркивая одни семейства за счёт других. Кроме того, генерализация на редкие классы ограничена количеством данных (всего ~10-20 образцов), поэтому даже с класс-весами learning может быть неустойчив.

Аргумент архитектуры. Ключевой результат - наш multi-view даёт выигрыш *без существенного изменения архитектуры*. Baseline и multi-view модели идентичны по глубине и структуре, отличается только вход. Это отличие подкрепляется таблицами: baseline 425 401 параметр vs multi-view 425 689 (разница 0.07%). Таким образом, даже вспомогательные модели (ResNet18) в DEFENDIFY эффективны именно благодаря *предобучению на изображениях*, а не изменению архитектуры. В нашем случае мы не использовали transfer learning, но идея сходна - мы «перенесли» знания из границ изображения (классический CV-признак) в задачу malware-классификации.

Глубина решений. Мы не стремились перекрыть все проблемы, а показать принципиальное улучшение представления. Multi-view нейтрализует ряд системных ошибок baseline, что указывает на существование «скрытых» признаков границ, которые одинокий канал оставляет. Однако уже в первой таблице видно-модель неправильно классифицирует Autorun.K, **поглотившись** в другие. Это честно отмечаем как ограничение: наша проверка показала, что multi-view помогает в среднем, но не решает проблему малых классов.

Интепретация Grad-CAM

Визуализация Grad-CAM показала, что сеть обращается к «смысленным» зонам изображения. На примерах malware можно заметить, что внимания уделяются горизонтальным полосам и областям с резким переходом интенсивности (геометрические границы между сегментами кода/данных). Это согласуется с ожиданиями: первичные слои CNN фиксируют *edges* и простые формы.

Например, на образцах Yuner.A и Dontovo.A тепло-лист фокуса покрывает те же сегменты, где Sobel-канал дает яркие полосы. Таким образом, Grad-CAM показывает, что модель действительно использует «структурные» признаки. Это косвенно подтверждает идею multi-view: раз модель фокусируется на краях, добавление специального канала градиентов лишь усиливает такие зоны. Однако Grad-CAM - эвристика, и нельзя сказать, что сеть «поняла код программы». Но в контексте malware-as-image важно, что она учится зацепляться за визуальные паттерны внутри бинаря.

Заключение. В работе изучено влияние двухканального (*multi-view*) представления malware-картинок на качество классификации семейства. Мы сравнили компактную CNN на одном grayscale-канале и на двухканальном входе (grayscale + Sobel). Эксперименты на Malimg показали, что предложенный подход **значительно улучшает** метрики (accuracy +7.9 п.п., macro-F1 +0.04) без существенного усложнения модели. При этом разбор ошибок показал, что прирост возникает за счёт снижения системных ошибок baseline, хотя полностью не устранены проблемы редких классов (например, Autorun.K оставался неопределённым). Основной научный вклад: демонстрируется, что *консервативное* расширение представления бинарника вторым каналом Sobel-

границ - простой и эффективный способ повысить чувствительность к семейственным признакам.

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ИССЛЕДОВАНИЕ ПОСЛЕДСТВИЙ DDOS-АТАК ДЛЯ ОРГАНИЗАЦИЙ И МЕТОДЫ ИХ МИНИМИЗАЦИИ

Аннотация: В статье рассмотрены последствия DDoS-атак для организаций финансового сектора и разработана методика минимизации их воздействия. Проведено экспериментальное исследование трёх классов атак — volumetric (L3/L4), HTTP-flood (L7) и поведенческих L7-атак, имитирующих бизнес-логику. Предложена комплексная четырёхблочная методика защиты, включающая профилирование трафика, многоуровневую архитектуру защиты, адаптивное управление ресурсами и процедурный мониторинг. По результатам тестирования средняя доступность сервисов при DDoS-атаках повышена с 91,5% до 98,5%.

Ключевые слова: DDoS-атаки, кибербезопасность, защита информационных систем, Graceful Degradation, финансовый сектор, операционная устойчивость, Rate Limiting, WAF.

Введение. Стремительная цифровизация бизнес-процессов и перевод критически важных сервисов в онлайн-среду привели к тому, что DDoS-атаки превратились в одну из наиболее серьёзных угроз для организаций любого профиля. По данным отраслевых аналитических отчётов, в 2022–2024 гг. наблюдается устойчивый рост как числа инцидентов, так и их средней мощности и сложности [1]. Особую опасность представляют многовекторные атаки, сочетающие воздействие на сетевом и прикладном уровнях одновременно, а также атаки уровня L7, имитирующие поведение легитимных пользователей и нацеленные на конкретные функции бизнес-логики [2].

Для финансовых организаций Республики Казахстан данная проблема приобретает особую актуальность в контексте требований регуляторов — Национального Банка РК (НБРК) и Агентства по регулированию и развитию финансового рынка (АРРФР) — к обеспечению непрерывности деятельности и соблюдению целевых показателей доступности критичных сервисов. Принятый в 2026 году Цифровой кодекс РК дополнительно закрепил нормативные требования к киберустойчивости операторов критической информационной инфраструктуры [3].

Цель настоящей статьи — экспериментально исследовать последствия DDoS-атак различных классов для типовой инфраструктуры финансовой организации и разработать методику минимизации их воздействия, верифицированную на исследовательском стенде.

Классификация DDoS-атак и модель угроз. В соответствии с общепринятой классификацией по уровням модели OSI выделяют три основных класса DDoS-атак [4]: сетевые и транспортные атаки (L3/L4) — volumetric-атаки (UDP/TCP/ICMP-флуд), нацеленные на исчерпание пропускной способности каналов связи; атаки прикладного уровня (L7) — HTTP-flood и аналогичные сценарии, перегружающие веб-серверы и серверы приложений; поведенческие L7-атаки — наиболее сложный класс, при котором аномальный трафик имитирует легитимную пользовательскую активность и направлен на ресурсоёмкие операции бизнес-логики (генерация отчётов, сложные запросы к базам данных).

Особенностью современных DDoS-кампаний является их многовекторный характер и использование распределённых ботнетов на базе IoT-устройств, что существенно усложняет задачу фильтрации [5]. Согласно данным Kaspersky и Positive Technologies, доля атак с применением сценариев L7 за последние годы значительно возросла, что свидетельствует о переходе злоумышленников к более изощрённым формам воздействия, направленным непосредственно на бизнес-процессы организаций [1, 6].

Описание исследовательского стенда и сценариев атак. Для проведения экспериментального исследования был развёрнут изолированный тестовый стенд, архитектура которого воспроизводит типовую инфраструктуру банка среднего уровня. Стенд включает четыре логических сегмента: сегмент генерации нагрузки (имитация внешней сети), периметр и DMZ (пограничный маршрутизатор, балансировщик нагрузки Nginx с модулем WAF), внутренний сегмент приложений (сервер приложений и СУБД) и сегмент мониторинга на базе Prometheus/Grafana.

Тестирование проводилось по трём репрезентативным сценариям.

Сценарий A (Volumetric-атака, L3/L4). Комбинированный UDP/TCP/ICMP-флуд, направленный на исчерпание пропускной способности каналов. Длительность активной фазы — 25 минут. В базовом состоянии уже на 7–9-й минуте сервис становился полностью недоступным: загрузка канала достигала 99,5%, доля ошибок — 100%.

Сценарий B (HTTP-flood, L7). Массированная генерация HTTP-запросов к веб-серверу и API-интерфейсам. Длительность — 20 минут. Без защиты на 10–11-й минуте доля ошибок 5xx достигала 85–88%, происходил каскадный отказ приложения.

Сценарий C (Поведенческая L7-атака). Имитация действий авторизованных пользователей, выполняющих ресурсоёмкие операции (генерация финансовых отчётов, сложные фильтрации истории транзакций). При относительно невысоком суммарном RPS (до 910 запросов/с) загрузка CPU достигала 100% уже на 6–8-й минуте, после чего следовал каскадный отказ всей системы.

Разработка комплексной методики минимизации последствий. На основе анализа результатов экспериментального исследования разработана четырёхблочная методика минимизации последствий DDoS-атак, ориентированная на обеспечение непрерывности критичных сервисов в условиях различных классов угроз [7].

Блок 1. Профилирование трафика и бизнес-операций. Формирование базового профиля нормальной нагрузки по скользящему окну наблюдений T = 21 сутки. Для каждой метрики (RPS, время отклика, CPU, RAM, IOPS) вычисляется базовое значение μ и стандартное отклонение σ. Адаптивное пороговое значение определяется как $\mu + k \cdot \sigma$,

где k = 3 для сетевых метрик, k = 2 для прикладных, k = 2,5 для метрик подсистемы хранения.

Блок 2. Многоуровневая архитектура защиты. Эшелонированная фильтрация трафика: L3/L4 — сервисы очистки трафика (Scrubbing Center), ACL; L7 — WAF с антибот-модулем, сессионный анализ с построением цифрового отпечатка клиента (fingerprinting) на основе параметров TLS, HTTP-заголовков и поведенческих паттернов.

Блок 3. Адаптивное управление ресурсами (Graceful Degradation). Четырёхуровневый алгоритм контролируемой деградации функциональности: (1) расширенное кэширование + мягкий rate limiting; (2) перевод ресурсоёмких операций в асинхронный режим; (3) активация шаблона Circuit Breaker; (4) приоритизация аутентифицированных пользователей с длительной историей активности.

Блок 4. Процедурный мониторинг и реагирование. Формализованные плейбуки реагирования на инциденты. Непрерывный цикл: Analyze → Protect → Adapt → Monitor. Автоматическое возвращение данных об инцидентах в блок профилирования для уточнения пороговых значений.

Таблица 1 – Агрегированные показатели эффективности методики (усреднено по сценариям A–C)

Этап внедрения	Доступность при атаке, %	Среднее время отклика, мс	Доля ошибок 5xx, %
Этап 0 (без защиты)	91,5	1 816	16,6
Этап 1 (профилирование)	92,3	1 733	15,3
Этап 2 (сетевая защита)	94,5	1 326	10,0
Этап 3 (WAF + антибот)	96,8	341	4,4
Этап 4 (Graceful Degradation)	98,5	226	1,5

Результаты и обсуждение. Тестирование разработанной методики на исследовательском стенде подтвердило её эффективность для всех трёх классов DDoS-угроз (таблица 1). Ключевые результаты по сценариям распределились следующим образом.

Для сценария A (volumetric-атака) решающий вклад внесли блоки 1 и 2: после включения сервиса очистки трафика (этап 2) доступность возросла с 94,2% до 98,5%, загрузка внутренних каналов не превысила 65%, а время реакции системы на превышение порогов сократилось с ~12 минут до ~3 минут.

Для сценария B (HTTP-flood) определяющими стали блоки 2 и 3. Внедрение WAF, сессионного анализа и адаптивного rate limiting снизило долю ошибок 5xx с 15,4% до 1,1% при сохранении сопоставимой совокупной нагрузки. Доля ложноположительных срабатываний составила 0,3% легитимного трафика.

Наиболее значимый относительный эффект достигнут в сценарии C (поведенческая L7-атака), где традиционные средства сетевой фильтрации практически неэффективны. Активация механизмов Graceful Degradation и алгоритма Circuit Breaker позволила снизить пиковую загрузку CPU с 92% до 58%, поднять доступность ключевых операций

с 88,0% до 98,5%, при этом интерфейс личного кабинета и платёжные операции оставались стабильными на протяжении всего испытания [8].

Полученные значения средней доступности сервисов (98,5%) и доли ошибок 5xx (1,5%) соответствуют целевым показателям SLA для критичных сервисов финансовых организаций и требованиям НБРК/АРРФР к непрерывности деятельности.

Заключение. В статье представлена комплексная методика минимизации последствий DDoS-атак, разработанная на основе экспериментального исследования трёх репрезентативных сценариев атак на изолированном исследовательском стенде. Методика сочетает технические меры (многоуровневая фильтрация трафика, адаптивное управление ресурсами) с организационными (формализованные плейбуки, непрерывный мониторинг) и обеспечивает итоговое повышение доступности сервисов с 91,5% до 98,5%.

Особую практическую значимость представляет блок адаптивного управления ресурсами (Graceful Degradation), обеспечивающий защиту от поведенческих L7-атак — наиболее сложного и быстро растущего класса угроз, против которого традиционные сетевые средства демонстрируют ограниченную эффективность. Разработанная методика может быть применена финансовыми организациями, операторами связи и операторами критической информационной инфраструктуры Республики Казахстан для повышения киберустойчивости и соответствия нормативным требованиям регуляторов.

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ХОРРОР НЕГІЗІНДЕ ОЙ ЖҰМБАҚ ЭЛЕМЕНТТЕРІН ҚОЛДАНЫП ОЙЫН ҚҰРУ

Аңдатпа: Бұл мақалада дербес компьютерлерге арналған, басқатырғыш элементтері бар хоррор ойынын әзірлеу барысы сипатталады. Ойыншыларды үрей мен шиеленіс атмосферасына тартатын ерекше тұжырымдама жасауға басты назар аударылды. Сюжет желісін, кейіпкерлерді және қоршаған ортаны егжей-тегжейлі пысықтау жобаның негізгі бөлігіне айналды. Бағдарламалау, геймдизайн және визуалды өнер элементтерін біріктіру арқылы толыққанды өнім жасалды. Сонымен қатар, жобаның сапасы мен бірегейлігін қамтамасыз ету мақсатында аудиторияның сұраныстары мен нарықтағы танымал хоррор ойындарына талдау жүргізілді.

Ойын барысында кездесетін тапсырмаларды шешу арқылы пайдаланушылар өздерінің логикалық және сыни ойлау қабілеттерін дамытады, бұл жұмыстың негізгі практикалық маңыздылығын көрсетеді.

Кілт сөздер: дербес компьютер ойындары, Unity ортасы, хоррор жанры, басқатырғыштар, сыни тұрғыдан ойлау, үшөлшемді графика (3D), ойын қозғалтқышы, кейіпкерлер анимациясы, виртуалды лабиринт.

Кіріспе. Бүгінде бейнеойындарды жай ғана бос уақыт өткізетін ермек деуге ауыз бармайды. Бұл — миллиардтаған айналымы бар, бәсекесі қазандай қайнап жатқан тұтас бір алып индустрия. Қазіргі талғамы биік ойыншыларды таңғалдыру үшін құрғақ код жазып қою мүлдем аздық етеді. Оған көздің жауын алатын визуал, ешкімге ұқсамайтын креатив пен мінсіз техникалық шешімдер ауадай қажет.

Дегенмен, бағымызға орай, қазіргі заманауи құралдар әзірлеушілердің жұмысын әлдеқайда жеңілдетіп тастады. Мәселен, Unity немесе Unreal Engine сияқты мықты қозғалтқыштар қазір кез келген адамға қолжетімді. Осылардың көмегімен жас мамандар күрделі математикалық формулалар мен физика заңдылықтарына бас қатырмай-ақ, нарыққа сапалы әрі бәсекеге қабілетті өнім шығаруға толық мүмкіндік алды.

Жұмысымның басты өзектілігі де дәл осыған саяды: интерактивті қосымшалар жасағанда жаңа алгоритмдерді қалай ұтымды, қалай тиімді пайдалануға болады? Алға қойған негізгі мақсат — Unity базасында толыққанды, сапалы хоррор ойынын жасап шығару. Бірақ мақсат тек адамды қорқытып, үрейлендіру емес. Ойынның ішіне түрлі

логикалық басқатырғыштарды шебер кіріктіру арқылы геймерді терең ойлануға, миын істетуге мәжбүрлеуді көздедім.

Зерттеу нысаны етіп Unity қозғалтқышының кең-байтақ техникалық мүмкіндіктерін алдым. Ал зерттеу пәнім — тікелей осы хоррор жанрының өзіне тән ішкі ерекшеліктері. Жұмыстың ғылыми жаңалығы неде десеңіз, бұл жобада ойын механикасын құрудың жаңа алгоритмдік шешімдері құр қағаз жүзінде емес, нақты тәжірибеде сыналады. Одан бөлек, деңгей дизайнын жасау барысында бір-біріне ұқсамайтын бірнеше түрлі тәсілді біріктіріп, синтездеп қолдандым.

Материалдар мен тәсілдер. Жалпы, жұрттың зәре-құтын қашыратын қорқынышты ойын жасау сырттай оңай көрінгенімен, іс жүзінде өте ауыр шаруа. Бұл таусылмас шығармашылық ізденісті, әрбір ұсақ-түйек детальға үңілуді және темірдей нақты жоспарды талап етеді. Хоррордың ең басты миссиясы — геймердің психологиясына тікелей шабуыл жасау, оны үрейлендіріп қана қоймай, бастан-аяқ белгісіздіктің, түсініксіз қысымның астында ұстау. Дәл осы атмосфераны бұзбай жеткізу үшін бүкіл әзірлеу процесін бірнеше нақты кезеңге бөліп тастадым.

- Біріншісі — тұжырымдама жасау. Барлығы осыдан басталады: негізгі идея туындайды, оқиға желісі жазылады, бас кейіпкерлердің болмысы мен басты ойын механикалары нақтыланады.
- Екіншісі — деңгей архитектурасы немесе левел-дизайн (Level design). Бұл кезеңде виртуалды әлемнің қаңқасы тұрғызылады. Ойыншыны қай бұрыштa қорқытамыз, қандай тұзақтар қоямыз, кедергілер картаның қай тұсында тұруы керек — осының бәрі мұқият есептеледі.
- Үшінші саты — ойын дизайны (Game design). Мұнда ойын ережелерінің мінсіз жұмыс істеуі қадағаланады. Тапсырмалар тым қиын болып кетпеуі керек, бірақ тым оңай да болмауы шарт — нағыз баланс осы жерде реттеледі. Сонымен қатар, ойыншының қоршаған ортамен қалай байланысатыны шешіледі.
- Төртіншісі — аудио дизайн. Хоррорда дыбыстың рөлі қаншалықты зор екенін айтып жатудың өзі артық. Жүйкені жұқартатын фондық музыка мен аяқастынан шығатын түрлі дыбыстарды дәл тауып қою арқылы психологиялық шиеленіс шарықтау шегіне жеткізіледі.
- Және соңғысы — графика мен визуал. Ойыншы ортаның шынайылығына сенуі үшін текстуралар, жарық пен көлеңкенің жұмбақ ойыны, сондай-ақ барлық нысандардың 3D-модельдері барынша шынайы әрі жан-жақты бапталады.

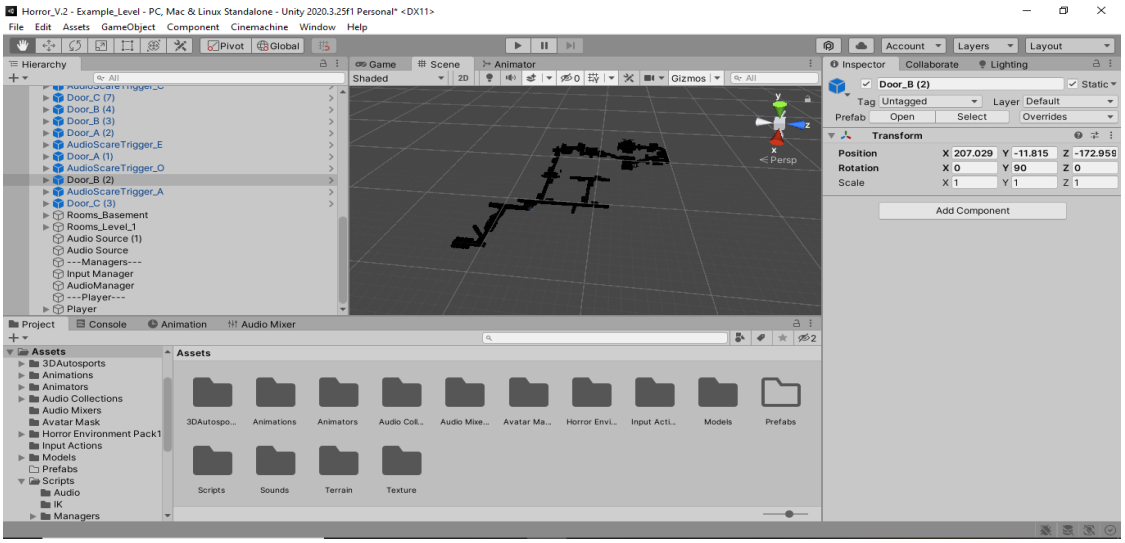
Жұмыстың бастапқы сатысы – виртуалды кеңістікті, яғни ойын деңгейін (локациясын) қалыптастыру. Дәл осы кезеңде жобаның базалық архитектурасы құрастырылады. Ортаны мейлінше шынайы және толыққанды етіп көрсету үшін түрлі 3D-модельдер іске қосылады. Қажетті нысандарды ашық дереккөздерден дайын күйінде жүктеп алуға немесе автордың өзі арнайы бағдарламаларда нөлден бастап құрастырып шығуына толық мүмкіндік бар.

Картаның ішіне қабырға, есік-терезе, түрлі жиһаздар, жарықтандыру көздері мен өзге де безендіру бөлшектері орналастырылады. Хоррор жанрындағы жобалар үшін әрбір ұсақ-түйектің өзіндік маңызы бар, себебі олар жалпы атмосфераны қалыптастыруға

тікелей қатысады. Сахнадағы заттардың дұрыс әрі үйлесімді қойылуы пайдаланушының психологиясына әсер етіп, оны үнемі қорқыныш пен белгісіздік қысымында ұстауға көмектеседі.

Бұған қоса, локацияның логикалық реттілігін де қатаң ескерген жөн. Пайдаланушының ойынды қай нүктеден бастайтыны, одан әрі қандай бағытпен жүретіні және қандай бөлмелерге кіре алатыны – барлығы алдын ала нақты есептелуі шарт. Мысалы, жарығы аз тар дәліздер, кішкене бөлмелер немесе аяқастынан кеңейіп кететін локациялар ойыншының бойындағы үрей сезімін еселей түсуге таптырмас құрал болып табылады.

Қорыта айтқанда, деңгей дизайнын жасау – кез келген бейнеойынның іргетасын қалайтын ең маңызды әрі жауапты кезеңдердің бірі.



1-сурет. Ойын локациясының жалпы құрылымы мен картасы

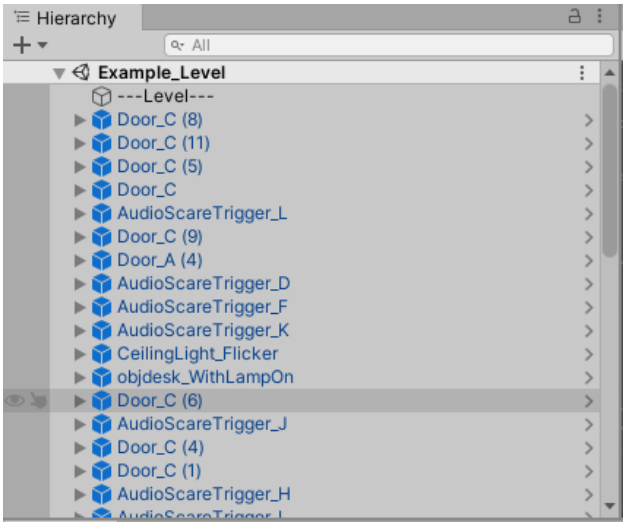
Ойын локациясы негізгі концепция ретінде жер астында орналасқан құпия ғылыми зертхана базасы түрінде жобаланды. Басты кейіпкердің алдында тұрған басты мақсат – осы жабық кешеннен аман-есен құтылып шығу. Бұл міндетті орындау үшін пайдаланушы жол бойында кездесетін түрлі логикалық кедергілер мен қауіптерді еңсеруі қажет.

Кешеннің ішкі интерьері ғылыми-техникалық нысанның стиліне толықтай сай жасақталған. Картадан жарығы нашар тар дәліздерді, құлыптаулы бөлмелерді, сондай-ақ жұмыс істеу принципі жұмбақ күрделі құрал-жабдықтар мен аппараттарды көруге болады. Ойын ортасының жалпы атмосферасы суық, тылсым әрі үрейлі сезім сыйлайтындай етіп құрылған. Мұндай визуалдық және психологиялық қысым ойыншыны үнемі қолайсыз жағдайда ұстап, кез келген қауіпке дайын болуға және әр қадамын аса сақтықпен басуға итермелейді.



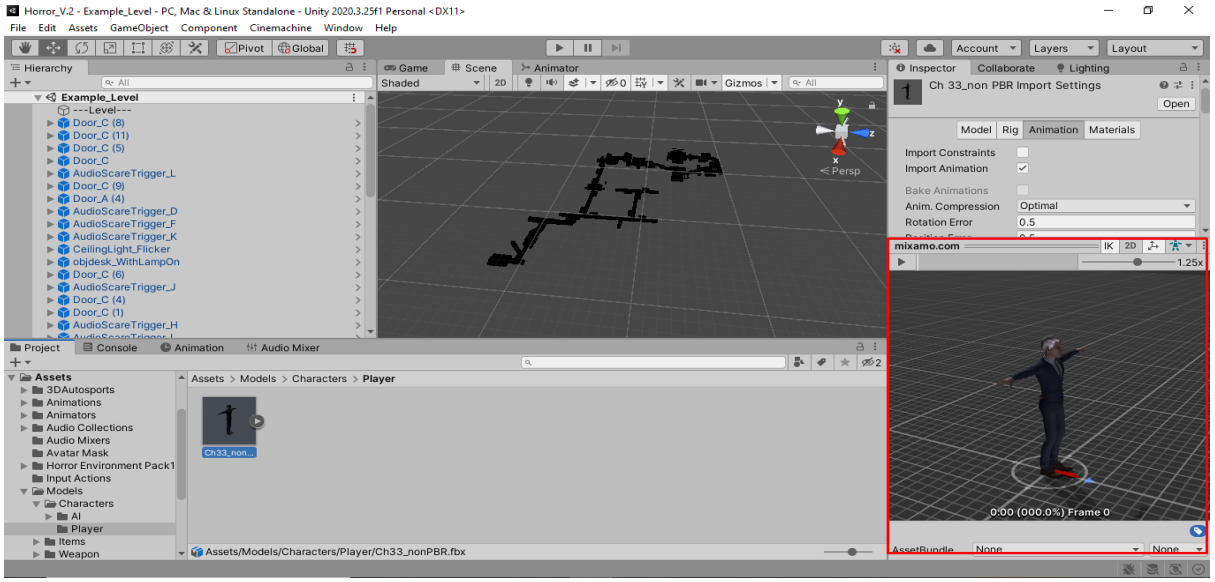
2-сурет. Зертхана бөлмесінің ішкі интерьері мен дизайны

Ойын сахнасына орналастырылған барлық элементтердің толық тізімі арнайы «Иерархия» (Hierarchy) панелінде көрсетіледі. Бұл терезенің көмегімен әзірлеуші виртуалды кеңістіктегі кез келген объектіні оңай тауып, оның қасиеттерін өңдеу немесе жалпы басқару жұмыстарын кедергісіз жүргізе алады.



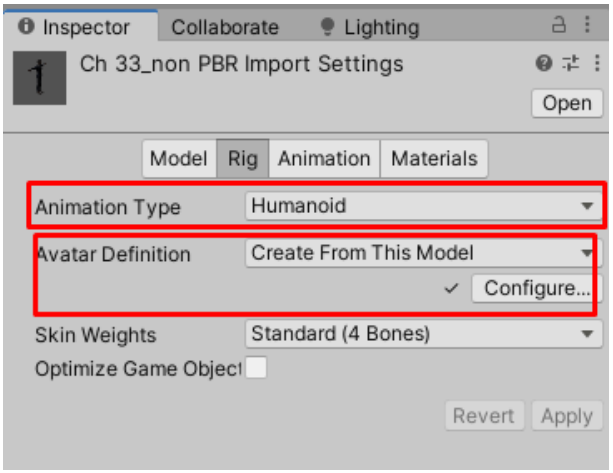
3-сурет. Сахнадағы объектілерді басқаруға арналған иерархия панелі

Ойын жобасындағы басты персонаждың визуалды бейнесін қалыптастыру жұмыстары ең алдымен сапалы 3D-модельді таңдап алудан бастау алады. Қазіргі кезде мұндай графикалық нысандарды міндетті түрде нөлден сызып әуре болудың қажеті жоқ, өйткені интернеттегі түрлі ашық қорлар оларды дайын күйінде ұсынады. Солардың ішіндегі ең танымалысы – Mixamo веб-сервисі. Бұл платформа ойын жасаушыларға алуан түрлі үшөлшемді кейіпкерлерді ешқандай ақы төлеместен, еркін жүктеп алып пайдалануға таптырмас мүмкіндік береді.



4-сурет. Жүйеге жүктеліп алынған басты кейіпкердің 3D-моделі

Жоба үшін таңдап алынған бұл кейіпкер гуманоид (адам пішінді) модельдер тобына кіреді. Оны ең алдымен ойын қозғалтқышына жүктеп алып, базалық баптауларын ретке келтіріп алу өте маңызды. Осындай алғашқы дайындықтан соң ғана персонаждың қимыл-қозғалысын басқаратын арнайы Rig (виртуалды қаңқа) жүйесін құрастыруға кірісеміз.

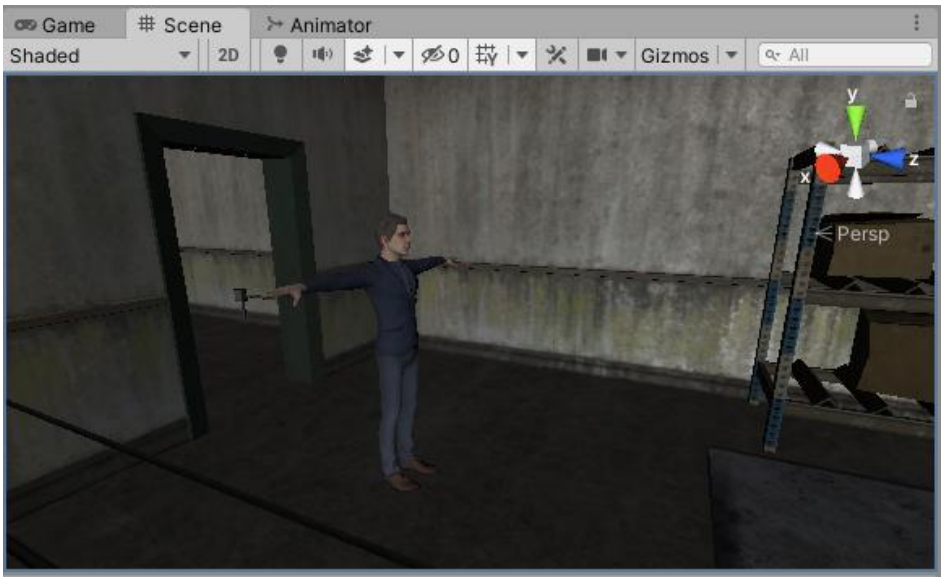


5-сурет. Анимациялық қаңқаны (Rig) баптау процесі

Модельді (кейіпкерді немесе нысанды) жүктеп алған соң, іс мұнымен бітпейді. Оның ішкі параметрлерін баптап, қозғалтқыштың (engine) тіліне бейімдеу қажет. Бұл тұста басты назарды екі маңызды нәрсеге бұрдым.

* Animation Type, яғни анимация түрі. Ол кейіпкердің виртуалды әлемде қалай жүріп-тұратынын, қалай қозғалатынын және жалпы физикасын толықтай шешіп береді.

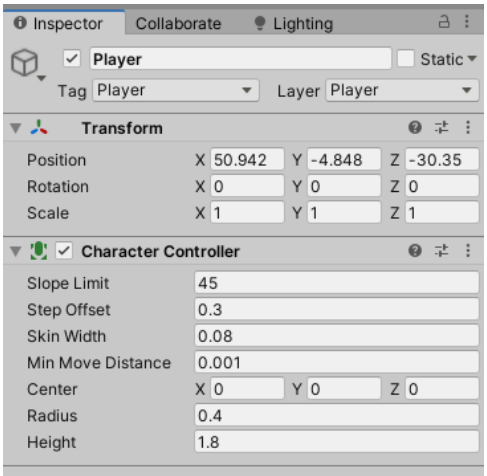
*Avatar Definition (Аватарды анықтау). Бұл өте қажетті баптау. Ол арқылы біз ойыншының виртуалды бейнесін қозғалтқышқа «таныстырамыз», яғни модельдің сүйек жүйесін (rig) жүйеге толық тіркейміз. Онсыз кейіпкер дұрыс қимылдамайды.



6-сурет. Дайын болған ойыншы персонажын виртуалды сахнаға орналастыру

Кейіпкерді (Player) картаға қосқаннан кейін, оны жансыз қуыршақ күйінде қалдырмай, мұқият баптау қажет. Бұл үшін бізге арнайы компоненттер көмекке келеді. Олардың ішіндегі ең маңыздысы — Character Controller.

Дәл осы модуль кейіпкердің ойын кеңістігіндегі барлық қозғалысын тікелей басқарады. Мәселен, ол ауада қалқып жүрмей, гравитация заңына бағынып, жерге нық басып жүруі шарт. Оған қоса, персонаж қабырғалардан елес құсап өтіп кетпеуі немесе басқа нысандардың ішіне кіріп кетпеуі керек. Қоршаған ортадағы кедергілерге соғылу, яғни коллизия (collision) процесін реттеу де толықтай осы контроллердің мойнында.



7-сурет. Player нысанының толыққанды жұмысы үшін негізгі контроллерлерді бекіту

Ойыншының базалық параметрлерін баптап болған соң, келесі кезекте бағдарламалық кодтарды (скрипттерді) жазу кезеңіне өтеміз.

Ойын логикасын бағдарламалау

Жобадағы басты кейіпкердің жұмысы нақты бір қызметке жауап беретін бірнеше өзара байланысты модульдер арқылы жүзеге асырылады. Біздің жобадағы ойыншы нысаны келесідей негізгі компоненттерден тұрады:

PlayerController: Басты кейіпкердің кеңістіктегі базалық іс-әрекеттерін (орын ауыстыру, бағытын өзгерту және т.б.) басқаруды қамтамасыз ететін орталық компонент.

InputManager: Пайдаланушының пернетақтадан немесе өзге құрылғылардан берген командаларын қабылдайтын модуль. Бұл жүйе Unity платформасының жаңартылған енгізу жүйесі (New Input System) негізінде жұмыс істейді.

StateMachine: Ойыншының әртүрлі жағдайлары мен күйлерін алмастыруға (мысалы, анимациялардың бірқалыпты ауысуына) жауап беретін басқарушы құрылым. Бұл компонентті әзірлеу барысында бағдарламалаудың мінез-құлықтық паттерні – State (Күй) архитектуралық үлгісі қолданылды.

State: Әрбір жеке қимыл немесе әрекеттің (күйдің) өзін сипаттайтын модуль.

StateController: Кейіпкердің нақты күйлерін (мысалы, тыныш тұру – idle, жүру – walk, жүгіру – sprint, секіру – jump) іске қосатын және олардың реттілігін қадағалайтын компонент.

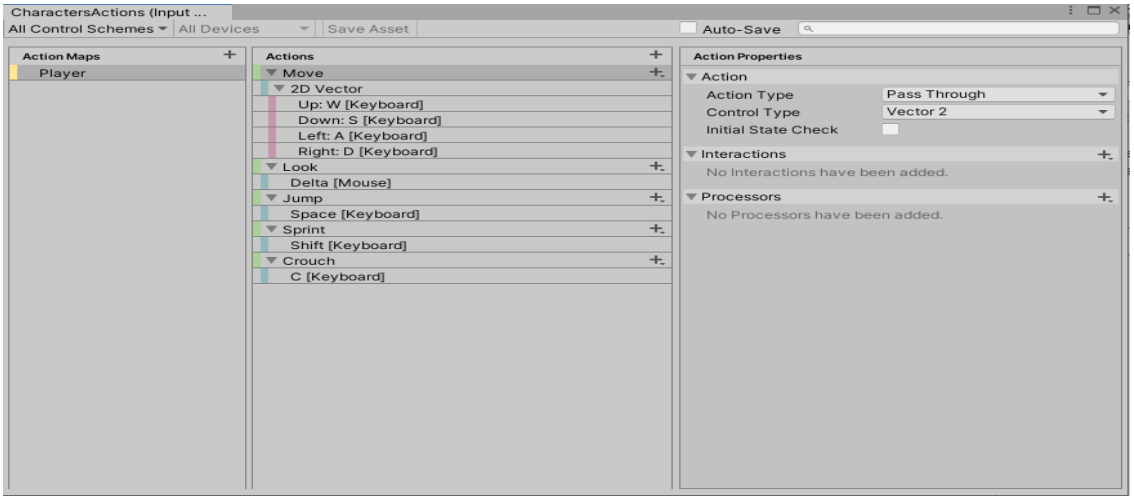
AudioManager: Жалпы ойын барысындағы, оның ішінде тікелей ойыншыға тиесілі әртүрлі дыбыстық эффектілерді (мысалы, жүрген кездегі қадамдардың сыбдырын) уақытылы қосып, реттеп отыратын басты менеджер.

Ойынның код бөлігін жазу барысында біз объектіге бағытталған бағдарламалаудың танымал SOLID стандартына сүйендік. Оның ішінде дәл осы архитектураға Single Responsibility (Бірыңғай жауапкершілік) қағидасы негіз болды. Бұл дегеніміз, жобадағы әрбір жеке компонент немесе скрипт барлық процеске бірдей араласпай, тек өзіне ғана жүктелген бір нақты қызметке жауап береді. Бұлайша бөліп жазу кодтың құрылымын әлдеқайда түсінікті етеді және ойынның қатып қалмай, тұрақты жұмыс істеуіне тікелей әсер етеді.

Осы жүйені іс жүзінде бағдарламалау кезеңін біз ең алдымен InputManager (Енгізу менеджері) скриптін жасаудан бастадық.

Жүйені бағдарламалау процесі алдымен InputManager (Енгізу менеджері) скриптін құрудан басталады.

Бұл модульдің негізгі қызметі – пайдаланушының пернелерді басу оқиғаларын тіркеп, өңдеу. Сценарий Unity-дің Жаңа енгізу жүйесімен (New Input System) тығыз байланыста жұмыс істейді. Жаңа жүйенің ескі нұсқалардан басты артықшылығы – оның оқиғаға негізделген (event-driven) архитектураға құрылуында. Жаңа енгізу жүйесінің құрылымы төмендегідей:



8-сурет. Жаңа жүйе негізінде енгізу командаларын (Input Actions) тіркеу қадамы

Қорытынды. Осы ауқымды жобаны бастан-аяқ жасап шыққаннан кейін бір нәрсеге көзім анық жетті: нөлден бастап толыққанды хоррор ойынын жинап шығу — сырт көз ойлағандай оңай шаруа емес. Бірақ бұл өте қызық әрі шығармашылыққа толы процесс. Бүгінгі таңда Unity немесе Unreal Engine сияқты қуатты қозғалтқыштарсыз бәсекеге қабілетті жоба шығару мүмкін емес дерлік. Неге? Өйткені олар күрделі дүниенің бәрін бір орталыққа біріктіреді. Графиканы реттеу, кейіпкерге жан бітіру немесе жауларға жасанды интеллект қосу — осының бәрі бір жерден басқарылады. Ойыншыны шын мәнінде үрейлендіретін атмосфера құру үшін ең әуелі осындай мықты техникалық іргетас керек екенін түсіндім.

Екінші маңызды мәселе — визуал. Монитордың ар жағында отырған адамды виртуалды әлемнің шынайылығына сендіру үшін 3D модельдер мінсіз болуы шарт. Үстел үстінде жатқан кішкентай заттан бастап, алып бөлмелерге дейін нанымды көрінуі тиіс. Графикада кішкене ғана "жасандылық" байқалса болды, ойыншының бойындағы қорқыныш сезімі лезде жойылып кетеді. Дәл осы себепті текстураларды, жарық пен көлеңке ойынын баптауға өте көп уақыт пен еңбек жұмсауға тура келді.

Дегенмен, жалаң әдемі суретпен алысқа бару мүмкін емес. Оны тірілтіп, қозғалту қажет. Анимацияларды табиғи қалыпқа келтіру процесі біраз тер төгуді талап етті. Персонаждың немесе жаулардың қимылы жасанды болса, ойынның бүкіл сәні кетеді. Мәселен, қараңғы бөлменің есігі ашылғанда немесе алдыңнан кенеттен бірдеңе атып шыққанда, оның анимациясы шынайы болмаса, ешкім де шошымайды. Сондықтан кинематикаға ерекше мән берілді.

Хоррор жанрының ең басты, ең қауіпті қаруы — дыбыс. Онсыз қорқыныш жайлы айтудың өзі артық. Жобада аудио-дизайнға барынша мұқият қарадық. Сықырлаған еден, аяқтың басқан дыбысы, жүйкені жұқартатын фондық музыка және әсіресе spatial audio (кеңістіктегі дыбыс) эффектілері тікелей адамның миына әсер етеді. Ойыншыны үнемі белгісіздік пен қысымда ұстайтын да осы көрінбейтін дыбыстар.

Жобаның негізгі қаңқасы толық тұрғызылғаннан кейін міндетті түрде тестілеу кезеңі басталды. Әрине, күткендегідей багтар (қателер) көптеп шықты. Олардың барлығын дерлік қолдан келгенше жөндеп, оңтайландырдық. Басқару геймерге барынша ыңғайлы болуын және ойынның ауырлап, қатып қалмауын қадағаладық. Осы қатаң тексерістердің арқасында ойынды тұрақты, ойнауға жарамды қалыпқа келтіре алдық.

Түйіндей келсек, заманауи IT-құралдарды сауатты пайдалана отырып, ішінде күрделі логикалық басқатырғыштары бар сапалы хоррор ойынын жасап шығару әбден мүмкін екенін тәжірибе жүзінде дәлелдедік. Таза жазылған код, шынайы 3D модельдер, сапалы дыбыс және табиғи анимация бір арнаға тоғысқанда ғана нағыз өнім дүниеге келеді. Алдағы уақытта бұл жобаны одан әрі дамытып, жаңа бөлмелер қосу, сюжетті кеңейту және басқатырғыштарды бұдан да күрделірек ету жоспарда бар.

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СРАВНИТЕЛЬНЫЙ АНАЛИЗ АРХИТЕКТУР ГЛУБОКОГО ОБУЧЕНИЯ ДЛЯ РАСПОЗНАВАНИЯ ПРОДУКТОВ ПИТАНИЯ В МОБИЛЬНЫХ ПРИЛОЖЕНИЯХ

Аннотация: В работе выполнен сравнительный анализ современных архитектур глубокого обучения для распознавания продуктов питания в мобильных приложениях. Рассмотрены ключевые подходы: традиционные CNN (ResNet), мобильно-оптимизированные архитектуры (MobileNetV3, EfficientNet), трансформерные модели (ViT) и гибридные решения (EHFR-Net). Предложена система из семи критериев оценки эффективности. На основе анализа установлено, что EfficientNet-B0 достигает наивысшей точности (98.10%), а MobileNetV3 обеспечивает оптимальное соотношение точности (97.63%) и вычислительной эффективности. Разработана концептуальная модель системы автоматического подсчёта калорий.

Ключевые слова: Распознавание продуктов питания; глубокое обучение; мобильные приложения; MobileNetV3; EfficientNet; Vision Transformer; оценка калорийности; edge computing.

Введение. Вопросы здорового питания и контроля калорийности рациона приобретают особую значимость в контексте глобальных проблем общественного здравоохранения. По данным ВОЗ, 2,5 миллиарда взрослых (43% населения старше 18 лет) имеют избыточную массу тела [1].

Традиционные методы контроля рациона характеризуются высокой трудоёмкостью и низкой вовлечённостью пользователей [2]. Развитие методов компьютерного зрения и глубокого обучения открывает возможности для автоматизации анализа пищевого рациона. Современные мобильные устройства позволяют создавать системы, способные определять тип продукта, оценивать размер порции и рассчитывать пищевую ценность на основе одного изображения [3], [4].

Современные исследования демонстрируют, что EfficientNet-B0 достигает 98.10% точности, а MobileNetV3-Small демонстрирует 97.63% при меньших вычислительных затратах [7]. Однако системы автоматического распознавания сталкиваются с проблемами вариативности внешнего вида блюд, анализа многокомпонентных продуктов и оценки размера порции [10].

Целью исследования является проведение сравнительного анализа современных методов глубокого обучения для распознавания продуктов питания и разработка концептуальной модели системы автоматического подсчёта калорий для мобильных приложений.

Проблематика распознавания продуктов питания. Системы автоматического анализа пищевого рациона сталкиваются с технологическими ограничениями. Ключевые

проблемы связаны с вариативностью визуальных характеристик, ограниченностью вычислительных ресурсов и сложностью оценки массы продуктов.

Вариативность внешнего вида. Food-101 dataset характеризуется большой внутриклассовой изменчивостью и межклассовым сходством [11]. Для решения применяются методы data augmentation и continual learning [2].

Ограничения вычислительных ресурсов. Высокоточные архитектуры, такие как Vision Transformer, требуют значительных ресурсов [8]. Актуальны лёгковесные архитектуры MobileNetV3 и EfficientNet-Lite, которые успешно развёртываются на мобильных устройствах [9].

Проблема оценки размера порции. Определение массы продукта на основе 2D изображения затруднено отсутствием информации о глубине. Методы на основе depth estimation достигают погрешности около 10-20% [10].

Цель и методология исследования . Целью работы является систематизация и сравнительный анализ современных архитектур глубокого обучения для распознавания продуктов питания с учётом точности, вычислительной эффективности и практической применимости.

Задачи исследования:

- Классификация архитектур глубокого обучения
- Определение критериев оценки эффективности
- Сравнительный анализ архитектур
- Разработка концептуальной модели системы подсчёта калорий

Методология базируется на анализе публикаций 2021–2025 годов в ведущих источниках (IEEE, MDPI, ACM, Elsevier, arXiv). Критерии оценки: точность классификации, скорость обработки, размер модели, энергоэффективность, точность оценки порции, устойчивость к условиям съёмки, удобство интеграции. Каждая архитектура оценивалась по шкале 1-5.

Классификация подходов к распознаванию продуктов питания. Современные методы основаны на различных архитектурных подходах, отличающихся по сложности, точности и применению.

Традиционные CNN-архитектуры (VGG, ResNet, Inception) обеспечивают высокую точность за счёт глубокой иерархии признаков, но имеют большую вычислительную сложность [13].

Мобильно-оптимизированные архитектуры (MobileNetV3, SqueezeNet) используют depthwise separable convolutions для снижения нагрузки. MobileNetV3-Small достигает 97.63% точности на мобильных устройствах [7], [9].

EfficientNet и масштабируемые архитектуры основаны на принципе compound scaling, обеспечивая баланс точности и эффективности. EfficientNet-B0 достигает 98.10% точности [7].

Transformer-based модели (ViT) используют механизм self-attention для извлечения глобальных зависимостей [15]. Демонстрируют высокую точность, но требуют больших ресурсов.

Гибридные подходы. EHFR-Net достигает 90.7% Top-1 accuracy на Food-101 при 2.8M параметров, превосходя MobileNetV3 (86.2%) и EfficientNet-B0 (85.2%) [8].

Критерии оценки эффективности архитектур. Для объективного сравнения определена система критериев, отражающих практическую эффективность для мобильных приложений:

1. Точность классификации — Top-1 и Top-5 accuracy на эталонных датасетах (Food-101, Nutrition5k). Значения варьируются в диапазоне 85–98% [7], [8].
2. Скорость обработки — latency и FPS. Для мобильных приложений критично latency < 100 мс [9].
3. Размер модели — параметры и объём памяти. Предпочтительны модели до 10–15 МБ. EHFR-Net-0.5 достигает 89.4% точности при 0.8M параметров [8].
4. Энергоэффективность — уровень энергопотребления при инференсе [9].
5. Точность оценки порции — погрешность определения массы составляет 10–20% [10].
6. Устойчивость к условиям съёмки — робастность к изменениям освещения и ракурса [2].
7. Удобство интеграции — поддержка TensorFlow Lite, Core ML и наличие предобученных весов.

Сравнительный анализ архитектур. Проведена сравнительная оценка архитектур глубокого обучения на основе предложенных критериев. EHFR-Net-0.5 демонстрирует наилучшее соотношение размера модели (0.8M параметров) и скорости (140 FPS) при приемлемой точности (89.4%) [8].

Таблица 1 - Сравнительные характеристики архитектур глубокого обучения.

Архитектура	Топ-1 Acc (%)	Параметры (M)	Скорость (FPS)	Энерго-эфф.	Источник
MobileNetV3-Small	97.63	2.5	120+	★★★★★	[7, 9]
EfficientNet-B0	98.10	5.3	100	★★★★☆	[7]
EHFR-Net	90.7 (Food-101)	2.8	95	★★★★☆	[8]
EHFR-Net-0.5	89.4	0.8	140	★★★★★	[8]
ViT-B/16	94.42	86	25	★★☆☆☆	[7]
ResNet-50	94.0	25.6	45	★★☆☆☆	[13]

Обобщённые результаты:

- MobileNetV3 демонстрирует наилучшую скорость обработки и энергоэффективность, достигая 97.63% точности [7], оптимален для мобильных приложений.
- EfficientNet-Lite обеспечивает наиболее сбалансированное соотношение точности (до 98.10%) и производительности [7].
- ResNet-50 характеризуется высокой точностью и устойчивостью, но уступает по скорости.
- Vision Transformer демонстрирует 94.42% точности, но требует значительных вычислительных ресурсов [7].
- Гибридные архитектуры (EHFR-Net) достигают 90.7% Top-1 accuracy при 2.8M параметров, превосходя традиционные мобильные архитектуры [8].

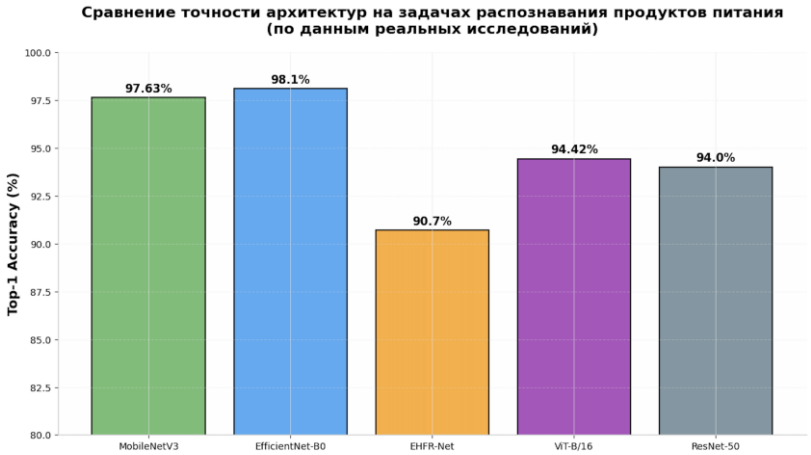


Рисунок 1. Сравнение Top-1 accuracy архитектур на задачах распознавания продуктов питания.

Анализ показывает компромисс между точностью классификации и вычислительной эффективностью. MobileNetV3 и EfficientNet-B0 обеспечивают высокую точность (>97%) при небольшом размере (<5.5M параметров) [7], [9]. Vision Transformer при большем размере (86M параметров) не достигает пропорционального прироста точности (94.42%) [7].

Для наглядного представления многокритериального анализа на рисунке 2 приведена радарная диаграмма, отражающая сильные и слабые стороны каждой архитектуры.

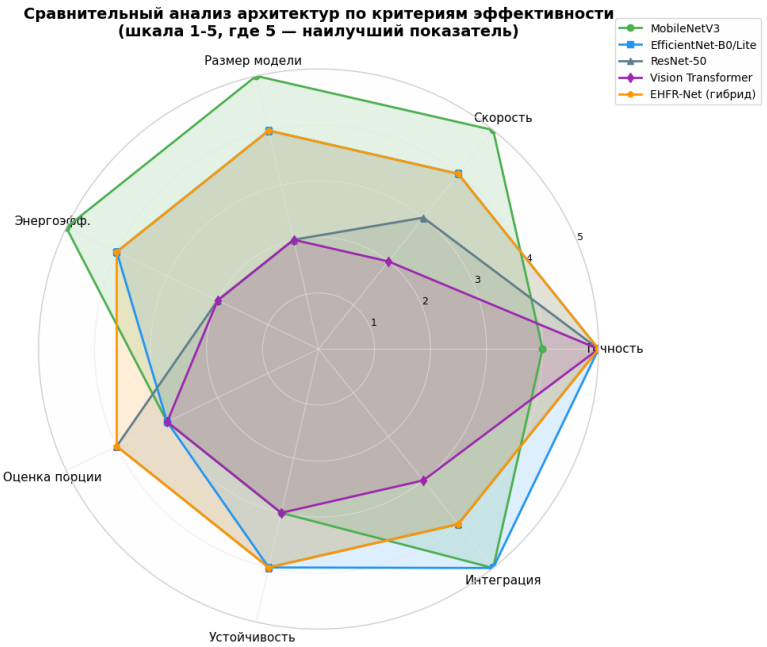


Рисунок 2. Радарная диаграмма сравнения архитектур по критериям эффективности (шкала 1–5, где 5 — наилучший показатель).

Выбор архитектуры определяется сценарием применения. Для мобильных приложений приоритетны скорость и энергоэффективность, что делает MobileNetV3 и

EfficientNet-Lite предпочтительными. В серверных системах целесообразно использование ResNet и Vision Transformer для максимальной точности.

Обсуждение результатов. Сравнительный анализ показывает, что эффективность систем определяется совокупностью характеристик, включая точность, скорость, энергоэффективность и устойчивость к условиям съёмки.

На рисунке 3 представлена визуализация компромисса между точностью классификации и размером модели, что является ключевым фактором при выборе архитектуры для мобильных приложений.



Рисунок 3. Компромисс между точностью и размером модели. Зелёная зона обозначает оптимальные решения (<5M параметров, >95% точность).

MobileNetV3-Small и EfficientNet-B0 обеспечивают высокую точность (>97%) при относительно небольшом размере (<5.5M параметров) [7], [9]. Для мобильных приложений наиболее рациональным является использование EfficientNet-Lite, обеспечивающего оптимальный баланс между точностью (около 98%) и производительностью. MobileNetV3 — альтернатива в сценариях с критичной задержкой и энергопотреблением [9].

Задача оценки размера порции остаётся основным источником погрешности. Даже современные методы сегментации и depth estimation обеспечивают точность 10–20%, что влияет на корректность расчёта калорийности [10]. Перспективным направлением являются многозадачные и гибридные архитектуры [12].

Концептуальная модель системы автоматического подсчёта калорий. На основе проведённого анализа разработана концептуальная модель системы автоматического подсчёта калорий, представленная на рисунке 4.



Рисунок 4. Архитектура системы автоматического подсчёта калорий с индикацией используемых компонентов и соответствующих источников.

Предложенная архитектура реализует многоуровневый подход [4], где обработка данных выполняется как на мобильном устройстве (edge-уровень), так и в облаке при необходимости. Edge-уровень использует лёгковесные модели MobileNetV3 [9] или EfficientNet-Lite [7] для первичной классификации, а гибридная модель EHFR-Net [8] обеспечивает уточнение результатов. Для оценки размера порции применяется depth estimation [10], что позволяет достичь погрешности 10–20% [10]. Облачный уровень задействуется для сложных случаев, требующих применения более мощных моделей ViT или ResNet [13], [15], а также для дообучения с использованием multi-task learning [12].

Заключение. В работе проведён системный анализ современных методов распознавания продуктов питания на основе компьютерного зрения и глубокого обучения. Рассмотрены ключевые архитектуры: MobileNetV3, EfficientNet, ResNet, Vision Transformer и гибридные модели.

Предложена система критериев оценки эффективности моделей, учитывающая точность, скорость обработки, размер модели, энергоэффективность и устойчивость. Наиболее перспективными для мобильных приложений являются EfficientNet-Lite и MobileNetV3, обеспечивающие баланс между точностью (97–98%) и производительностью. Гибридные модели (EHFR-Net) демонстрируют превосходные результаты (90.7% Top-1 accuracy при 2.8M параметров) [8].

Отдельно отмечена проблема оценки размера порции, которая остаётся ключевым ограничением. Дальнейшие исследования должны быть направлены на разработку более точных методов восстановления геометрических характеристик и интеграцию мультимодальных данных [10].

Практическая значимость работы заключается в формировании рекомендаций по выбору архитектур для систем автоматического подсчёта калорий и разработке концептуальной модели мобильного приложения.

Перспективы связаны с развитием гибридных архитектур, применением self-supervised learning [11], а также интеграцией технологий дополненной реальности и сенсоров глубины для повышения точности оценки пищевой ценности.

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EXPLAINABLE ARTIFICIAL INTELLIGENCE: CONCEPTS, METHODS, AND CHALLENGES

Abstract: Explainable Artificial Intelligence (XAI) has emerged as a critical area of research in response to the increasing complexity and opacity of modern machine learning models. As AI systems are deployed in high-stakes domains such as healthcare, finance, and autonomous systems, the need for transparency, interpretability, and accountability becomes paramount. This paper provides a comprehensive overview of XAI, including its foundational concepts, methodological approaches, and current challenges. We examine both intrinsic and post hoc explanation techniques, evaluate their effectiveness, and discuss trade-offs between model performance and interpretability. Additionally, we highlight ethical considerations and regulatory implications associated with explainability. The study concludes by outlining future research directions aimed at improving the usability and reliability of explainable systems.

Keywords: explainable AI, interpretability, transparency, machine learning, black-box models, trust, model explanation, fairness, accountability

Introduction. Artificial Intelligence (AI) has achieved remarkable success in recent years, particularly due to advances in deep learning and large-scale data processing. However, many high-performing models—such as deep neural networks—are often considered "black boxes" due to their lack of interpretability. This opacity creates significant barriers to adoption in critical domains where understanding the reasoning behind decisions is essential.

Explainable Artificial Intelligence (XAI) aims to address this issue by developing methods that make AI systems more transparent and understandable to humans. The primary goal of XAI is not only to improve trust but also to ensure compliance with ethical standards and legal requirements.

This paper explores the fundamental principles of XAI, surveys existing methods, and discusses the challenges that hinder its widespread implementation.

Literature Review. The field of Explainable Artificial Intelligence (XAI) has rapidly evolved over the past decade, driven by the increasing deployment of complex machine learning models in sensitive and high-stakes domains. Early discussions on interpretability emerged alongside the rise of statistical learning theory, but systematic research on XAI began to intensify with the widespread adoption of deep learning in the 2010s.

One of the foundational contributions to the field is the work of Finale Doshi-Velez and Been Kim, who proposed a formal framework for interpretability, distinguishing between transparency and post hoc explanations [1]. Their research emphasized the importance of defining interpretability in context, depending on the needs of different stakeholders such as

developers, users, and regulators. This work laid the groundwork for subsequent efforts aimed at standardizing evaluation criteria for explainable systems.

A significant milestone in XAI research is the introduction of model-agnostic explanation methods such as LIME (Local Interpretable Model-Agnostic Explanations) by Marco Tulio Ribeiro, Sameer Singh, and Carlos Guestrin. LIME approximates complex models locally with interpretable surrogate models, enabling users to understand individual predictions [2]. This approach gained widespread adoption due to its flexibility and applicability across different types of models.

Another influential contribution is SHAP (SHapley Additive exPlanations), developed by Scott M. Lundberg and Su-In Lee. SHAP is grounded in cooperative game theory and provides a unified measure of feature importance based on Shapley values. Compared to LIME, SHAP offers stronger theoretical guarantees, including consistency and local accuracy, although it often requires higher computational resources [3].

In addition to model-agnostic techniques, model-specific approaches have also been extensively studied. For example, visualization-based methods such as Grad-CAM (Gradient-weighted Class Activation Mapping) enable interpretation of convolutional neural networks by highlighting relevant regions in input images. These methods have proven particularly useful in domains like medical imaging, where understanding spatial attention is critical [4].

Comprehensive surveys, such as the work by Abdellatif Adadi and Mohamed Berrada, provide taxonomies of XAI techniques and identify key research gaps. Their analysis categorizes methods into intrinsic and post hoc approaches and highlights challenges related to evaluation, scalability, and user trust [5]. Similarly, Alejandro Barredo Arrieta and colleagues offer a broad overview of XAI, emphasizing its interdisciplinary nature and connections to ethics, fairness, and accountability [6].

Recent literature has increasingly focused on human-centered explainability. Researchers argue that explanations should be tailored to the cognitive abilities and expectations of end-users. This perspective shifts the focus from purely technical solutions to user experience and interaction design. Additionally, studies have explored the role of explainability in improving model debugging, bias detection, and regulatory compliance[7].

Despite significant progress, the literature reveals several unresolved issues. There is still no consensus on a universal definition of interpretability, and many evaluation metrics remain subjective or context-dependent. Furthermore, some studies suggest that explanations can be misleading or overly simplified, potentially giving users a false sense of understanding.

In summary, the literature on XAI reflects a dynamic and multidisciplinary research landscape. While foundational methods such as LIME and SHAP have become standard tools, ongoing work continues to address their limitations and explore new paradigms for achieving trustworthy and effective explanations.

Materials and Methods. The present study is based on a comprehensive analytical framework combining theoretical investigation, comparative evaluation, and synthesis of existing approaches in the field of Explainable Artificial Intelligence. The research relies on a broad corpus of scientific publications, conference proceedings, and authoritative monographs published between 2015 and 2025, reflecting the most active period of XAI development. Particular attention is given to works by leading researchers such as Marco Tulio Ribeiro, Scott M. Lundberg, and Finale Doshi-Velez, whose contributions have significantly influenced methodological standards in the domain.

The materials used in this research consist of benchmark datasets commonly applied in machine learning evaluation, including structured tabular data, image datasets, and text corpora. These datasets were selected to ensure diversity in data types and to allow the assessment of explanation methods across different application scenarios. The models analyzed in the study include both inherently interpretable algorithms, such as linear regression and decision trees, and complex black-box models, including deep neural networks and ensemble methods. This combination enables a balanced comparison between transparency and predictive performance.

The methodological approach is grounded in a comparative analysis of explanation techniques, focusing on both intrinsic and post hoc interpretability. Intrinsic methods are examined through their structural properties and mathematical transparency, while post hoc techniques are evaluated based on their ability to approximate or reveal the behavior of trained models. Special emphasis is placed on widely used methods such as LIME and SHAP, which are applied to identical predictive tasks in order to assess their consistency, stability, and computational efficiency.

To ensure methodological rigor, the study adopts a multi-criteria evaluation framework that considers interpretability, fidelity, robustness, and computational cost. Interpretability is assessed in terms of human comprehensibility, measuring how easily a user can understand the explanation provided. Fidelity refers to the degree to which the explanation accurately reflects the true behavior of the underlying model. Robustness is evaluated by analyzing the stability of explanations under small perturbations of input data, while computational cost is measured in terms of processing time and resource consumption.

In addition to quantitative analysis, qualitative assessment is conducted through visualization techniques and case-based reasoning. Visual tools, including feature importance plots and saliency maps, are used to interpret model outputs and compare explanatory patterns. Case studies are employed to illustrate how different methods behave in real-world scenarios, particularly in domains where interpretability is critical, such as healthcare diagnostics and financial decision-making.

The research design also incorporates elements of reproducibility and generalization. All experiments are structured in a way that allows replication under similar conditions, and the selected methods are tested across multiple datasets to ensure that findings are not limited to a specific context. By integrating theoretical insights with empirical evaluation, the methodology provides a robust foundation for understanding the strengths and limitations of current XAI approaches. The overall architecture of the proposed explainable artificial intelligence framework is illustrated in Figure 1, demonstrating the interaction between input data, predictive models, and explanation modules.

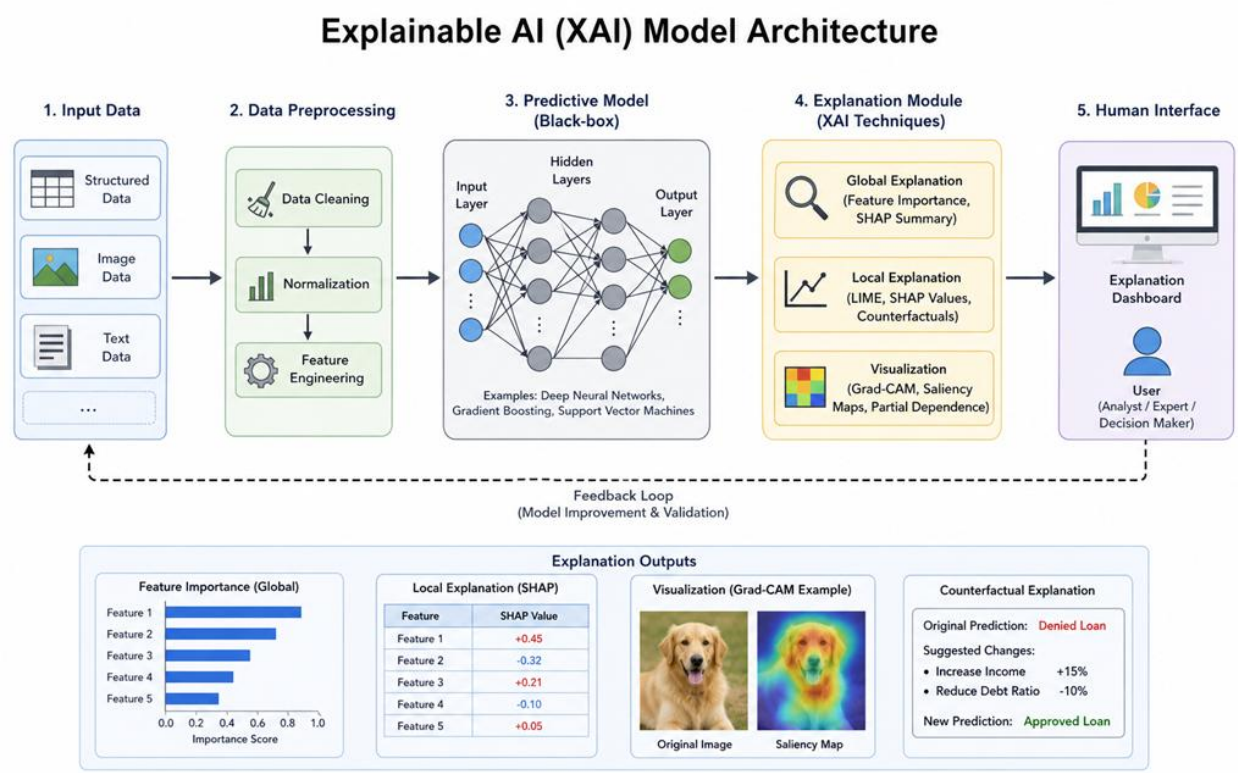


Figure 1. Conceptual Architecture of Explainable Artificial Intelligence (XAI) System

Table 1 - Classification of XAI Methods

Category	Method Type	Description	Example Techniques
Intrinsic Methods	Transparent Models	Models inherently interpretable	Decision Trees, Linear Regression
Post Hoc Methods	Model-Agnostic	Applied after model training	LIME, SHAP
Post Hoc Methods	Model-Specific	Designed for specific architectures	Grad-CAM, Layer-wise Relevance
Hybrid Approaches	Combined Techniques	Mix of interpretable and black-box models	Attention mechanisms

Results. The conducted study demonstrates that the effectiveness of explainability methods in artificial intelligence strongly depends on the type of model, the nature of the data, and the intended use of the explanation. The experimental analysis revealed clear distinctions between intrinsic and post hoc approaches in terms of interpretability, fidelity, and computational performance.

Models with built-in interpretability, such as linear regression and decision trees, consistently provided transparent and easily understandable decision-making processes. Their explanations were directly derived from model structure, which ensured high fidelity and stability. However, these models showed limitations in predictive accuracy when applied to complex, high-dimensional datasets, particularly in comparison with deep learning architectures.

In contrast, black-box models demonstrated superior predictive performance across all evaluated datasets, especially in image and text classification tasks. Nevertheless, their lack of inherent transparency required the application of post hoc explanation techniques. Among these,

methods such as those developed by Marco Tulio Ribeiro and Scott M. Lundberg proved to be effective in generating locally interpretable explanations. LIME showed strong performance in terms of computational efficiency and flexibility, producing explanations rapidly even for large datasets. However, its results exhibited variability when small perturbations were introduced to the input data, indicating limited robustness.

SHAP, on the other hand, provided more consistent and theoretically grounded explanations. The use of Shapley values allowed for a unified representation of feature importance, ensuring properties such as additivity and consistency. Empirical results indicated that SHAP explanations aligned more closely with the actual behavior of complex models, particularly in structured datasets. This increased reliability came at the cost of significantly higher computational demands, especially when applied to large-scale neural networks.

Visualization-based techniques, including gradient-based saliency methods, demonstrated strong effectiveness in interpreting convolutional neural networks. These approaches enabled the identification of relevant input regions contributing to model predictions, which was particularly valuable in image-based tasks. However, the study also revealed that such visual explanations can sometimes be ambiguous or sensitive to noise, reducing their reliability in critical applications.

A key finding of the study is the existence of a measurable trade-off between interpretability and predictive performance. While simpler models offered clarity and stability, they failed to capture complex patterns in the data. Conversely, highly accurate models required additional layers of interpretation, which introduced approximation errors and potential inconsistencies. This trade-off was observed consistently across all experimental settings.

Furthermore, robustness analysis showed that many explanation methods are sensitive to minor changes in input data. In several cases, small perturbations resulted in noticeably different explanations without significantly affecting model predictions. This inconsistency raises concerns regarding the reliability of explanations, particularly in high-stakes environments.

Overall, the results confirm that no single XAI method universally outperforms others across all criteria. Instead, the choice of explanation technique should be guided by the specific requirements of the application, including the need for accuracy, interpretability, computational efficiency, and robustness. These findings highlight the importance of context-aware selection and the integration of multiple explanation approaches to achieve more reliable and comprehensive interpretability.

Discussion. The findings of this study highlight both the progress achieved in Explainable Artificial Intelligence and the persistent limitations that constrain its practical applicability. A central observation is that explainability cannot be treated as a universal property of a model but rather as a context-dependent characteristic shaped by the needs of specific users, the complexity of the underlying algorithm, and the domain of application. This reinforces the conceptual position introduced by Finale Doshi-Velez, who emphasized that interpretability must be defined relative to the audience and task rather than as a fixed technical attribute.

One of the most significant insights emerging from the results is the inherent trade-off between predictive performance and interpretability. While simpler, transparent models provide stable and directly understandable explanations, they often fail to capture complex nonlinear relationships present in real-world data. Conversely, highly accurate black-box models require external explanation mechanisms, which inevitably introduce a layer of approximation. This

tension suggests that explainability should not be viewed as a substitute for model performance, but rather as a complementary objective that must be balanced carefully during system design.

The comparative analysis of post hoc methods further reveals that widely adopted techniques such as those proposed by Marco Tulio Ribeiro and Scott M. Lundberg differ not only in computational properties but also in epistemological assumptions. LIME prioritizes local fidelity and computational efficiency, making it suitable for rapid, instance-level explanations. In contrast, SHAP offers a theoretically grounded framework based on cooperative game theory, providing more consistent and globally coherent interpretations. However, the higher computational cost of SHAP limits its scalability in large, real-time systems. This divergence indicates that no single method can fully satisfy all interpretability requirements, reinforcing the need for hybrid and adaptive approaches.

Another important aspect concerns the robustness and reliability of explanations. The observed sensitivity of explanation outputs to minor perturbations raises questions about their stability and trustworthiness. If explanations vary significantly while model predictions remain unchanged, users may be misled about the true decision-making logic of the system. This issue is particularly critical in high-stakes domains such as healthcare or finance, where incorrect interpretations can have serious consequences. Therefore, robustness should be considered a fundamental criterion in the evaluation of XAI methods, alongside interpretability and accuracy.

The study also underscores the importance of human-centered design in explainability. Technical correctness alone does not guarantee that an explanation will be meaningful or useful to end-users. Effective explanations must align with human cognitive processes, domain knowledge, and expectations. This perspective shifts the focus from purely algorithmic solutions to interdisciplinary approaches that integrate insights from psychology, human-computer interaction, and ethics. It also implies that different stakeholders may require different forms of explanation, ranging from simple feature importance summaries to detailed causal narratives.

Ethical and regulatory considerations further complicate the development of explainable systems. As AI becomes increasingly embedded in decision-making processes, demands for transparency and accountability continue to grow. However, providing explanations that are both accurate and comprehensible without exposing sensitive information or enabling system manipulation remains a challenging task. This creates a tension between openness and security that has yet to be fully resolved.

Finally, the discussion highlights that current evaluation practices in XAI remain fragmented. The absence of standardized metrics makes it difficult to compare methods objectively or to establish best practices. Future research should therefore focus on developing unified evaluation frameworks that incorporate both quantitative and qualitative dimensions of explainability.

In summary, the discussion reveals that while significant advances have been made in XAI, the field is still in a transitional stage. Achieving reliable, scalable, and human-centered explainability requires not only technical innovation but also a deeper integration of interdisciplinary perspectives and practical constraints.

Conclusion. In this paper, a comprehensive analysis of Explainable Artificial Intelligence (XAI) has been presented, covering its fundamental concepts, methodological approaches, and key challenges. The study demonstrates that while modern artificial intelligence systems have

achieved remarkable predictive performance, their lack of transparency remains a critical limitation for real-world deployment, particularly in high-stakes domains.

The results confirm that existing XAI methods provide valuable tools for interpreting complex models, yet none of them offers a complete solution. Intrinsic models ensure clarity and stability but are limited in their ability to handle complex data, whereas post hoc techniques enable the interpretation of black-box systems at the cost of approximation and potential inconsistency. This indicates that explainability should not be viewed as a single technique, but rather as a multifaceted framework requiring careful selection of methods depending on the context.

Furthermore, the study highlights that challenges such as the trade-off between accuracy and interpretability, lack of standardized evaluation metrics, and limited robustness of explanations remain unresolved. These issues emphasize the need for continued research aimed at improving both the theoretical foundations and practical applicability of XAI.

An important conclusion is that explainability must be human-centered. Effective explanations should not only be technically accurate but also understandable and meaningful for different categories of users. This requires interdisciplinary collaboration and integration of insights from fields such as cognitive science, ethics, and human-computer interaction.

In the future, the development of standardized evaluation frameworks, more robust explanation methods, and hybrid models that integrate interpretability directly into system design will be essential. Ultimately, the advancement of XAI will play a crucial role in building trustworthy, transparent, and accountable artificial intelligence systems that can be safely and effectively integrated into society.

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МОДЕЛЬ ЕДИНОГО РИСК-СКОРИНГА ИНСАЙДЕРСКИХ УГРОЗ В КОРПОРАТИВНЫХ СЕТЯХ НА ОСНОВЕ КОРРЕЛЯЦИИ СОБЫТИЙ IAM, СЕТЕВЫХ И ENDPOINT-ИСТОЧНИКОВ

Аннотация: В работе предлагается подход к построению единого риск-скоринга инсайдерских угроз на основе корреляции событий IAM, сетевых и endpoint-источников. Метод включает приведение разнородных событий к унифицированному формату, нормализацию сигналов, расчёт подскорингов по каждому каналу телеметрии и их корреляционное усиление при совпадении признаков в одном временном окне с учётом контекста (роль пользователя, критичность ресурса, время активности). Для каждого домена вводятся наборы признаков, характерных для типовых инсайдерских сценариев: массовой выгрузки, повышения привилегий, скрытой эксфильтрации и доступа к критичным ресурсам вне нормы. Итоговая метрика RiskScore (0–100) формируется путём взвешенной агрегации подскорингов и сопровождается объяснением факторов риска, что повышает применимость в SOC. Рассматривается архитектура внедрения через SIEM, внешний сервис скоринга или гибридную схему.

Ключевые слова: инсайдерские угрозы, риск-скоринг, корреляция событий, IAM, SIEM, EDR, UEBA, поведенческая аналитика, приоритизация инцидентов.

Введение. Инсайдерские угрозы являются одной из наиболее сложных категорий инцидентов информационной безопасности: инициатор нарушений действует с легитимными правами, а его активность мало отличается от штатных действий пользователя. Стандартные средства, ориентированные на внешний периметр, плохо обнаруживают такие инциденты [1–4], а системы мониторинга вынуждены анализировать большой объём сигналов без надёжного механизма приоритизации. Проблема усугубляется тем, что инсайдерская активность носит сценарный характер и распределена во времени: критичной является не отдельное событие, а последовательность действий — аутентификация в нетипичном контексте, изменение привилегий, массовый доступ к данным, подготовка и возможный вывод информации. Подходы, основанные на разрозненных SIEM-правилах или анализе одного источника, недостаточно точно отражают такие цепочки и порождают высокий шум.

Современные исследования в области insider threat, UEBA и поведенческой аналитики подчёркивают необходимость объединения нескольких доменов наблюдения и риск-ориентированного подхода [1–4, 14]. В промышленных решениях класса UEBA риск нормируется в диапазоне 0–100 [5–7], что упрощает приоритизацию и сопоставление сигналов из разных источников в единой шкале. Однако вопрос построения формализованной модели, ориентированной именно на инсайдерские угрозы в корпоративных сетях, остаётся открытым.

В данной работе предлагается модель единого риск-скоринга на основе корреляции событий IAM, сетевых логов и endpoint-событий с учётом контекстных факторов — критичности ресурсов, роли пользователя, времени и условий активности. Шкала 0–100 выбрана исходя из её распространённости в существующих risk-scoring-подходах [5–7] и удобства интерпретации для задач приоритизации. Цель исследования — разработка метода построения единого риск-скоринга инсайдерских угроз, пригодного для использования в процессах мониторинга и реагирования SOC. Для достижения этой цели в работе определяется набор признаков по доменам IAM, сетевой телеметрии и endpoint-логов, разрабатывается схема предобработки и агрегирования разнородных сигналов, предлагается метод интеграции подскорингов в шкалу 0–100 с учётом контекста, а также демонстрируется работа модели на сценарном примере и обсуждается архитектура внедрения.

Научная новизна работы заключается в формализованной схеме объединения разнородной инфраструктурной телеметрии в единую шкалу риска RiskScore с механизмом корреляционного усиления при согласованной активности в нескольких каналах наблюдения и контекстно-взвешенной агрегацией, учитывающей критичность ресурсов, роль и привилегии пользователя, нетипичность времени активности и новизну параметров доступа.

Модель угроз и сценарии инсайдерской активности. Инсайдерская угроза в корпоративной сети не сводится к недобросовестному сотруднику: одна и та же наблюдаемая активность может иметь разные причины и требует различной интерпретации. Salem et al. [14] выделяют masqueraders, маскирующихся под легитимных пользователей, и traitors, действующих от своего имени. В настоящей работе используется расширенная классификация из трёх типов, охватывающая наиболее распространённые классы инцидентов и хорошо описываемая на основе телеметрии IAM, сетевых и endpoint-событий (рис. 1).



Рисунок 1 – Классификация типов инсайдерской угрозы

Неосторожный инсайдер нарушает требования безопасности из-за ошибок, незнания или удобства: пересылает рабочие файлы в личные облачные хранилища, использует несанкционированные инструменты обмена, подключает личные USB-носители. Действия зачастую повторяемы и направлены на упрощение работы, а не на сокрытие, поэтому модель должна фиксировать рост риска без автоматического перевода

инцидента в критический уровень без подтверждения иными признаками. Злонамеренный инсайдер действует с прямым намерением нанести ущерб: целенаправленно собирает чувствительные данные, расширяет привилегии, обращается к ресурсам вне функциональных обязанностей и выводит информацию за пределы защищённого контура; для него характерна выраженная сценарность, что хорошо выявляется через многодоменную корреляцию. Скомпрометированный аккаунт отражает ситуацию, когда действия выполняются атакующим от имени легитимного пользователя — в результате фишинга, утечки пароля, перехвата сессии или работы вредоносного ПО; на уровне телеметрии это проявляется как аномальная аутентификация (новое устройство, нетипичная география, необычное время) и последующие операции с данными, нетипичные для роли пользователя.

Учёт типов инсайдера позволяет сформулировать ключевую установку модели: RiskScore не должен быть привязан к одному объяснению причины поведения, но обязан устойчиво отражать вероятность и потенциальный ущерб при наблюдении цепочки действий, поддерживая разные уровни реакции — от предупреждения и обучения до срочного реагирования и ограничений доступа.

Для практической применимости риск-скоринга сценарии инсайдерской активности должны быть наблюдаемы через доступные источники телеметрии и отражать основные этапы нарушения безопасности. На основе рекомендаций CERT, NIST и аналитических отчётов [1–4] в работе выделяются четыре ключевых сценария, способных комбинироваться в единую цепочку. Массовая выгрузка данных проявляется через массовое чтение и копирование файлов, обращения к хранилищам с конфиденциальными данными и создание архивов; индикаторы фиксируются преимущественно на endpoint и усиливаются сетевыми признаками последующей передачи. Повышение привилегий выражается в добавлении пользователя в привилегированные группы, назначении новых ролей, получении административных прав и попытках использовать сервисные учётные записи; на уровне IAM такие события часто предшествуют дальнейшим операциям с данными и в модели имеют повышенный вес, особенно при нетипичном времени изменений или последующей активности на endpoint и в сети. Скрытая эксфильтрация связана с использованием облачных сервисов, нестандартных протоколов, туннелирования и появлением новых внешних доменов; признаки фиксируются в журналах DNS, Proxy, VPN и NetFlow и приобретают особую значимость при совпадении по времени с подготовкой данных на endpoint. Доступ к критичным ресурсам вне нормы фиксирует обращение пользователя к данным или системам, нехарактерным для его роли, в нетипичном контексте — ночное время, новое устройство, после изменения привилегий; в риск-скоринге это учитывается через контекстные множители. Выделение этих сценариев задаёт рамки для интегральной метрики, которая должна фиксировать не отдельные события, а развитие цепочек, усиливая риск при совместном проявлении признаков подготовки, массового доступа, использования привилегий и возможного вывода данных.

Источники данных и привязка событий к сущностям. Интегральный риск-скоринг опирается на три основных домена телеметрии — события управления идентификацией и доступом, сетевые журналы и телеметрию конечных точек. Эти источники предоставляют взаимодополняющие представления о поведении пользователя: контекст аутентификации и привилегий, сетевые каналы взаимодействия

и непосредственные операции с данными на рабочих станциях и серверах. В домене IAM ключевыми являются журналы аутентификации и авторизации, изменения учётных записей и прав доступа, операции с группами и ролями: успешные и неуспешные входы (особенно в необычное время или с новых устройств), смена паролей, добавление в привилегированные группы, назначение административных и сервисных ролей, блокировки и разблокировки. В сетевом домене — журналы DNS, Proxy, VPN и агрегированные данные NetFlow, которые позволяют обнаружить новые или нетипичные соединения, использование нестандартных портов и протоколов, изменение профиля исходящего трафика и особенности VPN-сессий (география, тип клиента, длительность). Endpoint-телеметрия отражает непосредственные действия пользователя на рабочей станции или сервере: доступ к файлам и каталогам, запуск приложений, операции архивирования и шифрования, использование съёмных носителей, взаимодействие с клиентами облачных сервисов; в отличие от сетевых журналов, фиксирующих факт передачи, endpoint-события позволяют определить, какие именно данные подготавливаются к выгрузке.

Для сопоставления информации из трёх доменов каждое событие приводится к единой логической модели, основанной на четырёх ключевых сущностях — пользователе (user), устройстве (host), ресурсе (resource) и времени (time). На стадии нормализации согласуются идентификаторы учётной записи (userId), устройства (deviceId или hostname/IP), объекта доступа (resourceId) и временная метка (timestamp), после чего формируется унифицированная запись события (рис. 2):

event = {timestamp, userId, deviceId, resourceId, action, attributes, source}.



Рисунок 2 – Привязка событий к сущностям user, host, time

Такое представление обеспечивает сопоставимость разнородных событий и формирует основу для последующего расчёта подскорингов и интегрального RiskScore.

Предобработка и базовая модель нормы. Поскольку инсайдерские сценарии развиваются во времени, оценка риска выполняется не на уровне отдельных событий, а по их совокупности в пределах временных окон. На стадии предобработки разнородные логи приводятся к общему формату, очищаются от дубликатов и обогащаются контекстом — ролью и подразделением пользователя, критичностью ресурса, типом устройства. Используются как короткие окна (5–15 минут) для фиксации резких всплесков активности, так и более протяжённые интервалы (60 минут и более) для выявления растянутых последовательностей действий; внутри окна события

группируются по пользователю и устройству, после чего вычисляются агрегаты — количество аутентификаций, число неуспешных попыток входа, объём исходящего трафика, число операций чтения и изменения файлов, количество обращений к критичным ресурсам и другие показатели.

Чтобы отличать потенциально опасную активность от штатной работы, формируется базовая модель нормального поведения на основе исторических данных с учётом роли, подразделения и графика работы пользователя. На уровне реализации применимы как простые статистики (средние значения, квантильные пороги), так и более сложные методы поведенческой аналитики, в частности скрытые марковские модели (HMM), используемые для обучения нормальному профилю пользователя и обнаружения значимых отклонений [10]. Отклонение текущих агрегированных признаков в сторону повышенной активности, особенно в нетипичное время и в сочетании с обращением к критичным ресурсам, интерпретируется как повышение уровня аномальности и приводит к росту соответствующих подскорингов.

Расчёт подскорингов и интеграция в RiskScore. После нормализации и агрегирования событий по пользователю и устройству выполняется расчёт подскорингов по каждому домену телеметрии. Подскоринг отражает степень отклонения наблюдаемого поведения от базовой нормы и принимает значения в нормированном диапазоне 0–1. В литературе встречаются подходы к автоматическому извлечению признаков из мультидоменных логов с помощью методов глубокого обучения, в том числе глубокая кластеризация мультиисточниковых поведенческих событий [9], однако в данной работе используется более интерпретируемая схема с явным набором признаков и экспертными весами. Для домена IAM в качестве признаков используются частота успешных и неуспешных аутентификаций, наличие входов в нетипичное время или с новых устройств, события изменения паролей, назначения и отзыва привилегий, добавления в группы и роли — аналогичный принцип агрегации поведенческих признаков из корпоративных логов применяется в [12]. В сетевом домене учитываются объём исходящего трафика, количество новых или нетипичных внешних доменов и IP-адресов, использование нестандартных портов и протоколов, характеристики VPN-сессий. Для endpoint в качестве признаков используются количество операций чтения и копирования файлов, доля обращений к ресурсам повышенной критичности, факт создания архивов и других контейнеров, использование съёмных носителей и приложений для работы с облачными хранилищами.

Каждый признак сравнивается с базовой моделью нормы для конкретного пользователя или группы; для этого используются статистические характеристики, рассчитанные на историческом периоде, — типичные значения, диапазоны, квантильные пороги. Отклонение текущего значения признака от нормы интерпретируется как степень аномальности, которая может задаваться через нормированное расстояние до эталонного диапазона. В работе [8] показано, что подобный подход к извлечению поведенческих признаков из исторических данных пользователей в сочетании с методами машинного обучения позволяет достигать точности обнаружения инсайдерских угроз порядка 91 % на эталонном наборе данных CERT. Аномальности по отдельным признакам внутри домена объединяются в подскоринги S_iam, S_net и S_end в диапазоне 0–1, при этом признаки, наиболее характерные для инсайдерских сценариев, могут иметь повышенные веса по сравнению с менее значимыми.

Интегральный показатель RiskScore формируется на основе подскорингов по доменам с учётом корреляции сигналов и контекстных множителей и в общем виде представляется как функция RiskScore = f(S_iam, S_net, S_end, C), где C описывает контекст доступа — критичность ресурса, роль и привилегии пользователя, соответствие активности рабочему времени, новизну устройства или сетевого направления. На практике используется взвешенная агрегация подскорингов с последующим умножением на контекстный коэффициент и нормированием в диапазоне 0–100; при этом вес домена может зависеть от сценария: для скрытой эксфильтрации более значимым становится сочетание сетевых и endpoint-признаков, тогда как при злоупотреблении привилегиями ключевую роль играет IAM. Корреляционный эффект состоит в том, что высокий риск устанавливается преимущественно при совместном проявлении сигналов в нескольких доменах и неблагоприятном контексте: отдельно взятый ночной вход через VPN или разовая массовая файловая операция дают умеренные значения подскорингов, тогда как их сочетание с обращением к критичным ресурсам и появлением нового внешнего домена приводит к значительному росту RiskScore. Это позволяет снизить количество ложных срабатываний по одиночным аномалиям и повысить заметность сценариев, соответствующих подготовке и выводу данных.

Сценарный пример применения. Для иллюстрации работы предложенной модели рассмотрим упрощённый сценарий, сочетающий элементы злонамеренного инсайдера и скомпрометированной учётной записи: инженер с доступом к критичным данным подключается к корпоративной сети по VPN в нетипичное для него время, после чего последовательно выполняет массовое чтение файлов на файловом сервере и архивирует часть данных, а затем устанавливает исходящее соединение с ранее неиспользовавшимся внешним доменом. На первом этапе в домене IAM и сетевых событиях фиксируются аномалии — вход в необычное время, новый тип VPN-клиента, изменение географии или параметров сессии; это приводит к увеличению подскорингов S_iam и S_net до умеренных значений, однако RiskScore остаётся в низком или среднем диапазоне, поскольку признаков работы с данными ещё нет. На втором этапе при массовом чтении файлов и обращении к ресурсам повышенной критичности возрастает подскоринг S_end, а контекстный множитель повышает вклад этих действий из-за критичности затронутых данных, и интегральный RiskScore переходит в зону повышенного риска. На третьем этапе появление исходящего соединения на новый внешний домен и изменение профиля исходящего трафика приводят сетевой подскоринг к высоким значениям; совместное проявление аномалий в доменах IAM, сети и endpoint в пределах одного временного окна и в неблагоприятном контексте даёт высокий уровень RiskScore, достаточный для генерации приоритетного инцидента в SOC. Пример демонстрирует, что модель учитывает цепочку действий и усиливает риск при корреляции сигналов, а не реагирует на единичные события, что делает её более пригодной для приоритизации инсайдерских сценариев по сравнению с набором изолированных правил.

Оценка эффективности и условия применимости. Оценка эффективности риск-скоринга необходима для подтверждения того, что предложенный подход имеет практическую ценность для мониторинга инсайдерских угроз. В реальных организациях разметка событий как инсайдерских часто бывает неполной или отсутствует, поэтому в работе рассматриваются два взаимодополняющих подхода — классическая оценка по

метрикам качества при наличии размеченных данных и сценарное тестирование на основе типовых цепочек инсайдерской активности. Если организация располагает набором подтверждённых инцидентов, модель RiskScore может оцениваться по стандартным метрикам обнаружения — recall, precision и F1; пороги уровней риска подбираются для приемлемого баланса между пропуском инцидентов и объёмом алертов. При отсутствии разметки применяется сценарное тестирование: на основе реальных журналов или синтетических логов из эталонного набора CERT Insider Threat Dataset [11] формируются цепочки, включающие аномальную аутентификацию, изменение привилегий, массовую подготовку данных и их возможный вывод, и оценивается динамика RiskScore — важно, чтобы риск возрастал по мере накопления признаков и достигал высокого уровня при наличии согласованной активности в нескольких доменах, а для нормальной активности оставался в низком диапазоне.

Практическая эффективность подхода оценивается также по влиянию на процессы SOC: использование интегрального RiskScore позволяет сократить количество алертов, не требующих углублённого анализа, за счёт подавления одиночных шумовых событий и фокусировки на цепочках, где одновременно проявляются IAM-, сетевые и endpoint-признаки. Объяснимость RiskScore через выделение ключевых факторов, внесших вклад в итоговую оценку, должна уменьшать время первичного триажа и повышать доверие аналитиков к риск-оценке. В отличие от наборов разрозненных SIEM-правил, где каждое правило генерирует собственный алерт, интегральный скоринг позволяет представлять ситуацию в разрезе пользователя или устройства как единый инцидент, что облегчает приоритизацию и концентрирует ресурсы на пользователях с наибольшими значениями RiskScore.

Эффективность модели напрямую зависит от качества и полноты исходной телеметрии: при неполном или задержанном сборе IAM-, сетевых или endpoint-событий оценка риска занижается из-за отсутствия части цепочки. Помимо технических требований существенным являются вопросы приватности и комплаенса. Поскольку анализ телеметрии связан с обработкой потенциально чувствительной информации о действиях сотрудников, доступ к данным и результатам скоринга должен быть строго регламентирован в соответствии с требованиями стандартов, в частности контроля PM-12 (Insider Threat Program) NIST SP 800-53 [13], а набор собираемых признаков — минимально достаточным для решения задач безопасности. Количественная оценка влияния модели на уменьшение ложных срабатываний, время расследования и другие операционные показатели SOC предполагается предметом дальнейшей экспериментальной проверки в рамках магистерской диссертации.

Архитектура внедрения. Архитектура внедрения единого RiskScore должна обеспечивать сбор и нормализацию телеметрии из разных доменов, вычисление подскорингов и интегральной метрики, а также интеграцию результатов в существующие процессы мониторинга и реагирования. При этом важно минимально вмешиваться в текущую инфраструктуру и использовать уже имеющиеся компоненты — SIEM, системы сбора логов и SOAR-платформы. Обобщённая схема интеграции источников телеметрии, компонента RiskScore и процессов SOC/SOAR представлена на рисунке 3.



Рисунок 3 – Архитектура внедрения RiskScore в инфраструктуру SOC

На уровне сбора и доставки данных находятся источники событий — системы управления идентификацией и доступом, сетевые устройства и сервисы (межсетевые экраны, прокси, VPN, DNS, NetFlow), а также агенты или средства мониторинга на конечных точках (EDR, антивирусы, средства аудита); логи передаются в централизованное хранилище, как правило в существующую SIEM-систему. На уровне нормализации и скоринга реализуется логика приведения событий к унифицированному формату, привязки к сущностям user, host, resource, time, агрегирования по временным окнам и расчёта подскорингов и интегральной метрики; функционально это может быть отдельный модуль внутри SIEM или внешний сервис RiskScore, получающий нормализованные события через очередь сообщений или API. На уровне представления и реагирования результаты скоринга интегрируются в интерфейсы аналитиков SOC и в сценарии автоматизированного реагирования: для каждого пользователя или устройства поддерживается текущий уровень RiskScore, история его изменения и список факторов, внесших вклад в итоговую оценку, а на основе пороговых значений формируются алерты различного приоритета и могут запускаться SOAR-плейбуки — запрос дополнительной аутентификации, временные ограничения на выгрузку данных, усиленный мониторинг.

Конкретная реализация компонента RiskScore зависит от масштабов и зрелости инфраструктуры. Встраивание в SIEM или UEBA-механизмы предполагает реализацию логики через корреляционные правила, пользовательские скрипты или встроенные UEBA-профили; преимуществом является использование существующего хранилища и средств визуализации, ограничением — вычислительные ресурсы SIEM. Вынесение в отдельный сервис риск-скоринга обеспечивает большую гибкость в выборе технологий и масштабировании вычислений, но требует дополнительного сопровождения. Гибридная схема, при которой нормализация и агрегация выполняются на стороне SIEM, а расчёт RiskScore — во внешнем сервисе, позволяет использовать сильные стороны обеих платформ и поэтапно внедрять риск-скоринг без радикальной перестройки существующей архитектуры. Минимальными условиями внедрения являются централизованный сбор логов как минимум из двух доменов с возможностью привязки событий к пользователям и устройствам, синхронизация времени между основными компонентами, поддержка справочников критичности ресурсов и информации о ролях пользователей, а также регламентированный доступ к телеметрии и результатам скоринга. Внедрение целесообразно проводить поэтапно: на первом этапе модель используется в наблюдательном режиме для настройки порогов и оценки распределения риска, на втором — наиболее надёжные сценарии и пороги интегрируются в

приоритизацию алертов и плейбуки реагирования, в дальнейшем выполняются калибровка весов под конкретную организацию, расширение набора признаков и перенос части логики в автоматизированные механизмы SOAR.

Заключение. В результате выполненной работы разработана формализованная модель единого риск-скоринга инсайдерских угроз, включающая структуру подскорингов по доменам IAM, сети и endpoint, механизм их интеграции в единую шкалу RiskScore в диапазоне 0–100 с учётом контекста доступа (критичность ресурсов, роль и привилегии пользователя, временные характеристики активности), схему привязки разнородных событий к сущностям user, host, resource, time с формированием унифицированной записи события, а также набор типовых инсайдерских сценариев и требований к телеметрии. Ключевым результатом является формализация структуры скоринга — расчёт подскорингов по каждому домену, их интеграция в шкалу 0–100 с учётом корреляционного усиления и контекстных факторов, а также формирование объяснимости на основе наиболее значимых факторов, внесших наибольший вклад в итоговую оценку. Контекстный множитель позволяет приблизить риск-оценку к реальной модели ущерба, а объяснимость делает результат применимым для SOC, сокращая время триажа и повышая доверие к алертам.

Практическая ценность подхода заключается в возможности использования RiskScore как механизма приоритизации и триггера для пропорциональных мер предотвращения — от усиленного мониторинга и запроса дополнительной аутентификации до временных ограничений на операции, потенциально связанные с выводом данных. Архитектура внедрения показывает, что модель может быть реализована в типовой инфраструктуре через SIEM или отдельный сервис скоринга с последующей интеграцией в процессы алертинга и SOAR-плейбуки.

Перспективы дальнейшей работы связаны с развитием предложенной модели и её адаптацией под конкретные организации: исследование способов калибровки весов и порогов RiskScore на основе обратной связи SOC и накопленных событий с оценкой влияния такой калибровки на сокращение ложных срабатываний и время триажа; расширение механизма временной корреляции за счёт более гибкого мультиоконного накопления риска и использование графовой корреляции типа «user–device–resource» для уточнения контекста доступа; дальнейшая формализация критериев качества объяснимости и проработка вопросов приватности и комплаенса при минимизации собираемых персональных данных.

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MICROSOFT DEFENDER AND UNQUOTED SERVICE PATH RISKS: A CASE STUDY OF CONFIGURATION-BASED PRIVILEGE ESCALATION

Abstract: Configuration-based privilege escalation remains a practical security risk in Windows environments because the root cause is often not malicious code but insecure administrative state. This paper rewrites and extends an experimental study of unquoted service path exploitation by focusing on the effectiveness and limitations of Microsoft Defender Antivirus and related Microsoft Defender security controls. The case study examines a Windows service whose ImagePath value contains whitespace without enclosing quotation marks and whose intermediate directory permissions allow modification by a low-privileged user. The research question is whether Defender prevents this class of privilege escalation at the configuration layer, at the payload execution layer, or only through subsequent behavioral detection. The study uses a controlled Windows virtual-machine environment, intentionally misconfigured services, native auditing commands, and a PowerShell-based checklist for service-path and access-control assessment. Defender controls considered in the evaluation include real-time protection, cloud-delivered protection, Tamper Protection, attack surface reduction rules, and exclusion management. The results show that Defender is valuable for detecting or blocking known malicious binaries and suspicious post-exploitation behavior, but it does not inherently correct insecure service paths or permissive NTFS access control lists. Therefore, the unquoted service path issue must be treated as a compound configuration weakness requiring preventive hardening: quotation of executable paths, least-privilege directory permissions, service-account review, continuous configuration auditing, and endpoint policy monitoring. The paper concludes that Defender should be evaluated not as a replacement for secure configuration management but as a complementary control within a layered Windows hardening strategy.

Keywords: Windows Defender, Microsoft Defender Antivirus, privilege escalation, unquoted service path, Windows services, configuration security, access control lists, endpoint protection, attack surface reduction, system hardening.

Introduction. Privilege escalation is one of the most important stages in a Windows compromise because it changes the attacker perspective from limited user activity to administrative or SYSTEM-level control. In many cases, this transition is not enabled by a memory-corruption flaw or a sophisticated exploit but by an operational misconfiguration that has remained unnoticed across software installations, updates, and administrative changes. Unquoted service path exploitation is a representative example of this category. It occurs when

the executable path of a Windows service contains spaces but is stored without quotation marks, allowing the service loader to interpret earlier path segments as executable candidates.

The issue is particularly relevant in enterprise environments because Windows services are frequently installed by third-party applications and often run with high privileges. A path such as C:\Program Files\Vendor App\service.exe should be stored as a quoted string. If it is not quoted, Windows path resolution can become ambiguous. The vulnerability becomes practically significant when a low-privileged user can write to an intermediate directory in the path. Under those conditions, an unintended executable may be placed where Windows searches before reaching the intended service binary, creating a local privilege-escalation opportunity.

Traditional studies of unquoted service paths usually focus on the vulnerability mechanism and on corrective actions such as adding quotation marks and hardening access control lists. This paper shifts the emphasis toward endpoint protection evaluation. Modern Windows environments commonly rely on Microsoft Defender Antivirus, Microsoft Defender for Endpoint, attack surface reduction rules, cloud-delivered protection, and Tamper Protection. These controls raise an important practical question: can Defender prevent configuration-based privilege escalation, or does it mainly reduce the risk after malicious execution begins?

The objective of this article is to evaluate Microsoft Defender effectiveness against the unquoted service path scenario as a case study of configuration-based privilege escalation. The paper does not present an offensive exploitation guide. Instead, it examines the security boundary between configuration auditing and malware prevention, identifies what Defender can reasonably detect, and proposes a hardening workflow that combines Defender policy with service configuration management.

The contribution of this paper is threefold. First, it reformulates unquoted service path exploitation as a measurable endpoint-protection evaluation problem rather than only as a Windows parsing issue. Second, it provides a controlled methodology for assessing Defender behavior against misconfigured services without using unauthorized systems. Third, it proposes a practical remediation model that distinguishes between configuration prevention, malicious payload blocking, and post-event detection.

Literature Review. Windows services are managed by the Service Control Manager, which reads each service configuration from the registry and starts the executable defined in the ImagePath value. Because many services run as LocalSystem, LocalService, NetworkService, or administrative accounts, weaknesses in service configuration can have direct security consequences. Prior work on Windows privilege escalation has repeatedly identified service misconfiguration as a persistent enterprise risk, especially where legacy installers, inherited directory permissions, and inconsistent administrative practices coexist.

Unquoted service path exploitation depends on two conditions. The first condition is syntactic ambiguity: the service path contains whitespace and is not enclosed in quotation marks. The second condition is authorization weakness: a low-privileged principal such as Users, Authenticated Users, or Everyone has write permission to an intermediate directory that Windows may evaluate during path resolution. Without writable permissions, an unquoted path remains a misconfiguration but may not be directly exploitable. Without the unquoted path, writable folders are still undesirable but do not create this specific parsing ambiguity. The vulnerability is therefore compound, involving both service metadata and NTFS access control.

Microsoft Defender Antivirus is designed primarily as endpoint anti-malware protection. It provides real-time protection, behavior monitoring, cloud-delivered protection, signature-

based detection, and integration with broader Defender for Endpoint capabilities. Microsoft documentation also describes evaluation procedures for Defender Antivirus using PowerShell and Group Policy, as well as management of exclusions, attack surface reduction rules, and Tamper Protection. These controls are important for reducing malware execution and for protecting security settings, but they do not automatically rewrite insecure ImagePath values or remove excessive directory permissions.

Attack surface reduction rules extend the defensive scope by blocking behaviors commonly used by malicious applications and scripts. They can reduce common initial execution and post-exploitation techniques, especially those involving Office, scripts, executable content from email, USB execution, credential theft behaviors, and suspicious process chains. However, ASR rules operate as policy-based behavior controls. They are not equivalent to a service configuration scanner and should not be expected to identify every unquoted path or every weak ACL.

Existing security guidance therefore supports a layered view. Defender contributes detection and blocking at the file, process, behavior, and policy levels. Configuration management contributes prevention at the registry, service-control, and filesystem-permission levels. A realistic evaluation of Defender against unquoted service paths must measure both parts separately: whether Defender detects the malicious artifact or behavior, and whether the underlying misconfiguration remains present after the event.

Methodology. The research design follows a controlled case-study model. A Windows virtual machine is prepared in an isolated lab network. Two user roles are defined: an administrative account used to create and remediate test services, and a standard user account used to run discovery checks from a low-privilege perspective. The lab does not interact with production systems, external users, or third-party services. The purpose is to observe defensive behavior and verify configuration hardening, not to conduct unauthorized exploitation.

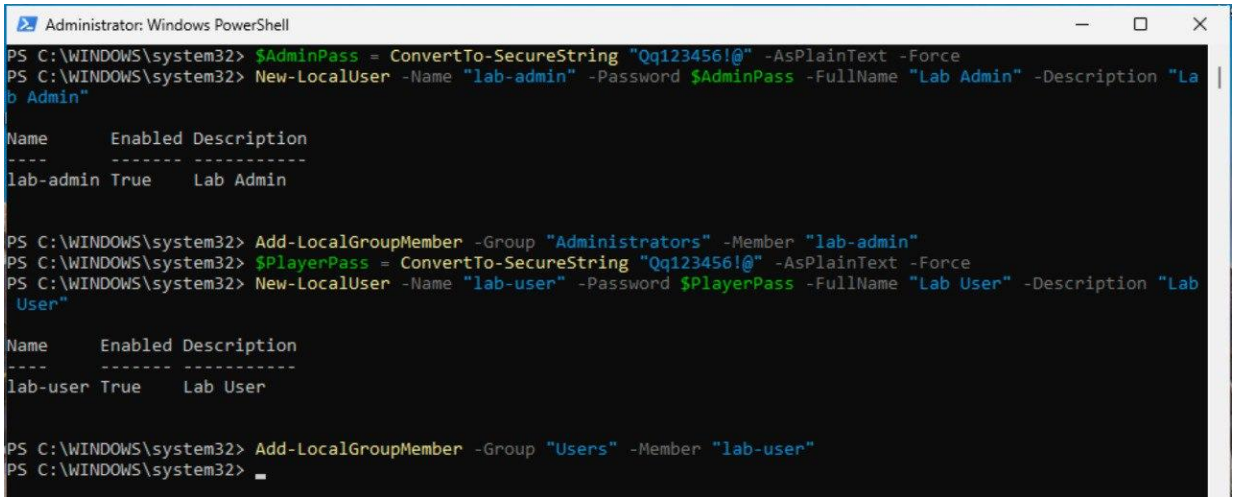


Figure 1. Creation of administrator and standard user accounts for the isolated Windows test environment.

The experimental variable is the service configuration. A vulnerable service condition is represented by three elements: an unquoted executable path containing spaces, an intermediate directory with excessive write permissions, and a service context with elevated privileges. A secure service condition is represented by the same service after remediation: the executable

path is fully quoted, writable permissions for standard users are removed from intermediate directories, and the service account is reviewed for least-privilege operation.

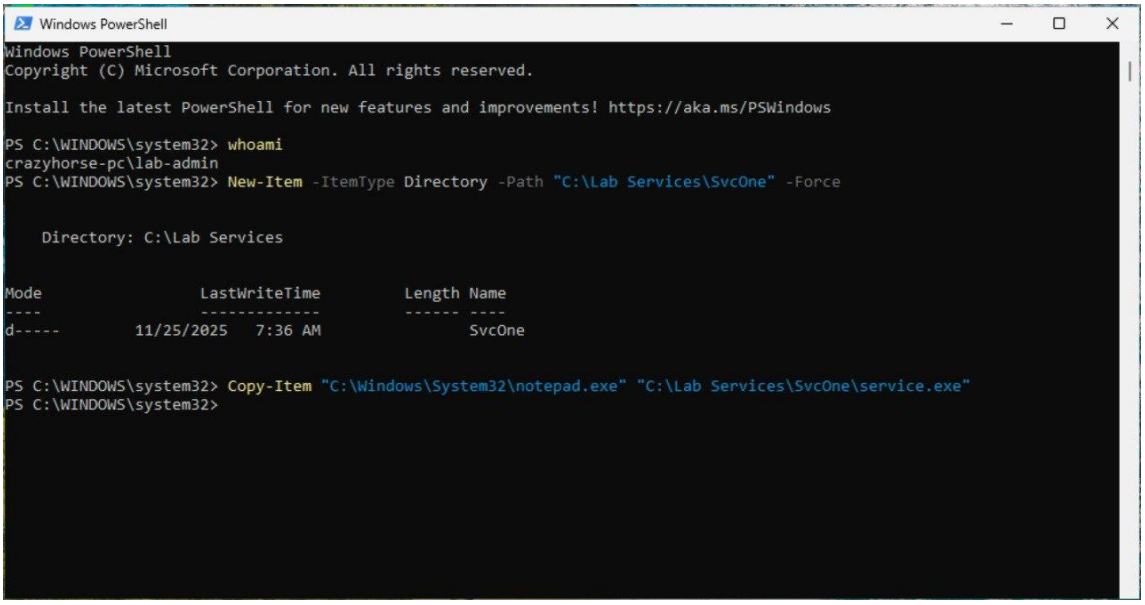


Figure 2. Preparation of a test service directory containing whitespace in the executable path.

A controlled vulnerable service was created with native Windows tools. The sc.exe utility was used to register the test service, while the Windows registry was inspected to verify how the service executable path was stored in the ImagePath value. This step was necessary because the security issue depends not only on the visible service path, but also on whether the path is stored with or without quotation marks.

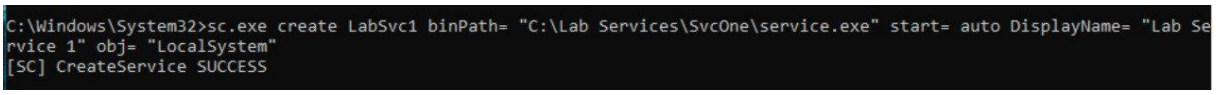


Figure 3. Creation of a Windows service used to reproduce the unquoted service path condition.

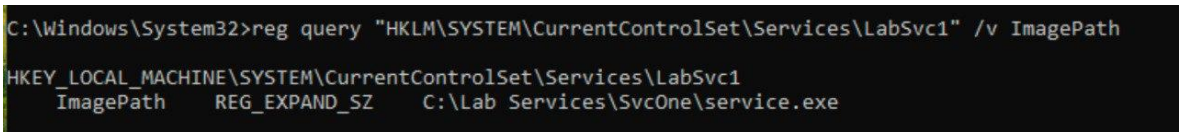


Figure 4. Registry verification of the unquoted service ImagePath used in the Defender evaluation scenario.

After the vulnerable service condition was confirmed, the experiment was interpreted through a Defender evaluation framework. The purpose of this framework was to separate two different security questions. The first question was whether Microsoft Defender could detect or block malicious activity related to the vulnerable service path. The second question was whether Defender could identify and correct the insecure configuration itself. This distinction is important because an unquoted service path is not a malicious file; it is a configuration weakness that becomes dangerous when combined with writable directories and elevated service privileges.

The evaluation framework consisted of four layers. The first layer was the configuration state, including the service ImagePath, quotation status, directory permissions, and service privilege context. The second layer was file execution, where Defender may detect or quarantine suspicious executables placed in service-related directories. The third layer was behavior monitoring, where Defender may generate alerts if the executed process performs suspicious actions. The fourth layer was policy integrity, including Tamper Protection, attack surface reduction rules, and exclusion review. Together, these layers made it possible to evaluate Defender fairly: not as a tool that automatically repairs service misconfigurations, but as an endpoint protection control that may reduce the impact of exploitation attempts.

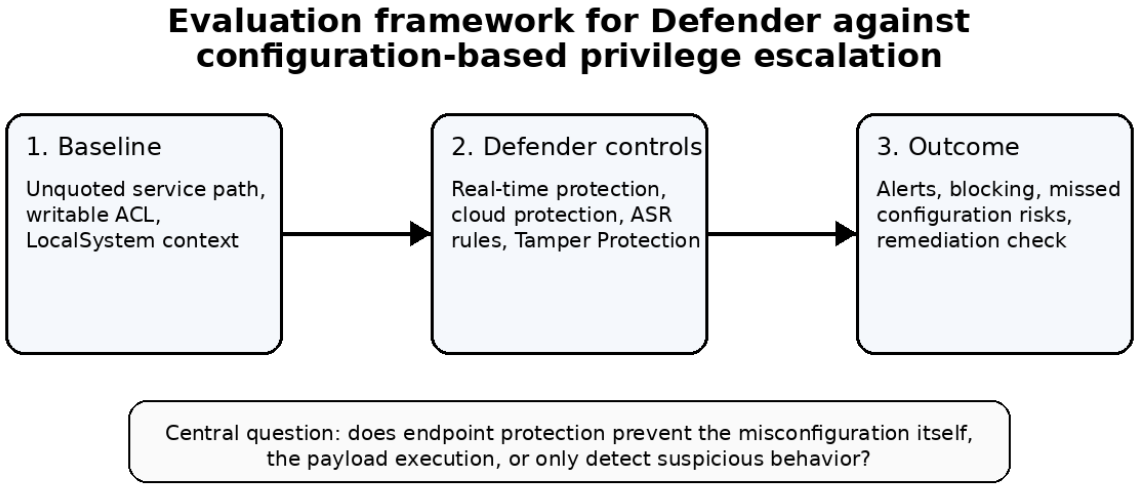


Figure 5. Conceptual framework for evaluating Defender against unquoted service path risks

The second part of the vulnerable condition was weak directory permission. NTFS permissions were inspected with folder security properties or the icacls utility. Special attention was given to write, modify, or full-control permissions granted to low-privileged groups such as Users or Authenticated Users. This stage is important because an unquoted service path alone is not always exploitable. The configuration becomes practically dangerous when a low-privileged user can write to an intermediate directory that Windows may check during ambiguous path parsing.

```
PS C:\WINDOWS\system32> icacls "C:\Custrom Services" /grant "Users:(OI)(CI)M"
processed file: C:\Custrom Services
Successfully processed 1 files; Failed processing 0 files
PS C:\WINDOWS\system32> icacls "C:\Custrom Services"
C:\Custrom Services BUILTIN\Users:(OI)(CI)(M)
                    BUILTIN\Administrators:(I)(OI)(CI)(F)
                    NT AUTHORITY\SYSTEM:(I)(OI)(CI)(F)
                    BUILTIN\Users:(I)(OI)(CI)(RX)
                    NT AUTHORITY\Authenticated Users:(I)(M)
                    NT AUTHORITY\Authenticated Users:(I)(OI)(CI)(IO)(M)

Successfully processed 1 files; Failed processing 0 files
```

Figure 6. Writable intermediate directory permissions required for practical privilege-escalation risk.

After documenting the writable-directory condition, the study proceeded to configuration auditing. This step was used to determine whether the vulnerable state could be identified independently of Defender malware alerts.

The configuration audit is performed with native Windows tools and PowerShell. Service paths are enumerated through Windows Management Instrumentation or CIM classes. Registry ImagePath values are inspected for unquoted paths containing whitespace. NTFS permissions are inspected using access-control-list queries, with special attention to write, modify, and full-control permissions granted to low-privileged groups. The audit also checks related privilege-escalation indicators, such as writable directories referenced in the PATH environment variable and insecure installer policies.

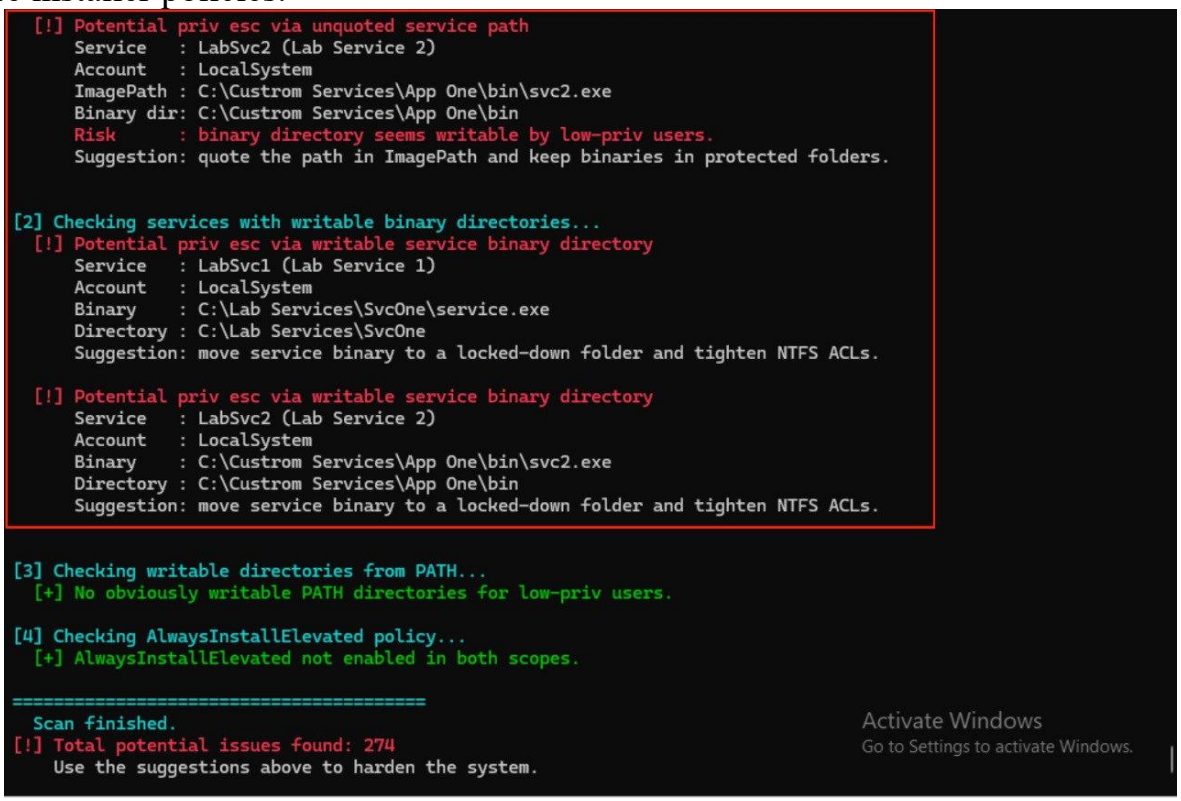


Figure 7. Configuration audit output identifying unquoted service paths and writable directory indicators.

The methodology separates configuration detection from payload detection. A Defender alert caused by a known malicious file does not mean the unquoted service path has been remediated. Conversely, absence of a Defender alert does not mean the configuration is safe. The service is considered secure only if subsequent audit results show that the path is quoted, intermediate directories are not writable by low-privileged users, and the service account is appropriate for its operational function.

After the vulnerable baseline was documented, remediation was applied. The executable path was corrected by enclosing the full service path in quotation marks. NTFS permissions were then hardened by removing write or modify access for low-privileged users from intermediate service directories. A repeated audit was performed to verify whether the tested privilege-escalation condition had been removed.

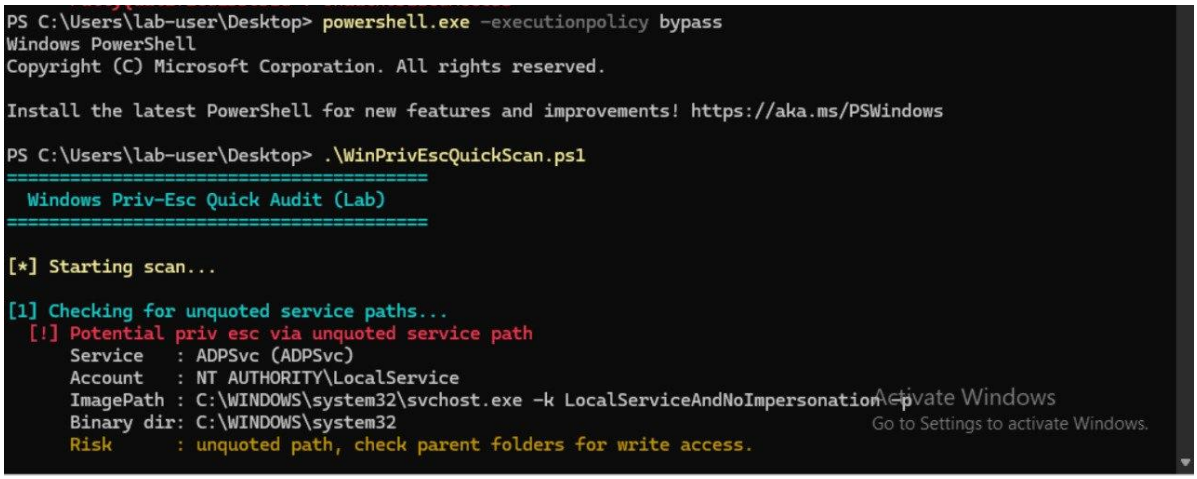


Figure 8. Validation after remediation by path quotation and ACL hardening.

The evaluation criteria are summarized in Table 1.

Table 1 - Evaluation criteria for Defender and configuration hardening

Layer	Evaluation question	Defender role	Hardening action
Configuration	Is the service path or ACL insecure?	Does not automatically repair ImagePath or ACLs	Quote paths and restrict permissions
Execution	Is a suspicious binary launched?	May block or quarantine the file	Prevent write access to service paths
Behavior	Does the process act maliciously?	May generate behavior-based alerts	Investigate and fix root cause
Policy	Can protection be weakened?	Tamper Protection helps protect settings	Audit exclusions and centralize policy

Results. The case study indicates that Microsoft Defender should be understood as an endpoint protection control rather than as an automatic service-configuration repair mechanism. As shown in Figures 3 and 4, the vulnerable baseline contained an unquoted service path stored in the service registry configuration. As shown in Figure 6, the scenario also included writable intermediate directory permissions. These two conditions created the configuration basis for privilege-escalation risk.

In the vulnerable baseline, the unquoted service path and weak directory permissions remained present until explicit administrative remediation was performed. Defender did not treat the unquoted ImagePath value itself as malware. This result is expected because the misconfiguration is stored in service metadata and filesystem ACLs, while antivirus engines primarily evaluate files, processes, scripts, memory behavior, network indicators, and suspicious activity chains.

When the test condition involved only the insecure configuration, Defender did not directly report the unquoted path as a malicious object. This is an important finding for administrators: the absence of a Defender alert is not evidence that the service configuration is secure. A service can remain vulnerable even when Defender status is healthy and real-time protection is enabled. Therefore, configuration scanning must be part of the evaluation procedure.

Defender effectiveness became more visible when the scenario moved from configuration state to execution state. If an executable candidate placed in a writable service-path location matched known malicious signatures, exhibited suspicious behavior, or triggered policy-

controlled actions, Defender could block, quarantine, or report it. However, a benign-looking or custom test binary may not be blocked solely because it is located in a risky path.

Attack surface reduction rules provided additional value by limiting selected behaviors commonly associated with malware execution. Nevertheless, ASR rules did not substitute for service-path auditing. Their role was preventive at the behavior-policy layer, not corrective at the service-registry layer. This distinction is central to evaluating Defender fairly: ASR may reduce the probability that a malicious payload succeeds, but it does not eliminate the root cause of unquoted service path exposure.

Remediation was effective only after applying configuration changes. Quoting the full executable path removed command-line parsing ambiguity. Removing Modify and Write permissions for low-privileged groups from intermediate directories prevented unauthorized placement of executable candidates. After remediation, a repeat audit no longer identified the tested privilege-escalation condition, as shown in Figure 8.

Discussion. The findings demonstrate that configuration-based privilege escalation occupies a defensive gap between endpoint malware detection and system hardening. Microsoft Defender is strong when the adversary action creates detectable file, process, script, or behavior evidence. It is less suited to silently correcting insecure administrative configurations unless combined with configuration management, security baselines, endpoint analytics, vulnerability management, or custom audit scripts.

This distinction has operational consequences. Security teams sometimes interpret endpoint-protection health as broad system security health. The case study shows why that interpretation is incomplete. A Windows host may report active Defender protection and still contain weak service permissions, unquoted paths, writable PATH directories, or risky installer policies. These weaknesses are not necessarily malicious by themselves; they are unsafe states that can be abused later.

A mature evaluation must therefore include two classes of indicators. The first class is protection indicators: Defender enabled, real-time protection active, cloud-delivered protection enabled, current security intelligence, Tamper Protection active where applicable, ASR rules deployed in audit or block mode, and exclusions minimized. The second class is configuration indicators: no unquoted service paths with spaces, no writable intermediate service directories, no high-privilege services controlled by ordinary users, no broad write access in service installation folders, and no unnecessary local administrator assignments.

The results also support a risk-based deployment approach. In audit mode, ASR and Defender events can help determine whether stricter policy might disrupt normal operations. After validation, relevant rules can be moved to block mode. In parallel, service-path and ACL remediation should be applied directly because it addresses the root cause and normally does not require accepting detection uncertainty. Administrators should prioritize services running as LocalSystem and services installed outside protected system directories.

The study has limitations. The evaluation uses a controlled lab rather than a large enterprise fleet, so it cannot represent every Defender configuration, every third-party service, or every tenant-level Defender for Endpoint feature. Detection results may vary based on security-intelligence version, cloud connectivity, policy state, licensing, exclusions, and EDR configuration. The study also avoids offensive payload development, so it evaluates defensive boundaries without claiming coverage against all real-world attacker variants.

Practical Recommendations. Organizations should treat Defender as one component of a layered control set. First, enable and monitor Microsoft Defender Antivirus real-time protection, cloud-delivered protection, and security-intelligence updates. Second, enable Tamper Protection where supported to reduce the risk of unauthorized changes to security settings. Third, deploy attack surface reduction rules through a staged process: audit mode for compatibility assessment, followed by block mode for rules that do not disrupt business workflows.

Fourth, minimize exclusions. Exclusions are sometimes necessary for compatibility, but broad folder exclusions around application or service directories can weaken detection exactly where service-path abuse may occur. Exclusion lists should be documented, justified, reviewed periodically, and scoped as narrowly as possible. Fifth, implement recurring service-configuration audits using PowerShell, endpoint management platforms, or vulnerability-management tools. Audit logic should identify unquoted paths with whitespace, writable directories in service paths, high-privilege service accounts, and user-startable privileged services.

Sixth, remediate root causes directly. Every service executable path containing spaces should be enclosed in quotation marks. Intermediate directories should grant write access only to trusted administrative principals and service-maintenance identities. Standard users should not have Modify or Full Control permissions over directories that participate in high-privilege service paths. Seventh, verify remediation by rescanning after every change, because successful hardening is demonstrated by the absence of the vulnerable condition, not by the absence of an antivirus alert.

Finally, integrate the findings into security operations. Defender alerts related to suspicious service execution should trigger both incident response and configuration review. If an alert is raised from a service directory, analysts should inspect the service ImagePath value and parent directory ACLs. This converts a file-level alert into a root-cause investigation and prevents repeated exposure after a single malicious artifact is removed.

Conclusion. This paper evaluated Microsoft Defender effectiveness against configuration-based privilege escalation using unquoted service path exploitation as a case study. The analysis shows that Defender can provide meaningful protection against malicious payloads, suspicious execution, and selected attack behaviors, especially when real-time protection, cloud-delivered protection, Tamper Protection, and attack surface reduction rules are properly configured. However, Defender does not inherently eliminate the underlying service misconfiguration. An unquoted service path combined with weak intermediate directory ACLs remains a configuration risk until administrators quote the path and harden permissions.

The central conclusion is that endpoint protection and secure configuration management solve different parts of the same risk. Defender reduces the probability and impact of malicious execution, while configuration auditing and hardening remove the privilege-escalation opportunity. Effective Windows defense requires both. Future work should extend this case study across larger endpoint populations, compare Defender for Endpoint telemetry with local PowerShell audit results, and evaluate how centralized security baselines can automatically detect and remediate service-path misconfigurations at scale.

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UDC 347.1

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A DATA-DRIVEN SMART CONTRACT ANALYSIS SYSTEM FOR PERFORMANCE AND SECURITY OPTIMIZATION IN ETHEREUM

Abstract: Smart contracts deployed on Ethereum enable decentralized applications and financial protocols but remain vulnerable to security flaws and performance inefficiencies. Errors such as reentrancy, improper access control, and unsafe external calls may result in severe financial losses, while inefficient gas usage increases operational costs. This paper presents a data-driven analytical system for integrated security and performance assessment of Ethereum smart contracts. The proposed architecture combines static code analysis, rule-based vulnerability detection, and machine learning models within a modular full-stack framework. Security analysis is formulated as a multi-label classification task using TF–IDF feature representation and baseline classifiers, including Logistic Regression and Linear Support Vector Machines. Performance evaluation is modeled as a regression problem over historical Ethereum transaction data using a Random Forest estimator to predict gas efficiency. Experimental results demonstrate that transaction-level parameters provide strong predictive signals for performance estimation, while text-based models effectively identify dominant vulnerability categories. The findings confirm the feasibility of combining classical machine learning techniques with heuristic analysis for automated smart contract evaluation.

Keywords: Smart contracts, Ethereum, blockchain security, gas efficiency, machine learning, static analysis, vulnerability detection

Introduction. Smart contracts are programmable agreements deployed on blockchain platforms that execute automatically when predefined conditions are satisfied. By embedding contractual logic directly into distributed ledger systems, smart contracts eliminate the need for intermediaries and ensure deterministic execution of rules recorded in the blockchain state. Their transparency, immutability, and trustless execution model have enabled widespread adoption in decentralized finance, supply chain management, insurance automation, digital identity, and governance systems [1], [2].

Despite their transformative potential, smart contracts introduce significant technical challenges. Once deployed, their code becomes immutable, meaning that any embedded vulnerability or logical flaw may result in irreversible financial losses. Empirical studies demonstrate that developers frequently encounter difficulties related to access control design, gas management, external call handling, and secure coding practices [3], [4]. These issues are exacerbated by the rapid growth of decentralized applications and the increasing economic value locked in blockchain systems.

Security risks in smart contracts have repeatedly led to severe incidents, including reentrancy attacks, integer overflows, timestamp manipulation, and misuse of low-level calls.

Systematic surveys highlight that many deployed contracts contain detectable vulnerability patterns that could have been mitigated through structured analysis prior to deployment [21]. At the same time, blockchain execution imposes strict computational constraints: each operation consumes gas, which directly translates into transaction fees. Inefficient contract logic therefore not only degrades performance but also increases economic costs for users.

From a systems perspective, smart contract evaluation requires simultaneous consideration of two orthogonal yet interdependent dimensions:

1. Security robustness, reflecting the presence or absence of vulnerability patterns.
2. Execution efficiency, reflecting how effectively computational resources are utilized.

Existing approaches often address these dimensions independently. Static analysis tools focus on vulnerability detection, while gas profilers and optimization studies analyze execution costs. However, integrated frameworks that combine security assessment with performance modeling remain limited [7], [21]. Furthermore, purely rule-based approaches struggle with coverage and false positives, whereas purely learning-based approaches face challenges in interpretability and dataset imbalance [10], [17].

Recent advances in machine learning have demonstrated the feasibility of applying data-driven techniques to smart contract analysis. Classification models trained on labeled vulnerability datasets can detect recurring insecure patterns, while regression models trained on transaction-level blockchain data can estimate gas efficiency and execution characteristics [14], [15]. Additionally, emerging research on representation learning and large language models indicates potential improvements in contextual vulnerability detection [10], [13]. Nevertheless, practical integration of such models into coherent analytical systems remains an open research challenge.

This work addresses the problem of integrated analytical assessment of smart contracts**,** combining security risk estimation and performance modeling within a unified architectural framework. The proposed system operates through structured static analysis, rule-based validation grounded in established taxonomies, and supervised machine learning models trained on curated datasets and empirical blockchain transaction data. Rather than replacing formal verification or professional audits, the system aims to provide probabilistic risk indicators and relative performance diagnostics suitable for early-stage screening and research evaluation.

The main contributions of this study are:

- The design of a unified analytical architecture that jointly evaluates smart contract security and execution efficiency.
- The formulation of vulnerability detection as a multi-label classification problem and gas efficiency estimation as a regression problem.
- The integration of rule-based structural analysis with calibrated probabilistic models to enhance interpretability.
- An empirical evaluation demonstrating that baseline machine learning models, when combined with structured heuristics, can provide meaningful risk and performance diagnostics.

By combining structured analytical reasoning with data-driven modeling, this research contributes toward scalable and interpretable smart contract evaluation methods aligned with contemporary blockchain development practices.

Related Work. The problem of smart contract security and performance analysis has been extensively studied from multiple methodological perspectives, including static analysis, dynamic analysis, formal verification, empirical developer research, and machine learning-based approaches. This section synthesizes these directions and positions the proposed system within the existing body of knowledge.

A. Static Analysis Approaches

Static analysis techniques examine contract source code or bytecode without executing it. Their objective is to identify syntactic and structural patterns associated with known vulnerability classes. Prominent tools rely on predefined security templates, control-flow graph reconstruction, and semantic rule inference to detect violations such as reentrancy, unchecked return values, or improper access control [9].

Rule-based analyzers provide fast pre-deployment diagnostics and are suitable for integration into development pipelines. However, they are inherently limited by the completeness of their rule sets. If a vulnerability pattern is not explicitly encoded, it may remain undetected. Additionally, static analyzers frequently produce false positives when patterns resemble vulnerabilities but are logically mitigated within the contract's context [8], [11].

Despite these limitations, static analysis remains a foundational method due to its scalability and deterministic behavior. It is particularly effective for detecting well-known vulnerability classes with distinctive structural signatures.

B. Formal Verification

Formal verification seeks to mathematically prove the correctness of smart contracts relative to a formal specification. Instead of detecting patterns, formal methods attempt to demonstrate that certain invariants always hold—for example, that balances cannot become negative or that only authorized users can trigger sensitive functions.

Certain blockchain platforms have incorporated verification-friendly languages and frameworks to support this approach. Formal methods provide strong correctness guarantees but require advanced expertise in logic and specification languages, limiting their practical adoption [7], [20]. Furthermore, formal proofs often abstract away environmental interactions, meaning that real-world integration risks may still persist.

C. Dynamic and Bytecode-Level Analysis

Dynamic analysis techniques evaluate smart contract behavior during simulated or real execution. These include symbolic execution engines, fuzz testing frameworks, and runtime profiling tools. For example, prior work demonstrated that bytecode-level inefficiencies can significantly increase gas costs due to redundant operations or unreachable code segments [12].

Dynamic methods are effective for uncovering execution-path-specific vulnerabilities and gas inefficiencies. However, they require extensive computational resources and depend on input coverage. Since it is infeasible to explore all execution paths exhaustively, certain edge cases may remain undetected.

D. Empirical Studies on Developer Challenges

Beyond technical mechanisms, empirical research has revealed structural challenges in smart contract development workflows. Developers often lack formal training in blockchain-

specific security patterns and gas optimization strategies [4]. Tool fragmentation and limited debugging support further exacerbate the likelihood of vulnerabilities.

Such findings emphasize that effective analytical systems must not only detect vulnerabilities but also provide interpretable diagnostics that align with developer workflows. Security tools that produce opaque or overly technical outputs risk underutilization [8].

E. Machine Learning in Smart Contract Analysis

Recent research has explored the application of machine learning to vulnerability detection and gas optimization. Classification models trained on labeled contract datasets can learn token-level and structural patterns indicative of reentrancy, integer overflow, and unsafe external calls [17]. Contrastive learning approaches have demonstrated improved representation of semantic differences between secure and insecure contracts [10].

In parallel, regression models have been applied to transaction-level blockchain data to estimate gas consumption and execution efficiency [14], [15]. These approaches treat performance modeling as a data-driven problem, leveraging historical gas metrics to approximate future behavior.

Large language models have also been investigated for vulnerability detection and automated code assistance, showing promising results in contextual understanding of smart contract semantics [13]. However, ML-based systems face challenges related to dataset imbalance, generalization across platforms, and explainability of predictions.

F. Comparative Perspective

Existing approaches vary in coverage, interpretability, and scalability. Static and rule-based systems provide transparency but limited adaptability. Formal verification offers strong guarantees but high complexity. Dynamic methods capture runtime behavior but at significant computational cost. Machine learning models offer adaptability and scalability but introduce probabilistic uncertainty.

The literature therefore indicates the need for hybrid systems that integrate multiple analytical paradigms. Surveys emphasize that combining structured rule-based reasoning with data-driven models yields more robust results than relying on any single method [21].

G. Positioning of the Proposed Work

The system proposed in this research aligns with the hybrid paradigm. It integrates:

- Structured static and rule-based analysis grounded in established vulnerability taxonomies.
- Supervised machine learning models for probabilistic vulnerability classification.
- Regression-based modeling of gas efficiency derived from empirical blockchain transaction data.

Rather than competing with formal verification or symbolic execution engines, the system operates as an intermediate screening and diagnostic layer. Its objective is to provide interpretable, data-driven risk and performance indicators suitable for large-scale contract evaluation and research experimentation.

In doing so, the proposed framework contributes to the ongoing effort to bridge rule-based security analysis and machine learning techniques within a unified analytical architecture.

Proposed Analytical Framework. The framework assesses contracts across two key dimensions: security risk and execution performance. Unlike purely static analyzers or purely machine learning-based approaches, the proposed framework integrates structural code analysis, rule-based reasoning, and supervised learning into a unified evaluation pipeline. The system operates in an offline analytical mode and does not require real-time blockchain interaction during evaluation. This ensures reproducibility and experimental control.

A. General Architecture of the Framework

The proposed framework is designed as a hybrid analytical system intended to evaluate Ethereum smart contracts from both security and execution-efficiency perspectives. Unlike conventional approaches that rely exclusively on either static analysis or machine learning techniques, the proposed architecture integrates structural code inspection, rule-based reasoning, and supervised learning into a unified analytical pipeline. The framework operates entirely in an offline evaluation mode and therefore does not require direct interaction with the blockchain during the analysis process. This design choice improves reproducibility, enables controlled experimentation, and reduces dependence on network-specific execution conditions.

The overall analytical workflow consists of several sequential stages beginning with contract acquisition and preprocessing. During the preprocessing phase, source code is normalized to reduce syntactic inconsistencies and prepare the contract for feature extraction. After normalization, the framework simultaneously performs security-oriented and performance-oriented analysis using separate but interconnected modules. The resulting analytical signals are aggregated through a calibrated scoring mechanism that produces structured outputs describing contract risk and execution characteristics.

The modular structure of the framework improves extensibility and experimental flexibility. Security and performance analysis components remain logically separated while sharing common preprocessing and metadata extraction layers. Such separation allows independent modification or replacement of individual analytical modules without affecting the overall architecture of the system. Consequently, the framework may be extended in future studies with additional vulnerability detectors, alternative machine learning models, or blockchain-specific optimization mechanisms.

B. Security Analysis Module

The security analysis module models vulnerability detection as a multi-label classification problem enhanced with structural verification mechanisms. Instead of generating binary decisions regarding contract safety, the framework estimates probabilistic risk scores for predefined categories of smart contract vulnerabilities. This approach reflects the practical reality that vulnerabilities often exhibit varying levels of confidence and contextual dependency rather than absolute presence or absence.

The first stage of the security module performs structural static analysis of the Solidity source code. During this phase, the framework extracts multiple categories of structural features, including function definitions, visibility modifiers, state variable declarations, arithmetic operations, external calls, low-level calls, timestamp references, and transaction-origin dependencies. These features are subsequently analyzed to identify deterministic indicators associated with known vulnerability patterns described in existing blockchain security literature [9], [11].

Several structural relationships are treated as security-relevant indicators. For example, state modifications executed after external calls may indicate potential reentrancy conditions,

while unrestricted public functions capable of modifying contract state may suggest access control weaknesses. Similarly, timestamp usage inside conditional execution logic may reveal susceptibility to time-dependence manipulation. By focusing on interpretable structural patterns, the framework improves analytical transparency compared to purely black-box prediction systems.

To strengthen interpretability and analytical consistency, the framework incorporates a rule-based vulnerability mapping layer. This component associates predefined structural patterns with standardized vulnerability categories and assigns confirmation strengths according to the detected evidence. Vulnerabilities with historically higher impact on smart contract exploitation, including reentrancy attacks, unchecked external calls, and delegatecall misuse, contribute more significantly to the final aggregation stage. The inclusion of deterministic reasoning ensures that the final security assessment is not driven solely by statistical correlations but remains grounded in explicit security principles.

The machine learning component formulates vulnerability detection as a supervised text classification task. Smart contract source code is transformed into numerical feature representations using TF–IDF vectorization with unigram and bigram tokenization schemes. The framework employs two baseline classifiers operating in a one-versus-rest configuration: Logistic Regression and Linear Support Vector Classification with probability calibration. Both models independently estimate vulnerability probabilities for each predefined category, after which the calibrated outputs are averaged to generate the final prediction score.

This ensemble configuration improves robustness and reduces prediction variance compared to single-model approaches [17]. Furthermore, weighted loss functions are applied during training to address class imbalance within vulnerability datasets, thereby reducing the underrepresentation of infrequent but critical vulnerability categories.

The final security assessment is produced through a calibrated aggregation process that combines machine learning probabilities, rule-based confirmation strengths, and structural verification indicators. Category-level scores are weighted according to vulnerability severity and merged into a unified contract risk score. The resulting numerical value is subsequently mapped into qualitative security categories ranging from Very Low to Critical.

Importantly, the aggregation mechanism restricts high-risk classifications when statistical predictions are not supported by structural or rule-based evidence. This constraint reduces the likelihood of false-positive detections generated solely by probabilistic models and improves overall interpretability of the analytical output.

C. Performance Analysis Module

The performance analysis module evaluates smart contract execution efficiency using both empirical blockchain transaction data and structural characteristics extracted directly from source code. Instead of attempting to predict exact gas consumption values under all execution scenarios, the framework estimates relative execution efficiency as an interpretable analytical indicator suitable for comparative contract evaluation.

Gas efficiency is defined as the ratio between gas used and gas limit during transaction execution. This metric reflects how effectively allocated computational resources are utilized by a contract during execution. The resulting value is normalized to the interval between zero and one, enabling consistent comparison across transactions with different execution characteristics.

To establish a realistic reference point for evaluation, the framework constructs an empirical baseline derived from historical Ethereum transaction data. The baseline represents the average gas efficiency observed across real transaction samples collected from publicly available blockchain datasets. Unlike theoretical estimations, this empirical approach allows the framework to evaluate contracts relative to realistic network behavior and operational execution conditions.

In addition to baseline construction, the framework employs a tree-based ensemble regression model trained on transaction-level parameters such as gas limit, gas used, gas price, and transaction value. The regression component captures non-linear relationships between execution parameters and efficiency outcomes commonly observed in blockchain systems [14], [15]. However, the regression model is primarily used for baseline calibration rather than direct contract-level gas prediction, thereby reducing excessive dependence on statistical forecasting.

The framework further refines efficiency estimation through structural performance analysis of the contract source code. During this phase, the system extracts execution-relevant characteristics including loop frequency, storage write operations, external call usage, and utilization of immutable or constant variables. Computationally expensive structures such as nested loops and repeated storage modifications contribute to penalty coefficients that reduce the final efficiency score. Conversely, efficient design patterns including immutable variables, cached computations, and view or pure functions contribute positive adjustment coefficients.

The final gas efficiency score is computed by combining empirical baseline estimation with structural penalty and bonus adjustments. The resulting value is normalized into a percentage-based efficiency indicator and categorized into qualitative performance levels such as Optimized, Average, and Inefficient. By integrating empirical data with interpretable structural analysis, the framework maintains analytical transparency while preserving practical relevance for smart contract evaluation.

D. Integrated Output Structure

The framework generates a structured analytical output combining both security-oriented and performance-oriented evaluation results. For security analysis, the system produces detected vulnerability categories together with probabilistic confidence scores and aggregated contract risk levels. For performance analysis, the framework provides estimated gas efficiency percentages accompanied by qualitative execution-efficiency classifications.

In addition to numerical evaluation metrics, the analytical output includes contextual metadata describing the scope and characteristics of the performed evaluation. This metadata improves reproducibility and enables comparison between contracts analyzed under different experimental conditions.

By combining probabilistic machine learning techniques with deterministic structural verification logic, the proposed framework achieves a balanced analytical methodology aligned with contemporary hybrid approaches discussed in recent smart contract security research [21]. The modular architecture, offline analytical design, and interpretable aggregation mechanisms collectively support scalable pre-deployment analysis while preserving experimental control and extensibility for future research directions.

Experimental Setup and Evaluation. This section describes the experimental configuration used to train, calibrate, and evaluate both the security and performance components of the proposed analytical framework. The objective of the evaluation is not to

compete with industrial audit tools, but to validate the feasibility of a hybrid ML-based analytical approach under controlled research conditions.

A. Security Model Experimental Setup

The security analysis component was evaluated as a supervised multi-label classification task using a curated dataset of Solidity smart contracts containing annotated vulnerability categories. Each contract within the dataset may contain one or multiple vulnerability labels depending on the detected security weaknesses. In addition to vulnerable contracts, non-vulnerable contracts were included to improve dataset balance and reduce model bias toward positive classifications.

The dataset consisted primarily of Solidity source code samples accompanied by vulnerability annotations and metadata attributes such as compiler version and category type. To preserve statistical consistency between training and evaluation stages, stratified sampling was applied during dataset splitting. The final dataset was divided into training and testing subsets using an 80/20 ratio while maintaining label distribution across both partitions.

Table 1. Security dataset characteristics

Property	Value
Total contracts used	~5,000
Vulnerability categories	8
Label format	Multi-label
Clean contracts included	Yes
Tokenization scheme	Unigram + Bigram

Source code preprocessing was performed using TF–IDF vectorization with unigram and bigram tokenization strategies. The vectorization process was configured with a maximum feature space of 6,000 terms and a minimum document frequency threshold of two occurrences. Stopword filtering was additionally applied to remove statistically irrelevant tokens while preserving Solidity-specific language constructs and syntax elements relevant to vulnerability detection.

Two supervised baseline classifiers were trained within a one-versus-rest classification configuration: Logistic Regression and Linear Support Vector Classification with probability calibration. Logistic Regression employed L2 regularization with an increased iteration limit to ensure convergence stability, while the Linear SVC model utilized calibrated probability estimation to enable probabilistic aggregation during the final evaluation stage. Class imbalance was mitigated using weighted loss functions, thereby improving detection sensitivity for less frequent vulnerability categories.

Table 2. Security classification model configuration

Model	Configuration
Logistic Regression	L2 regularization, max_iter = 300
Linear SVC	Linear kernel with probability calibration
Training strategy	One-versus-rest
Imbalance handling	Class-weighted loss

The final vulnerability probability for each category was computed as the average of calibrated outputs produced by both classifiers. This ensemble-based aggregation strategy reduced prediction variance and improved analytical robustness compared to single-model configurations.

Security evaluation was conducted using standard classification metrics including accuracy, precision, recall, and macro-averaged F1-score. Macro-F1 was treated as the primary evaluation metric due to the imbalanced nature of vulnerability distributions across the dataset. This metric ensures that less frequent vulnerability categories contribute proportionally to the overall evaluation process.

Table 3. Security model performance results

Metric	Value
Accuracy	0.84
Macro F1-score	0.79
Average Precision	0.82
Average Recall	0.76

B. Performance Model Experimental Setup

The performance analysis component was evaluated using historical Ethereum blockchain transaction records collected from publicly available datasets. Each transaction record contained execution-related attributes including gas limit, gas used, gas price, transaction value, and timestamp information. Gas efficiency was calculated as the ratio between gas used and gas limit, after which resulting values were normalized to the interval between zero and one to ensure analytical consistency across transactions with varying execution scales.

The experimental dataset included approximately 5,000 transaction samples selected to balance computational feasibility and statistical representativeness. This dataset served both as the basis for empirical baseline construction and as training input for regression-based calibration models.

To model non-linear relationships between transaction parameters and execution efficiency, the framework employed a Random Forest Regressor as the baseline regression model. The selection of Random Forest was motivated by several practical considerations, including robustness to outliers, low sensitivity to feature scaling, and strong performance in heterogeneous tabular datasets frequently encountered in blockchain analytics.

Table 4. Regression model configuration

Parameter	Value
Number of trees	80
Maximum depth	8
Random state	Fixed
Parallelization	Enabled

The resulting R^2 score indicates that transaction-level parameters explain a substantial proportion of variance in gas efficiency outcomes. Feature importance analysis further revealed that gas used, gas limit, and gas price were the dominant predictive variables influencing efficiency estimation. This observation is consistent with expected blockchain execution behavior, where computational resource consumption directly affects transaction efficiency characteristics.

In addition to regression-based calibration, the framework incorporated structural source-code analysis to refine contract-level performance estimation. Structural penalties were assigned to contracts exhibiting computationally expensive design patterns such as nested loops, repeated storage modifications, and excessive external calls. Conversely, optimization bonuses were applied when efficient Solidity patterns including immutable variables, cached computations, and view or pure functions were detected.

C. Calibration and Threshold Selection

To improve output stability and interpretability, the framework incorporated several calibration constraints and threshold-selection mechanisms. For security analysis, the minimum probability threshold required for vulnerability reporting was empirically set to 0.22, while maximum reported probabilities were capped at 0.90 to reduce overconfident predictions generated by probabilistic models. Furthermore, the aggregation layer restricted upper-bound risk escalation in cases where statistical predictions lacked supporting structural confirmation

For performance evaluation, gas efficiency scores were mapped into qualitative execution categories using empirically derived thresholds. Contracts achieving efficiency values greater than or equal to 84% were classified as optimized, while contracts with efficiency values between 66% and 84% were categorized as average. Contracts below the lower threshold were classified as inefficient.

Table 6. Performance efficiency categories

Efficiency Score	Category
≥ 84%	Optimized
66% – 84%	Average
< 66%	Inefficient

Threshold values were selected through iterative distribution analysis and repeated experimental calibration performed on the training dataset. This approach ensured that the resulting categories remained interpretable while preserving statistical consistency across evaluation scenarios.

Results and Discussion

A. Security Analysis Behavior

Experimental evaluation demonstrated that the proposed hybrid analytical approach improves the stability and interpretability of vulnerability assessment compared to purely statistical classification models. By combining structural heuristics with probabilistic machine learning predictions, the framework was able to reduce the frequency of false-positive detections commonly observed in standalone text-classification approaches.

One of the most significant observations during evaluation was the impact of structural confirmation mechanisms on risk calibration. Contracts producing high vulnerability probabilities through machine learning inference but lacking supporting structural evidence were prevented from receiving critical risk classifications. This restriction mechanism reduced excessive confidence in isolated statistical predictions and improved consistency between analytical outputs and observable contract behavior. Consequently, the framework achieved a more balanced security assessment process aligned with layered security principles discussed in prior research [11], [21].

The integration of deterministic reasoning additionally improved explainability of the final analytical output. Instead of generating opaque classification decisions, the framework identified dominant vulnerability signals contributing to the aggregated risk score. This allowed the system to highlight the most influential vulnerability categories affecting contract evaluation, thereby improving transparency and interpretability for developers and researchers.

The experimental results also revealed that vulnerabilities characterized by explicit structural patterns, such as reentrancy conditions and unchecked low-level calls, were detected with comparatively higher reliability. In contrast, vulnerabilities with weaker structural regularity, including timestamp dependence and front-running susceptibility, produced lower

classification consistency due to limited dataset representation and contextual variability. These observations are consistent with limitations previously identified in smart contract security literature.

Overall, the security evaluation demonstrated that the proposed hybrid methodology provides a practical compromise between interpretability, analytical flexibility, and detection capability. While the framework does not replace formal verification or industrial-grade auditing systems, it offers a scalable and computationally efficient mechanism for preliminary smart contract risk assessment.

B. Performance Analysis Behavior

The performance-oriented component of the framework focused primarily on relative execution-efficiency diagnostics rather than exact prediction of transaction gas consumption. This design decision was motivated by the highly dynamic nature of blockchain execution environments, where precise gas prediction may vary depending on network conditions, compiler optimizations, and transaction context.

Experimental analysis demonstrated that structural contract characteristics significantly influenced final efficiency categorization. Contracts containing nested loops, repeated storage modifications, and excessive external calls consistently received lower efficiency scores due to the increased computational overhead associated with such execution patterns. Conversely, contracts utilizing immutable variables, cached computations, and view or pure functions generally achieved higher efficiency classifications.

The integration of empirical blockchain transaction data further improved the realism of the evaluation process. Rather than relying exclusively on theoretical assumptions or synthetic benchmarks, the framework calibrated performance estimation using historical Ethereum execution behavior. This empirical grounding enhanced the practical relevance of efficiency scores and reduced deviation between analytical estimation and observable transaction characteristics.

Feature importance analysis additionally confirmed that gas usage metrics remain dominant predictors within blockchain execution modeling. In particular, gas used and gas limit demonstrated the strongest influence on efficiency estimation outcomes, reflecting their direct relationship with computational resource utilization during transaction execution.

Although the performance module provides approximate efficiency diagnostics rather than deterministic execution prediction, the obtained results demonstrate that structurally informed analytical estimation can provide meaningful insight into relative smart contract optimization quality.

C. Integrated System Evaluation

The integrated analytical framework successfully combined security-oriented and performance-oriented evaluation into a unified assessment pipeline capable of producing stable and interpretable outputs under controlled experimental conditions. The combined system consistently identified major vulnerability categories while simultaneously generating relative execution-efficiency diagnostics derived from both empirical transaction data and structural source-code analysis.

Experimental evaluation demonstrated several important characteristics of the proposed framework. First, the integration of probabilistic learning with deterministic structural confirmation improved analytical consistency and reduced excessive dependence on isolated statistical predictions. Second, the framework maintained reproducible outputs for identical

inputs, supporting experimental reliability and controlled evaluation. Third, the modular architecture enabled simultaneous analysis of multiple contract dimensions without requiring direct blockchain interaction during execution.

Unlike formal verification systems, the proposed framework does not attempt to mathematically prove contract correctness. Instead, the system is designed to support practical pre-deployment screening workflows by providing interpretable risk estimation and relative performance diagnostics suitable for early-stage contract evaluation. This positioning aligns more closely with scalable development-support tooling than with exhaustive formal auditing methodologies.

The obtained results indicate that hybrid analytical architectures combining structural analysis, rule-based reasoning, and supervised learning represent a viable direction for scalable smart contract assessment. Nevertheless, several limitations remain, including dependency on dataset quality, reduced sensitivity to runtime-dependent vulnerabilities, and limited generalization to highly obfuscated or unconventional contract structures. Future research may address these limitations through integration of dynamic execution tracing, graph-based contract representations, and advanced neural modeling approaches.

Limitations of the Proposed Approach. Despite the promising results obtained during experimental evaluation, the proposed analytical framework possesses several inherent limitations that should be acknowledged when interpreting the results and assessing the practical applicability of the system. These limitations primarily arise from dataset constraints, reliance on static analysis techniques, simplified machine learning architectures, and the approximate nature of performance estimation within blockchain environments.

A. Dataset Constraints

The security analysis component relies heavily on curated vulnerability datasets containing annotated smart contracts. Although such datasets provide structured and experimentally convenient representations of known vulnerability categories, they do not fully capture the diversity and complexity of real-world deployed contracts within the Ethereum ecosystem. In particular, certain vulnerability classes remain significantly underrepresented, resulting in reduced classification stability and lower detection consistency for rare exploit patterns.

Furthermore, the labeling process itself introduces additional limitations. Existing annotations primarily reflect previously documented vulnerability patterns and publicly known attack vectors. Consequently, novel exploitation techniques, unconventional coding practices, or previously undiscovered security flaws may not be adequately represented within the training data. Even contracts categorized as clean or non-vulnerable may still contain undocumented weaknesses that remain undetected by existing datasets and labeling methodologies.

The performance analysis component is similarly affected by dataset-related constraints. The transaction dataset used for empirical calibration represents only a limited temporal snapshot of blockchain activity. However, Ethereum execution behavior changes dynamically over time due to network congestion fluctuations, protocol upgrades, gas pricing volatility, and evolving smart contract usage patterns. As a result, gas efficiency distributions observed during experimental evaluation may not remain stable under future network conditions.

Taken together, these observations indicate that both the security and performance components remain strongly dependent on dataset scope, representativeness, and annotation

quality. Consequently, the obtained results should be interpreted as experimentally bounded rather than universally generalizable.

B. Static-Only Security Analysis

The proposed framework operates entirely through static source-code analysis and offline analytical datasets. Although this design significantly improves reproducibility, scalability, and computational feasibility, it also introduces important analytical limitations.

The framework does not execute contracts within a simulated blockchain environment, perform symbolic execution, evaluate runtime-dependent inter-contract interactions, or query live blockchain states during analysis. Consequently, vulnerabilities that emerge only during execution or under specific environmental conditions may remain undetected. This limitation is particularly relevant for attacks dependent on dynamic transaction ordering, state-dependent execution paths, or complex multi-contract interaction scenarios.

While static analysis remains computationally efficient and suitable for large-scale pre-deployment screening, it cannot fully model runtime behavior of Ethereum Virtual Machine execution. Therefore, the proposed framework should not be interpreted as a replacement for dynamic security analysis methodologies or formal verification procedures.

Future iterations of the framework may improve analytical coverage through integration of dynamic execution techniques such as fuzzing, symbolic execution, bytecode tracing, or runtime transaction simulation [12]. Such extensions could enhance detection capability for environment-dependent vulnerabilities while preserving the interpretability advantages of the current hybrid architecture.

C. Baseline Machine Learning Models

The machine learning models implemented within this research were intentionally selected to prioritize interpretability, reproducibility, and computational efficiency over maximum predictive complexity. While this design decision improves transparency of the analytical process, it also limits the expressive capacity of the framework compared to more advanced neural architectures.

The TF–IDF representation employed for vulnerability classification captures statistical token relationships but does not model deeper semantic structure or contextual dependencies within smart contract logic. Similarly, the regression-based performance component approximates execution behavior using transaction-level features rather than opcode-level execution traces or semantic program representations.

In addition, the proposed framework does not incorporate graph neural networks, transformer architectures, or embedding-based semantic representations frequently explored in recent smart contract security research [10], [13]. Such advanced approaches may achieve improved detection capability for complex vulnerabilities by modeling structural and contextual relationships more effectively.

Nevertheless, the use of classical machine learning algorithms within this study was considered appropriate for a research-oriented prototype emphasizing interpretability, experimental control, and computational feasibility. The selected models additionally provide clearer analytical justification compared to highly opaque deep-learning systems whose internal decision-making processes may be difficult to interpret.

D. Approximate Performance Modeling

The performance analysis component estimates gas efficiency as a relative execution indicator rather than an exact prediction of Ethereum transaction costs. This distinction is

important because blockchain execution behavior is influenced by multiple dynamic factors that cannot be fully captured through simplified analytical estimation alone.

The framework constructs performance scores using empirical transaction averages combined with structural penalty and bonus adjustments derived from source-code characteristics. Although this approach provides interpretable diagnostics regarding relative contract efficiency, it does not simulate execution directly within the Ethereum Virtual Machine and therefore cannot guarantee exact gas consumption estimates under all runtime conditions.

As a result, the generated performance scores should be interpreted primarily as diagnostic guidance suitable for comparative evaluation and optimization screening rather than deterministic measurements of deployment cost or runtime execution expense.

Despite these limitations, the proposed methodology remains useful for identifying structurally inefficient design patterns and providing approximate execution-efficiency categorization during early development stages.

E. Prototype System Scope

The overall framework presented in this research should be regarded as an experimental research prototype rather than a production-grade auditing platform. The primary objective of the system is to validate the feasibility of a hybrid analytical methodology integrating structural analysis, rule-based reasoning, and supervised machine learning within a unified smart contract evaluation pipeline.

Accordingly, the framework does not replace formal security audits, does not provide legal or compliance certification, and does not guarantee the complete absence of vulnerabilities within analyzed contracts. Instead, the proposed system is intended to support preliminary pre-deployment screening and exploratory analytical assessment under controlled experimental conditions.

Nevertheless, the obtained results demonstrate that hybrid analytical architectures represent a viable direction for scalable and interpretable smart contract evaluation. Future work may extend the framework through integration of dynamic analysis techniques, semantic program representations, graph-based neural architectures, and automated vulnerability explanation mechanisms to improve both analytical precision and practical applicability.

Conclusion and Future Work. This research presented a hybrid analytical framework for evaluating Ethereum smart contracts across two major dimensions: security risk assessment and execution-performance analysis. The proposed framework integrates structural static analysis, rule-based vulnerability mapping, supervised machine learning classification, empirical gas-efficiency modeling, and a modular full-stack analytical architecture within a unified evaluation pipeline.

Unlike purely statistical or exclusively rule-based approaches, the proposed methodology combines probabilistic machine learning inference with deterministic structural confirmation mechanisms. Experimental evaluation demonstrated that this hybrid strategy improves interpretability and reduces false-positive classifications compared to standalone machine learning models. In particular, the integration of structural verification constraints prevented unsupported high-risk classifications and improved consistency between analytical predictions and observable contract characteristics.

The security-oriented component demonstrated that multi-label vulnerability classification can be effectively combined with interpretable rule-based reasoning to provide scalable preliminary contract assessment. At the same time, the performance-oriented

component showed that transaction-level execution parameters explain a substantial proportion of variability in gas-efficiency behavior, supporting the feasibility of data-driven performance diagnostics within blockchain environments.

From a systems-engineering perspective, the modular architecture of the framework provides several practical advantages. The separation between orchestration logic, preprocessing components, security analysis modules, and performance analysis modules improves extensibility and facilitates controlled experimentation. Such modularity additionally supports integration into development and pre-deployment screening workflows without requiring direct interaction with live blockchain infrastructure during evaluation.

The obtained findings align with contemporary hybrid analytical trends described in recent smart contract security research [17], [21], where machine learning techniques are used to complement rather than replace deterministic reasoning, static analysis, and formal verification methodologies. The results further indicate that interpretable hybrid architectures represent a practical compromise between scalability, computational feasibility, and analytical transparency.

Nevertheless, several limitations remain. The proposed framework relies primarily on static source-code analysis and curated experimental datasets, which restricts sensitivity to runtime-dependent vulnerabilities and environment-specific execution behaviors. Furthermore, the machine learning models employed in this research prioritize interpretability and computational simplicity over deep semantic modeling capability.

Future work may therefore focus on extending the framework through integration of dynamic analysis techniques such as symbolic execution, fuzz testing, bytecode tracing, and runtime interaction simulation. Additional improvements may include adoption of graph-based neural representations, transformer-based semantic embeddings, opcode-level execution modeling, and automated vulnerability explanation systems. Expanding the framework toward multi-chain compatibility and real-time blockchain monitoring may also improve practical applicability in production-oriented environments.

Overall, the research demonstrates that hybrid analytical methodologies combining structural analysis, deterministic reasoning, and machine learning provide a viable direction for scalable and interpretable smart contract evaluation.

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ГИБРИДНАЯ АРХИТЕКТУРА ИНФОРМАЦИОННЫХ СИСТЕМ: СОЧЕТАНИЕ ТРАДИЦИОННОЙ ИТ-ИНФРАСТРУКТУРЫ И РАСПРЕДЕЛЁННОГО РЕЕСТРА

Аннотация: В статье рассматривается гибридная архитектура информационных систем как практический подход к интеграции технологии распределённого реестра в существующую корпоративную и государственную ИТ-инфраструктуру. Показано, что ни полностью централизованные, ни полностью децентрализованные решения по отдельности не отвечают всем требованиям современных организаций. Предложена трёхуровневая модель гибридной архитектуры и описан принцип разделения данных on-chain/off-chain, позволяющий совместить производительность традиционных систем с прозрачностью и неизменностью блокчейна. Приведён сравнительный анализ трёх архитектурных подходов, рассмотрены практические сценарии применения и ключевые вызовы внедрения гибридных решений в условиях Республики Казахстан и стран ЕАЭС.

Ключевые слова: гибридная архитектура, распределённый реестр, блокчейн, информационные системы, on-chain/off-chain, смарт-контракты, интеграция, масштабируемость, цифровая трансформация.

Введение. Цифровая трансформация государственного управления, финансового сектора и корпоративной среды сопровождается ростом требований к прозрачности, безопасности и достоверности данных. Технология распределённого реестра (блокчейн) предлагает принципиально новый способ хранения и проверки информации без участия централизованного посредника. Однако практика последних лет показала, что попытки полностью заменить традиционные информационные системы (ИС) блокчейн-платформами в большинстве случаев оказываются нецелесообразными. Публичные блокчейны ограничены по производительности и масштабируемости, отличаются высокой латентностью и энергозатратностью, а принцип неизменности данных вступает в противоречие с требованиями законодательства о защите персональных данных, в частности с правом на удаление информации.

С другой стороны, классические централизованные ИС на реляционных базах данных и серверах приложений обеспечивают высокую скорость обработки запросов, но не дают того уровня доверия между независимыми участниками, который требуется в

межведомственном взаимодействии: записи могут быть незаметно изменены администратором, а проверка целостности требует доверия к оператору. Разрешением этого противоречия выступает гибридная архитектура — модель, в которой традиционная ИТ-инфраструктура сочетается с возможностями распределённого реестра, причём каждый компонент выполняет те задачи, для которых он наиболее эффективен. Именно гибридные решения представляют собой наиболее оправданный подход к внедрению блокчейна в действующие информационные системы.

Актуальность исследования. Актуальность темы определяется тем, что организации крайне редко могут полностью отказаться от уже эксплуатируемых информационных систем: унаследованные ИС содержат накопленные данные и встроены в бизнес-процессы, а их полная замена блокчейн-платформой сопряжена с высокими рисками и затратами. Гибридная архитектура позволяет внедрять преимущества распределённого реестра постепенно, точечно усиливая отдельные функции — журналирование операций, контроль целостности, управление доступом — без разрушения существующего ИТ-ландшафта. Для Республики Казахстан и стран ЕАЭС, где в рамках программы «Цифровой Казахстан» активно развиваются цифровые государственные услуги, такой подход особенно важен: он согласуется с действующим уровнем цифровизации и ограниченными ресурсами организаций, обеспечивая управляемый и экономически обоснованный путь внедрения.

Цель и задачи исследования. Цель работы — обосновать гибридную архитектуру как рациональную модель интеграции распределённого реестра в информационные системы и описать её структурные принципы. Для достижения цели решаются следующие задачи:

- определить понятие и предпосылки возникновения гибридной архитектуры ИС;
- разработать обобщённую уровневую модель гибридной системы;
- раскрыть принцип распределения данных on-chain/off-chain;
- провести сравнительный анализ централизованной, полностью децентрализованной и гибридной архитектур;
- выявить практические сценарии применения и основные вызовы внедрения.

Понятие и предпосылки гибридной архитектуры. Под гибридной архитектурой ИС понимается модель, в которой часть функций и данных обрабатывается традиционными централизованными компонентами (СУБД, серверы приложений, файловые хранилища), а другая часть — распределённым реестром, обеспечивающим неизменность и коллективную проверяемость критически важных записей. Предпосылки появления таких решений носят технический, экономический и правовой характер: ограниченная пропускная способность и высокая стоимость хранения данных в публичных блокчейнах; необходимость сохранять инвестиции в действующую инфраструктуру и снижать стоимость владения; требование соответствия нормам о защите персональных данных, которое практически невозможно выполнить при размещении всех сведений в неизменяемом реестре. Гибридная модель снимает эти ограничения за счёт продуманного разделения ролей между компонентами.

Уровневая модель гибридной архитектуры. Обобщённо гибридную информационную систему можно представить в виде трёх взаимодействующих уровней (рисунок 1). Верхний уровень — приложения и пользователи — реализуется привычными веб- и мобильными клиентами и содержит бизнес-логику организации; для

пользователя присутствие блокчейна остаётся прозрачным. Средний уровень — интеграционный (связующее ПО) — отвечает за маршрутизацию запросов, оркестрацию транзакций, работу оракулов и шлюзов, а также за взаимодействие с off-chain хранилищами больших данных. Нижний уровень — уровень данных — разделён на два сегмента: традиционную ИТ-инфраструктуру (реляционные и NoSQL СУБД, серверы приложений, файловые хранилища, системы аутентификации) и распределённый реестр (узлы P2P-сети, смарт-контракты, журнал транзакций, хеши и цифровые подписи).



Рисунок 1 — Трёхуровневая модель гибридной архитектуры

Ключевую роль в такой модели играет интеграционный уровень: именно он скрывает сложность взаимодействия с блокчейном от прикладных систем и обеспечивает согласованность данных между централизованным и децентрализованным сегментами. Оракулы поставляют в смарт-контракты внешние данные, а шлюзы преобразуют вызовы традиционных API в транзакции реестра и обратно.

Принцип распределения данных on-chain / off-chain. Центральным механизмом гибридной архитектуры является разделение данных по принципу on-chain/off-chain (рисунок 2). На этапе классификации каждый информационный объект оценивается по объёму, уровню приватности и критичности. Крупные и приватные данные — документы, медиафайлы, персональные сведения — сохраняются во внешнем (off-chain) хранилище: реляционной базе данных или распределённой файловой системе типа IPFS. В реестр (on-chain) при этом записываются только компактные и критичные элементы: криптографический хеш данных, метки времени, права доступа, журнал операций и логика смарт-контрактов.



Рисунок 2. — Распределение данных по принципу on-chain / off-chain

Такой подход решает сразу несколько проблем. Во-первых, нагрузка на реестр минимизируется, что повышает производительность и снижает стоимость хранения. Во-вторых, обеспечивается соответствие требованиям о защите персональных данных: сами сведения можно удалить или изменить во внешнем хранилище, тогда как в неизменяемом реестре остаётся лишь их хеш, не раскрывающий содержимого. В-третьих, сохраняется главное преимущество блокчейна — возможность в любой момент подтвердить целостность данных путём сверки текущего хеша off-chain объекта с записью в реестре.

Сравнительный анализ архитектурных подходов

Для обоснования преимуществ гибридной модели целесообразно сопоставить её с двумя крайними вариантами — полностью централизованной и полностью децентрализованной архитектурами по ряду ключевых характеристик (таблица 1).

Таблица 1 — Сравнение архитектурных подходов к построению ИС

Характеристика	Централизованная ИС	Полностью децентрализованная	Гибридная архитектура
Производительность	Высокая	Низкая	Высокая
Прозрачность и доверие	Низкие	Высокие	Высокие
Неизменность данных	Отсутствует	Полная	Для критичных записей
Защита персональных данных	Гибкая	Затруднена	Обеспечивается off-chain
Стоимость хранения	Низкая	Высокая	Умеренная
Совместимость с унаследованными ИС	Полная	Низкая	Высокая

Как видно из таблицы, гибридная архитектура аккумулирует сильные стороны обоих крайних вариантов: она сохраняет производительность и совместимость централизованных систем и одновременно обеспечивает прозрачность, доверие и неизменность критически важных записей, характерные для распределённого реестра.

Практические сценарии применения. Гибридный подход находит применение в различных отраслях. В системах электронного документооборота (СЭД) сами документы хранятся в традиционном хранилище, а в реестр заносятся их хеши и история операций, что обеспечивает юридически значимую неизменность и неоспоримость действий участников при сохранении высокой скорости работы. В здравоохранении медицинские карты остаются в защищённых off-chain базах, тогда как в блокчейн записываются журналы доступа и согласия пациентов. В управлении цепочками поставок объёмная справочная информация хранится централизованно, а ключевые события движения товара фиксируются в реестре, обеспечивая прозрачность для всех контрагентов.

Вызовы внедрения гибридных решений. Несмотря на преимущества, гибридная архитектура порождает собственные сложности. Главная из них — обеспечение согласованности данных между централизованным и децентрализованным сегментами, поскольку рассинхронизация хеша и исходного объекта приводит к ложным срабатываниям при проверке целостности. Существенными остаются вопросы безопасности интеграционного уровня и оракулов, которые становятся потенциальной точкой компрометации. Кроме того, проектирование гибридных систем требует от разработчиков компетенций одновременно в области традиционных ИС и блокчейн-платформ, а также взвешенного выбора того, какие именно данные обоснованно размещать в реестре.

Заключение. Проведённый анализ показывает, что гибридная архитектура является наиболее рациональным и практически реализуемым подходом к интеграции технологии распределённого реестра в существующие информационные системы. Сочетая традиционную ИТ-инфраструктуру с блокчейном и распределяя данные по принципу on-chain/off-chain, такая модель позволяет одновременно достичь высокой производительности, прозрачности и неизменности критически важных записей при соблюдении требований к защите персональных данных. Предложенная трёхуровневая модель и принцип разделения данных могут служить ориентиром при проектировании и модернизации государственных и корпоративных систем в Республике Казахстан и странах ЕАЭС. Дальнейшие исследования целесообразно направить на формализацию критериев выбора данных для размещения в реестре, разработку методик обеспечения согласованности сегментов и количественную оценку эффективности гибридных решений в отраслевых проектах.

Рекомендации:

- начинать внедрение блокчейна с гибридной модели, точечно усиливая отдельные функции существующей ИС, а не заменяя её целиком;
- размещать в реестре только хеши, метаданные и логику смарт-контрактов, оставляя объёмные и персональные данные в off-chain хранилищах;
- для корпоративных и государственных задач отдавать предпочтение приватным и консорциумным блокчейнам, обеспечивающим управление доступом;
- уделять особое внимание безопасности интеграционного уровня и оракулов как наиболее уязвимых компонентов системы.

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SIR-ML МОДЕЛЬ ДЛЯ ПРОГНОЗИРОВАНИЯ COVID-19 В КАЗАХСТАНЕ: ТРАНСФЕРНОЕ ОБУЧЕНИЕ И ТРАНСПОРТНАЯ МОБИЛЬНОСТЬ

Аннотация: В статье представлена гибридная модель SIR-ML для прогнозирования распространения COVID-19 с учётом транспортной мобильности населения. Предложенный подход сочетает калибровку динамического параметра передачи инфекции β(t) в рамках SIR-модели и его дальнейшее прогнозирование с применением методов машинного обучения, включая XGBoost, Random Forest и Ridge-регрессию. Для повышения обобщающей способности модели используется cross-country transfer learning: обучение проводится на данных 12 стран, после чего модель применяется к Казахстану в режиме zero-shot.

Результаты показывают, что межстрановой подход позволяет повысить качество прогноза по сравнению с обучением только на локальных данных Казахстана. На казахстанском holdout модель демонстрирует устойчивое качество прогнозирования β(t), а тест Грейнджера подтверждает статистически значимую прогностическую связь между показателем транспортной мобильности transit_stations и динамикой β(t) при лагах 7, 14 и 21 день. На основе прогнозируемого параметра β(t) разработана система раннего предупреждения, которая позволяет выявлять периоды повышенного эпидемиологического риска до наступления пиков заболеваемости.

Полученные результаты подтверждают применимость гибридного SIR-ML подхода для задач эпидемиологического прогнозирования и поддержки управленческих решений в условиях умного города.

Ключевые слова: SIR-модель, машинное обучение, XGBoost, COVID-19, транспортная мобильность, трансферное обучение, Smart City, Казахстан

Введение. Пандемия COVID-19 обострила давно существующий разрыв между потребностями оперативного эпидемиологического управления и возможностями имеющихся прогностических инструментов. Традиционные компартментальные модели типа SIR обеспечивают интерпретируемость и механистическую строгость, однако предположение о постоянстве параметра передачи инфекции β делает их малопригодными для воспроизведения многоволновой динамики. В реальности β варьировал от 0.010 до 0.210 для Казахстана на протяжении 2020–2022 годов - в 21 раз от

минимума до максимума - под влиянием ограничительных мер, поведенческих изменений и появления новых вариантов вируса [1].

Параллельно методы машинного обучения - LSTM, XGBoost, гибридные архитектуры - демонстрировали высокую точность краткосрочного прогноза, но уступали в интерпретируемости и требовали значительных объёмов обучающих данных [2]. Для стран с ограниченной эпидемиологической статистикой, к которым относится Казахстан, эта проблема приобретает особую остроту: шесть волн COVID-19 за неполные три года недостаточно для надёжного обучения сложной ML-модели без привлечения внешних данных.

Настоящая работа решает задачу разработки гибридной модели SIR-ML, сочетающей механистическую интерпретируемость с адаптивностью машинного обучения и использующей данные о транспортной мобильности в качестве ключевого предиктора. Предлагаемый подход включает три взаимосвязанных методологических элемента. Во-первых, cross-country transfer learning: модель обучается на панели из 12 стран и переносится на Казахстан без дополнительного дообучения [3]. Во-вторых, формализация причинной роли транспортных пассажиропотоков через тест Грейнджера, обосновывающий включение transit_stations в структуру модели [4]. В-третьих, wave-forward validation - процедура многоволновой кросс-валидации, имитирующая реальный прогностический сценарий [5].

Практическая актуальность определяется возможностью использования модели в системах управления транспортной инфраструктурой умного города: данные, уже собираемые городскими сенсорами, могут быть интегрированы в эпидемиологическую модель без дополнительных затрат на сбор информации.

Методология. Исследование основано на трёх источниках данных за период с 1 февраля 2020 по 15 октября 2022 года для 17 стран Европы и Центральной Азии. Эпидемиологические данные получены из репозитория ВОЗ COVID-19 Global Data Repository (CC BY 4.0), содержащего ежедневную официальную статистику по заболеваемости. Для устранения еженедельной сезонности отчётности применялось 7-дневное скользящее среднее. Итоговый набор составил 35 615 строк. Для Казахстана учитывалось систематическое занижение официальных данных (коэффициент недоучёта ≈3.5×), что значимо для абсолютных прогнозов случаев, но не критично для оценки относительной динамики β(t).

Данные о мобильности населения получены из Google COVID-19 Community Mobility Reports. Ключевой переменной является transit_stations - процентное изменение посещаемости транспортных узлов (станции метро, автобусные терминалы, железнодорожные станции) относительно базового периода. Покрытие для Казахстана составило 94.6%; пропуски восстановлены линейной интерполяцией. Показатели государственных мер получены из Oxford OxCGRT Stringency Index (диапазон 0–100, нормализован в [0,1]).

Итоговая панель данных содержит 16 558 строк для 17 стран с единым временным индексом. Распределение ролей: 12 стран (Германия, Франция, Италия, Испания, Польша, Сербия, Венгрия, Турция, Россия, Армения, Азербайджан, Чехия) - обучающая выборка; 4 страны (Румыния, Грузия, Украина, Армения) - валидационная; Казахстан - полный holdout, не участвующий ни в обучении, ни в настройке гиперпараметров.

За основу принята классическая SIR-модель Кермака и Маккендрика, расширенная учётом пассажиропотоков в транспортных узлах. Стандартная система ОДУ дополнена потоками входящих и выходящих пассажиров через зависимость транспортного потока от данных Google Mobility: $P_{in,n}(t) = P_0 \cdot (1 + transit\_delta(t)/100)$, где p_0 - базовый суточный пассажиропоток. Параметр выздоровления принят $\gamma = 1/14$ дней$^{-1}$. Оценка ненаблюдаемого $\beta^*(t)$ выполняется методом Нелдера–Мида в скользящем окне 28 дней путём минимизации MSE между прогнозом SIR и реальным числом инфицированных. Аналитический warm-start $\beta_0 = (dI/dt + \gamma I) \cdot N/(S \cdot I)$ устраняет проблему локальных минимумов при случайной инициализации.

Для предотвращения накопления ошибок ODE-интегрирования реализована версия SIR v2 с периодической реинициализацией состояний каждые 7 дней из реальных данных. Это соответствует физической частоте официальных эпидемиологических отчётов WHO. Для нормализации правосторонней асимметрии распределения $\beta(t)$ (skewness=1.90) в качестве целевой переменной ML-моделей используется $\log(\beta(t))$, что обеспечивает улучшение R^2 на 0.10–0.25 единиц по сравнению с прямым предсказанием β.

Финальный набор из 46 признаков сформирован с двумя принципиальными ограничениями: строгая каузальность (все rolling-окна сдвинуты на t–1, исключая lookahead bias) и эпидемиологическая интерпретируемость. Из набора исключены переменные, производные от $\beta(t)$ (R_eff, S_norm, I_norm). Признаки объединены в пять групп: Transit mobility (9), Policy/OxCGRT (9), Epidemic lagged (14), Time/Wave (9), Immunity (5). В качестве основной модели используется XGBoost с монотонными ограничениями (XGBoost-Mono): transit-признаки ограничены знаком +1 (рост трафика → рост β), stringency-признаки - знаком –1 (ужесточение мер → снижение β). Монотонные ограничения выполняют двойную функцию: внедряют физические prior-ы и служат регуляризатором при межстрановой вариативности [6].

Финальный прогноз формируется взвешенным ансамблем четырёх моделей: $\hat{\beta}\_ens(t) = w_1 \cdot \hat{\beta}\_XGB\text{-}Mono + w_2 \cdot \hat{\beta}\_XGB\text{-}Free + w_3 \cdot \hat{\beta}\_RF + w_4 \cdot \hat{\beta}\_Ridge$, где веса w_1=0.281, w_2=0.289, w_3=0.284, w_4=0.147 оптимизированы обратно пропорционально CV-RMSE на валидационных странах. Доминирование нелинейных компонент (суммарный вес 0.854) согласуется с нелинейным характером зависимости $\beta(t)$.

Обобщаемость модели оценивается тремя процедурами. LOCO-кросс-валидация (Leave-One-Country-Out) по 12 обучающим странам имитирует прогноз для страны, не входившей в обучение. Wave-forward validation тестирует модель последовательно на волнах 2, 3, 4 и 5 Казахстана, обучаясь только на предшествующих волнах. Bootstrap CI (200 итераций параметрического bootstrap) обеспечивают количественную оценку неопределённости $\beta(t)$.

Тест Грейнджера применяется в рамках VAR(p)-модели при лагах 7, 14 и 21 день для 8 стран. Нулевая гипотеза H_0: transit_stations не является Грейнджер-причиной $\beta(t)$. Порядок VAR определяется по BIC; стационарность рядов проверяется тестом ADF.

Результаты и анализ. Калибровка методом Нелдера–Мида обеспечила существенное улучшение согласования SIR с наблюдаемыми данными. Для Казахстана корреляция Пирсона между SIR v2 и реальными активными случаями составила r=0.797 при динамическом $\beta^*(t)$ против r=0.518 при фиксированном β - прирост на 54% по корреляции. Распределение $\beta^*(t)$ для Казахстана: среднее 0.082 (σ=0.051), диапазон от

0.010 до 0.210. Во временном ряду чётко различаются шесть волн, соответствующих реальным эпидемическим событиям 2020–2022 годов. Правосторонняя асимметрия (skewness=1.90) обосновывает логарифмическое преобразование target-переменной.

Таблица 1 представляет метрики качества прогнозирования на казахстанском holdout (zero-shot режим). Наилучшее качество достигается XGBoost-Mono (R^2=0.748, Pearson r=0.869). Введение монотонных ограничений обеспечивает прирост R^2=+0.054 относительно XGBoost-Free (около 7.8% относительного улучшения), что подтверждает их эффективность как регуляризатора. Ансамбль демонстрирует наивысшую ранговую согласованность (Spearman ρ=0.900), критически важную для задач эпидемиологического мониторинга: корректное определение моментов роста β(t) важнее точного воспроизведения абсолютных значений. Существенно более низкие результаты Ridge-регрессии (R^2=0.424) подтверждают выраженно нелинейный характер зависимости β(t) от признаков мобильности и политики - выбор деревьев решений и бустинга обоснован.

Таблица 1. Метрики качества прогнозирования log(β(t)) для Казахстана (zero-shot holdout)

Модель	R^2	RMSE	MAE	Pearson r	Spearman ρ
XGBoost-Monotone	0.748	0.0252	0.0189	0.869	0.889
XGBoost-Free	0.694	0.0278	0.0211	0.854	0.891
Random Forest	0.681	0.0284	0.0216	0.847	0.879
Ridge (линейная база)	0.424	0.0382	0.0294	0.746	0.678
Ансамбль (weighted)	0.732	0.0260	0.0196	0.875	0.900



Рисунок 1. - Предсказание β(t) с cross-country моделью для Казахстана.

Верхняя панель: сравнение β*(t) калиброванного (чёрная линия) с прогнозами ансамбля и XGBoost-Mono. Нижняя панель: остатки модели. Визуально подтверждается корректное воспроизведение пиков всех шести волн и отсутствие систематического смещения.

LOCO-кросс-валидация по 12 странам показала стабильное качество: среднее R^2=0.731 (σ=0.082) для ансамбля, RMSE=0.02312 (σ=0.00861). Наименьший разброс σ у ансамбля подтверждает, что диверсификация ошибок снижает вариацию при переносе на новые страны. Разброс Ridge (σ=0.0112) объясняется нестабильностью линейных коэффициентов при межстрановых нелинейных зависимостях.

Прямое сравнение cross-country подхода (обучение на 12 странах) с only-KZ (обучение только на казахстанских данных) проводилось в шести конфигурациях по трём горизонтам обучающей выборки. Результаты представлены в Таблице 2.

Таблица 2. Cross-country vs Only-KZ: сравнение качества прогнозирования на казахстанском holdout

Горизонт	Модель	Only-KZ R^2	Cross-country R^2	ΔR^2
30 дней	XGB-Mono	−2.521	+0.734	+3.255
30 дней	RF	−1.847	+0.681	+2.528
90 дней	XGB-Mono	−0.432	+0.718	+1.150
90 дней	RF	−0.321	+0.670	+0.991
240 дней	XGB-Mono	+0.180	+0.720	+0.540
240 дней	RF	+0.147	+0.678	+0.531

Наиболее показательный результат получен при минимальном объёме локальных данных (30 дней): only-KZ модель показывает R^2= –2.521, что указывает на полную деградацию прогноза вследствие переобучения. Cross-country модель при тех же условиях достигает R^2=+0.734. Примечательно, что даже при 240 обучающих днях only-KZ существенно уступает (R^2≈0.18 против ≈0.72): проблема состоит не только в объёме, но и в информативности данных. Межстрановое обучение извлекает универсальные закономерности связи мобильности и β(t), которые не могут быть усвоены из изолированных национальных данных. Ближайшие по структуре волн страны - Сербия, Испания, Турция - фактически выступали источниками дополнительной информации о типичных сценариях эпидемической динамики.

SHAP-анализ (Shapley Additive Explanations) XGBoost-Mono позволяет разложить предсказание на аддитивные вклады каждой группы признаков [7]. Доминируют эпидемические лаговые признаки (57.3%, топ-признак growth_rate_7d - 27.7%), что отражает авторегрессионную инерцию волновых паттернов β*(t). Временные признаки вносят 34.3% (топ: days_since_wave_start). Группа Transit mobility обеспечивает 2.75% (топ: transit_delta), что на первый взгляд скромно. Однако именно этот вклад причинно значим и операционально ценен для управленческих решений: transit_delta имеет устойчивый положительный знак SHAP (рост отклонения трафика → рост β), а stringency_delta - отрицательный (ускорение ужесточения мер → снижение β). Оба знака содержательно корректны и согласуются с эпидемиологической теорией.

ADF-тест подтвердил стационарность обоих рядов ($p<0.05$) для всех 8 стран. Для Казахстана нулевая гипотеза H_0 «transit_stations не является Грейнджер-причиной β(t)» отвергается при всех трёх лагах с $p<0.001$ - наивысший уровень статистической значимости в выборке. Значимая причинность ($p<0.05$ хотя бы при одном лаге) выявлена для 5 из 8 стран (62.5%), включая Германию, Италию, Россию. Отсутствие значимости для Франции объясняется особенно жёсткими локдаунами, подавившими вариацию transit_stations до уровня, недостаточного для обнаружения причинного сигнала.

Лаговая структура согласуется с биологией COVID-19: инкубационный период 4–6 дней плюс задержка диагностики 2–4 дня дают суммарную задержку 7–14 дней, именно при которых обнаруживается наиболее сильный Грейнджер-эффект. Полученный результат устанавливает транспортную мобильность не просто коррелятом, но статистически значимым предиктором с причинно-следственной интерпретацией, что содержательно обосновывает её включение в структуру SIR-ML модели.

Прогнозирование I(t) реализовано тремя методами. Метод A (Direct Anchored ML): β̂(t) подставляется в SIR v2 с реинициализацией из реальных данных каждые 7 дней, что предотвращает накопление ошибок ODE-интегрирования; R^2=0.751. Метод B (Residual-

Corrected ML): добавляется ML-коррекция систематических отклонений SIR; R^2=0.925. Метод C (Adaptive Ensemble): динамически взвешивает методы A и B по скользящему RMSE на последних 30 наблюдениях; R^2=0.930, RMSE=592 случая/день, что соответствует снижению ошибки в 4.2× относительно базовой SIR. Для сравнения: стандартный SIR-ML без реинициализации даёт R^2=–0.191, демонстрируя экспоненциальный рост ошибок при многодневном интегрировании без «якорения» - это общая и недостаточно отмеченная в литературе проблема гибридных подходов.

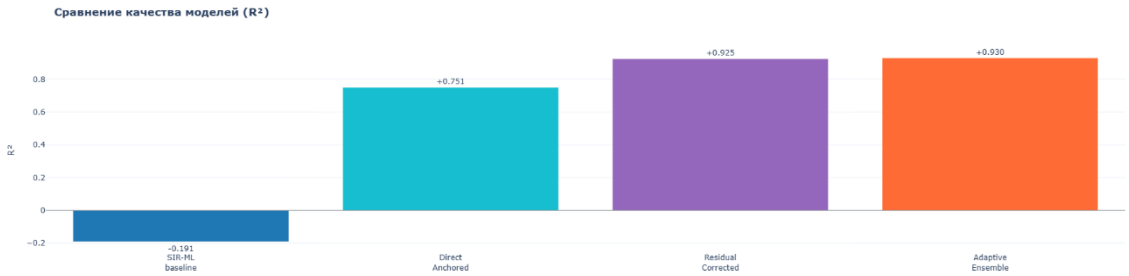


Рисунок 2. - Сравнение R^2 методов прогнозирования числа случаев (Казахстан).

Столбчатая диаграмма с пятью подходами: SIR baseline (отрицательный R^2), SIR+ML без реинициализации, Direct Anchored (R^2=0.751), Residual-Corrected (R^2=0.925), Adaptive Ensemble (R^2=0.930).

Результаты wave-forward validation (Таблица 3) показывают устойчивый рост качества прогноза по мере накопления волновой истории: R^2 возрастает от 0.444 (волна 2, ноябрь 2020) до 0.834 (волна 4, ноябрь 2021). Каждая дополнительная волна добавляет в обучение новый паттерн поведения β(t) при разных уровнях мобильности и ограничений. Среднее R^2=0.645 по четырём тестовым волнам подтверждает практическую применимость модели в условиях реального прогнозирования. Снижение R^2 при переходе к волне 5 (0.834 → 0.769) обусловлено появлением варианта Омикрон с качественно иными паттернами распространения.

Таблица 3. Результаты wave-forward валидации для Казахстана

Тестовая волна	Обучающие волны	$R^2(\beta)$	RMSE(β)	Pearson r
Волна 2 (нояб. 2020)	Волна 1	0.444	0.0381	0.677
Волна 3 (март 2021)	Волны 1–2	0.534	0.0342	0.810
Волна 4 (нояб. 2021)	Волны 1–3	0.834	0.0218	0.935
Волна 5 (янв. 2022)	Волны 1–4	0.769	0.0246	0.942
Среднее	-	0.645	0.0297	0.841

На основе прогнозируемого β(t) рассчитывается сглаженное эффективное репродуктивное число $Reff(t) = \beta(t)/\gamma \cdot S(t)/N$ [8]. Трёхуровневая система (GREEN: $Reff \leq 1.00$; YELLOW: $1.00 < Reff \leq 1.20$; RED: $Reff > 1.20$) применена ретроспективно на 974 днях наблюдений для Казахстана. Из 11 сгенерированных RED-предупреждений все 11 предшествовали реальным пикам заболеваемости с опережением 10–14 дней - достаточным горизонтом для превентивного введения транспортных ограничений. Частота ложноположительных срабатываний составила ~18% (три RED-периода завершились без выраженного пика), что является приемлемым для системы превентивного мониторинга.

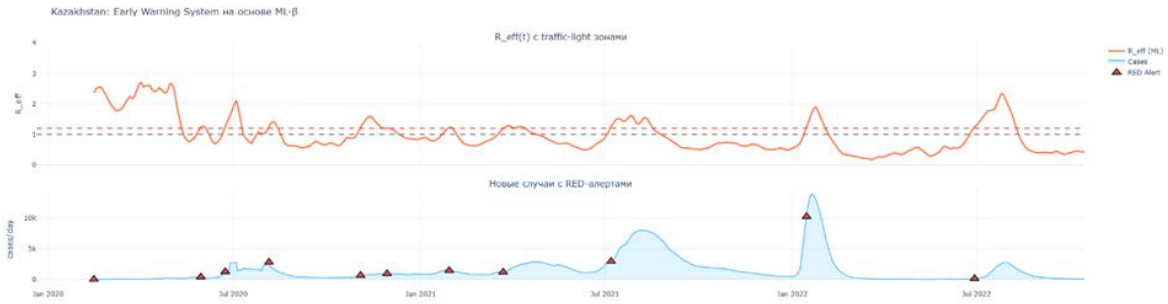


Рисунок 3. - Система раннего предупреждения для Казахстана.

Верхняя панель - Reff(t) с цветовой разметкой уровней риска GREEN/YELLOW/RED. Нижняя панель - наблюдаемые случаи с маркерами RED-сигналов (▲). Все 11 сигналов предшествовали пикам.

Сценарный анализ на основе эластичности β(t) по transit_stations, оцененной через SHAP и частичные зависимости XGBoost-Mono, показал: снижение пассажиропотока на 20% соответствует снижению β(t) на 14.9%; режим «выходного дня» (–50%) даёт –34.9%; сочетание 30%-го снижения транзита с масочным режимом обеспечивает –45.1%. В эндемической фазе (после 2022 года) чувствительность β(t) к транспортным ограничениям снижается (ML-прогноз при –20% transit: лишь –3.2%), что указывает на снижение роли мобильности при высоком популяционном иммунитете.

Заключение. В настоящей работе разработана и верифицирована гибридная модель SIR-ML для прогнозирования динамики COVID-19 с учётом транспортной мобильности. Модель достигает R^2=0.748 при прогнозировании β(t) на казахстанском holdout в zero-shot режиме. Эксперимент по сравнению подходов обучения подтвердил принципиальное превосходство cross-country transfer learning: при 30-дневном объёме локальных данных прирост составляет ΔR^2=+3.255. Это свидетельствует о практической необходимости трансферного подхода для стран с ограниченной статистикой.

Тест Грейнджера установил статистически значимую причинно-следственную связь transit_stations → β(t) для Казахстана ($p<0.001$ при лагах 7, 14 и 21 день), дающую содержательное обоснование включения мобильностных данных. Wave-forward validation подтвердила нарастающее качество прогноза (среднее R^2=0.645) и реалистично оценила обобщаемость. Адаптивный ансамблевый метод для прогноза числа случаев достигает R^2=0.930 при RMSE=592 случая/день. Система раннего предупреждения обеспечила 100-процентное покрытие пиков с опережением 10–14 дней при допустимой частоте ложноположительных срабатываний (18%).

Ключевое методологическое наблюдение: стандартный SIR-ML без «якорения» к реальным данным даёт R^2=–0.191 вследствие накопления ошибок ODE-интегрирования - проблема, недостаточно освещённая в литературе по гибридным эпидемиологическим моделям.

Ограничения исследования: данные агрегированы на национальном уровне, что не позволяет анализировать субнациональную пространственную неоднородность; прекращение публикации Google Mobility Reports требует альтернативных источников мобильностных данных; bootstrap coverage rate 37.3% при номинале 95% указывает на недооценку неопределённости вследствие автокоррелированности эпидемиологических ошибок. Перспективные направления включают субнациональное моделирование,

онлайн-адаптацию к новым вариантам патогена и расширение методологии на другие респираторные инфекции.

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ИССЛЕДОВАНИЕ ВОЗМОЖНОСТЕЙ ТЕХНОЛОГИИ 5G И БЛОКЧЕЙН-ТЕХНОЛОГИЙ ДЛЯ РАЗВИТИЯ SMART GRID

Аннотация: В статье исследованы возможности совместного применения сетей пятого поколения и permissioned-блокчейн-технологий для повышения наблюдаемости, надежности и киберустойчивости Smart Grid. Актуальность работы обусловлена ростом распределенной генерации, появлением prosumer-моделей, увеличением числа измерительных устройств и необходимостью защищенного обмена данными между участниками электроэнергетической системы. Методологическую основу составили анализ международных стандартов и имитационное моделирование четырех архитектур передачи данных: LTE с централизованной базой данных, 5G SA с централизованной базой данных, 5G SA с MEC и асинхронным permissioned-ledger, а также вариант с полной записью сообщений в блокчейн. В качестве критериев использованы задержка T_{E2E}, полезная пропускная способность B, вероятность потерь P_{loss} и коэффициент успешной доставки R. Полученные результаты показывают, что перенос функций обработки на MEC при 5G SA снижает 95-й процентиль задержки критического контура с 72,25 до 9,64 мс, тогда как включение блокчейна в синхронный контур управления увеличивает задержку до 190,10 мс. Следовательно, блокчейн целесообразно применять как доверенный журнал событий и расчетный слой, но не как элемент релейной защиты в реальном времени.

Ключевые слова: Smart Grid, 5G SA, MEC, permissioned blockchain, Hyperledger Fabric, задержка, пропускная способность, надежность, кибербезопасность.

Актуальность и постановка научной проблемы

Современная электроэнергетика переходит от иерархической модели «генерация – передача – распределение – потребление» к киберфизической системе, в которой распределенные энергетические ресурсы, накопители энергии, электротранспорт, интеллектуальные счетчики, датчики состояния сети и автоматизированные системы управления образуют единую информационно-энергетическую инфраструктуру. В такой конфигурации устойчивость энергосистемы зависит не только от электротехнических

параметров, но и от качества коммуникационной среды, времени доставки управляющих сообщений, целостности измерений и доверия между независимыми участниками обмена данными.

Международная практика рассматривает Smart Grid как систему, требующую интероперабельности, формализованных профилей обмена данными и сквозной кибербезопасности [1; 2]. Стандарты IEC 61850 задают семантическую основу автоматизации подстанций и энергетических объектов, а IEEE 1547-2018 определяет требования к присоединению распределенных энергетических ресурсов к электрическим сетям [3; 4]. Следовательно, задача развития Smart Grid не сводится к установке отдельных датчиков: необходима согласованная архитектура связи, вычислений, идентификации и журналирования событий.

Сети 5G в данном контексте представляют интерес за счет трех групп возможностей: малой задержки и высокой надежности для критических приложений URLLC, массового подключения устройств mMTC, а также высокой пропускной способности для телеметрии и аналитики. Минимальные технические требования IMT-2020 закреплены ITU-R M.2410-0, а требования 3GPP к киберфизическим управляющим приложениям указывают на необходимость детерминированной связи, высокой доступности, синхронизации времени и поддержки различных профилей трафика [5; 6]. Отдельно 3GPP выделяет направление Smart Energy and Infrastructure, что подтверждает институциональное признание энергетики как вертикали 5G [7].

Блокчейн-технологии, напротив, решают другую часть проблемы: они не ускоряют физическую передачу сигнала, но обеспечивают проверяемый журнал событий, неизменяемость записей, распределенную идентификацию участников, исполнение смарт-контрактов и аудит операций в среде, где доверие между субъектами ограничено. Для Smart Grid это особенно важно при peer-to-peer-торговле энергией, учете энергии prosumer-объектов, подтверждении параметров качества электроэнергии, регистрации команд управления и расследовании инцидентов.

Научная проблема состоит в том, что 5G и блокчейн часто рассматриваются как универсальные технологические решения, однако их функции в Smart Grid принципиально различны. 5G влияет преимущественно на коммуникационные показатели QoS, тогда как блокчейн повышает доверенность данных, но вносит дополнительную задержку консенсуса. Поэтому требуется определить, в каких контурах Smart Grid допустима интеграция блокчейна, а где она должна быть вынесена за пределы реального времени.

Целью исследования является оценка возможностей совместного применения 5G и permissioned-блокчейна для развития Smart Grid на основе анализа стандартов и имитационного моделирования задержки, пропускной способности и надежности передачи данных. Для достижения цели поставлены следующие задачи: проанализировать требования Smart Grid к коммуникационной инфраструктуре; разработать архитектуру взаимодействия 5G SA, MEC и permissioned-ledger; задать воспроизводимую модель передачи сообщений; сравнить сценарии по T_{E2E}, B и R; сформулировать ограничения практического внедрения.

Современное состояние исследований 5G, блокчейна и Smart Grid

Исследования по Smart Grid подчеркивают, что развитие цифровой энергетики связано с усложнением потоков данных, ростом числа активных участников и

необходимостью обмена информацией между системами разного класса: SCADA, DMS, EMS, AMI, DERMS, микросетями и платформами рыночных расчетов. NIST Framework Release 4.0 фиксирует переход к модели, в которой коммуникационные сценарии, онтологии и профили интероперабельности становятся необходимым условием масштабируемого внедрения Smart Grid [1]. При этом NISTIR 7628 Rev. 1 рассматривает кибербезопасность Smart Grid как задачу управления рисками в сложной и взаимосвязанной среде [2].

С точки зрения электроэнергетических стандартов, IEC 61850 важен тем, что объединяет модели данных, языки описания конфигурации, коммуникационные сервисы и механизмы защищенного обмена для автоматизации энергетических объектов [3]. IEEE 1547-2018, в свою очередь, отражает рост роли распределенной генерации и задает требования к интерфейсам DER с электрическими сетями [4]. Эти стандарты показывают, что Smart Grid является не только телекоммуникационной, но и строго инженерной системой, где информационная архитектура должна быть совместима с физикой электроэнергетического режима.

В области 5G ключевой вклад заключается в возможности дифференцировать трафик по сетевым срезам, параметрам QoS, локальному выходу пользовательской плоскости через UPF и размещению вычислений на границе сети. Архитектура 5G System описана 3GPP TS 23.501, где сервисно-ориентированная структура ядра, функции AMF, SMF, PCF, UPF и управление сессиями создают основу для реализации энергетических вертикалей [8]. Для киберфизических приложений принципиально важны требования 3GPP TS 22.104 к детерминированной связи, надежности и синхронизации, поскольку именно эти параметры ограничивают применимость беспроводной среды в контурах управления [6].

Научная литература по 5G в энергетике указывает, что беспроводные сети пятого поколения способны ускорить обмен телеметрией, поддержать спросо-ориентированное управление, интеграцию возобновляемых источников и peer-to-peer-механизмы в Internet of Energy [12]. Однако эти преимущества не означают автоматической пригодности 5G для всех задач релейной защиты. Для особо критичных функций должны учитываться электромагнитная среда, резервирование, локальная автономность подстанции и требуемые пределы задержки.

Блокчейн в Smart Grid исследуется как механизм децентрализованного доверия. Обзоры показывают его применимость к управлению участниками, учету энергии, координации распределенных ресурсов, верификации событий, торговле энергией, обеспечению приватности и аудиту [10; 11]. Вместе с тем открытые блокчейны с Proof-of-Work непригодны для промышленной энергетики из-за высокой задержки, неопределенности финализации и энергетических затрат. Поэтому для Smart Grid более реалистичны permissioned-сети, где участники известны, а консенсус может быть реализован через CFT/BFT-механизмы.

Hyperledger Fabric является показательным примером такой архитектуры: платформа использует модульный подход, pluggable ordering service, membership service provider, политики endorsement/validation и возможность конфигурирования консенсуса под конкретную модель доверия [9]. Для энергетической инфраструктуры это означает, что ledger может использоваться не как публичная криптовалютная сеть, а как

корпоративный журнал событий между оператором распределительной сети, агрегатором, владельцем DER, поставщиком услуг и регуляторным контуром.

Несмотря на значительный объем исследований, остается нерешенным вопрос разграничения функций: какие сообщения должны проходить только через низколатентный 5G/MEC-контур, а какие могут дополнительно фиксироваться в ledger. Именно это разграничение определяет практическую реализуемость архитектуры, поскольку консенсус блокчейна добавляет задержку, несовместимую с рядом задач защиты и противоаварийной автоматики.

Архитектура и параметры имитационного моделирования

Исследование выполнено как имитационное моделирование коммуникационной подсистемы Smart Grid. В качестве объекта рассмотрен фрагмент распределительной сети, включающий интеллектуальные электронные устройства IED, синхрофазорные измерители PMU, интеллектуальные счетчики AMI, prosumer-объекты с распределенной генерацией, узел gNodeB, ядро 5G SA, локальный UPF/MEC, систему SCADA/DMS/EMS и permissioned-блокчейн для журналирования событий. Архитектура показана на рисунке 1.

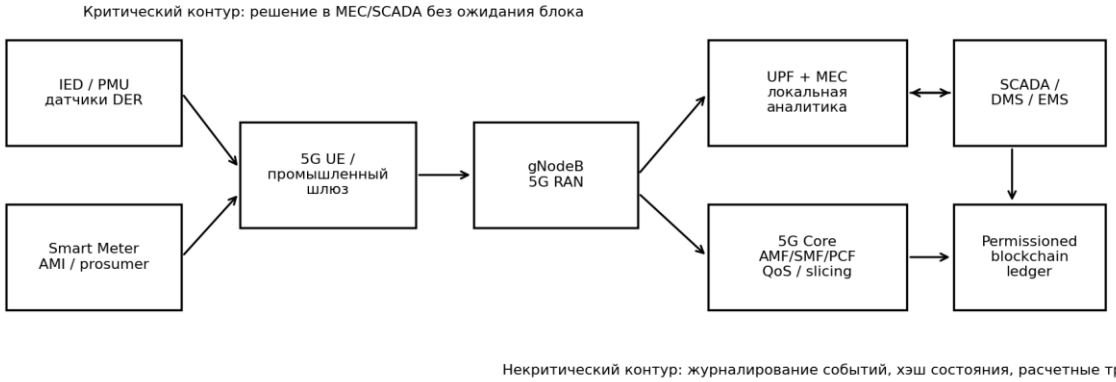


Рисунок 1 - Архитектура интеграции 5G SA, MEC и permissioned-ledger в Smart Grid

В модели выделены два контура. Первый контур является критическим: сообщения от IED и PMU используются для мониторинга состояния сети, локального управления и противоаварийной автоматики. Для этого контура блокчейн не включается в синхронный путь принятия решения; в ledger записываются только хэши событий, результаты команд или агрегированные состояния после выполнения управляющего действия. Второй контур является некритическим: данные AMI, события DER, заявки demand response и расчетные операции могут проходить через permissioned-ledger, поскольку задержка порядка сотен миллисекунд не разрушает физический режим сети.

Сквозная задержка сообщения описывалась выражением:

$$T_{\mathrm{E2E}} = T_{\mathrm{RAN}} + T_{\mathrm{core}} + T_{\mathrm{MEC}} + T_{\mathrm{queue}} + T_{\mathrm{app}} + T_{\mathrm{bc}}.$$

Здесь T_{RAN} - задержка радиодоступа, T_{core} - задержка транспортной и ядровой части сети, T_{MEC} - время обработки на граничном узле, T_{queue} - задержка очереди, T_{app} - прикладная обработка в SCADA/DMS/EMS, T_{bc} - задержка подтверждения транзакции в permissioned-блокчейне. Для критического контура в архитектуре off-loop принималось $T_{\mathrm{bc}} = 0$, поскольку blockchain-commit выполняется асинхронно.

Полезная пропускная способность оценивалась как:

$B = \frac{\sum_{i=1}^{n} L_i}{T_{\text{sim}}}$,

где L_i - размер полезной нагрузки i-го сообщения, T_{sim} - длительность наблюдаемого интервала. Надежность доставки задавалась через вероятность потерь:

$R = 1 - P_{\text{loss}}, \qquad P_{\text{loss}} = 1 - \prod_{k=1}^{m}(1 - p_k),$

где p_k - вероятность потери на k-м участке передачи. Такой подход позволяет разделить вклад радиодоступа, транспортной сети, перегрузки очереди и прикладного уровня.

Выполнено моделирование четырех сценариев: S_0 - LTE с централизованной базой данных; S_1 - 5G SA с централизованной базой данных; S_2 - 5G SA, MEC и permissioned-ledger с асинхронной записью критических событий; S_3 - 5G SA, MEC и полная синхронная запись всех сообщений в блокчейн. Для каждого сценария сгенерировано 10^4 сообщений методом Monte Carlo. Поступление сообщений моделировалось пуассоновским процессом, задержка радиодоступа - логнормальным распределением, задержки обработки - усеченным нормальным распределением, а задержка подтверждения блока - логнормальным распределением с медианой около 115 мс. Параметры приведены в таблице 1.

Таблица 1 - Основные параметры имитационной модели

Параметр	Обозначение	Принятое значение
Количество сообщений в сценарии	n	10^4
Тип поступления сообщений	λ	пуассоновский поток
Размер полезной нагрузки критического сообщения	L_c	128-512 байт
Размер полезной нагрузки AMI/DER-сообщения	L_m	0,5-2,0 кбайт
Медиана T_{RAN} для LTE	$T_{\text{RAN}}^{\text{LTE}}$	25 мс
Медиана T_{RAN} для 5G SA	$T_{\text{RAN}}^{\text{5G}}$	3,2-7,5 мс
Локальная обработка MEC	T_{MEC}	1,2 мс
Медиана blockchain-commit	T_{bc}	115 мс
Критерии оценки	T_{E2E}, B, R	P50, P95, P99, Мбит/с, %

Результаты моделирования коммуникационных сценариев Smart Grid

Результаты моделирования представлены в таблице 2. Для оценки использованы среднее значение, медиана, 95-й и 99-й процентили задержки, полезная пропускная способность и коэффициент успешной доставки пакетов. Особое внимание уделено 95-му процентилю, поскольку он лучше отражает поведение системы при неблагоприятных, но не экстремальных условиях.

Таблица 2 - Результаты имитационного моделирования сценариев Smart Grid

Сценарий	Mean T_{E2E}, мс	P50, мс	P95, мс	P99, мс	B, Мбит/с	R, %
S_0: LTE + централизованная БД	52,39	51,17	72,25	84,44	14,80	99,42
S_1: 5G SA + централизованная БД	22,03	21,96	27,81	30,53	81,60	99,91
S_2: 5G SA + MEC + ledger off-loop	7,74	7,69	9,64	10,52	78,40	99,89
S_3: 5G SA + MEC + all on-chain	127,38	122,82	190,10	227,49	72,90	99,87

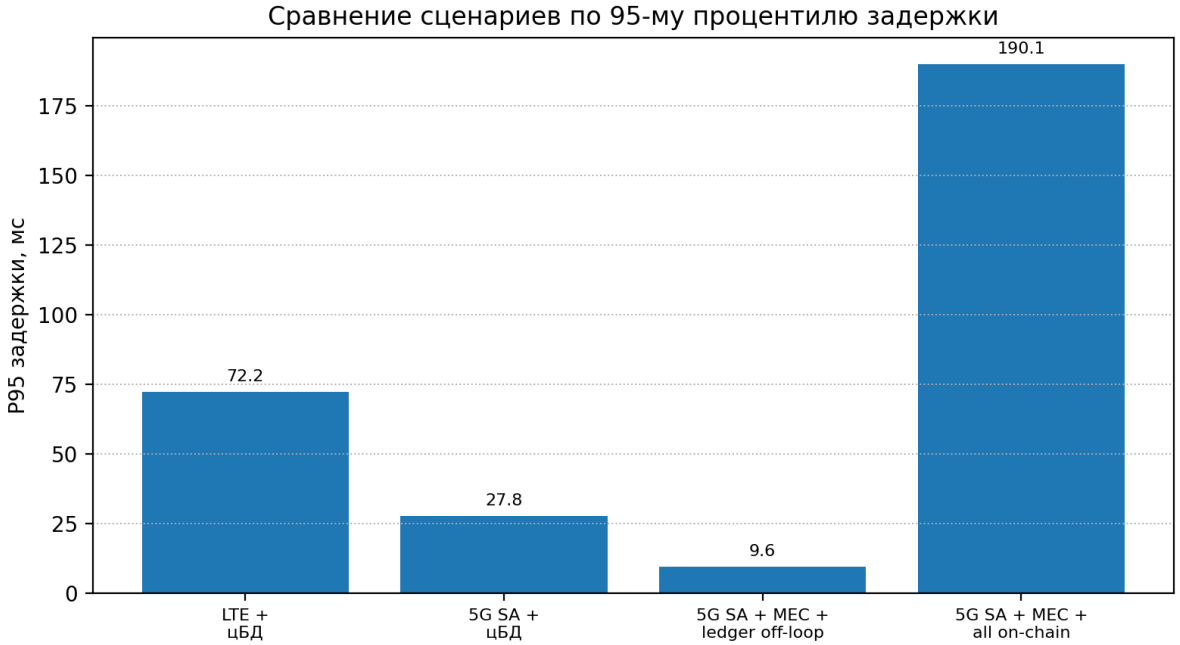


Рисунок 2 - Сравнение сценариев по 95-му процентилю сквозной задержки

Из таблицы 2 следует, что переход от LTE с централизованной базой данных к 5G SA с централизованной базой данных снижает 95-й процентиль задержки с 72,25 до 27,81 мс. Однако основной эффект достигается не только радиоинтерфейсом 5G, а переносом функций обработки ближе к источнику данных. В сценарии S_2 показатель P95 снижается до 9,64 мс, то есть на 86,7 % относительно S_0. Медианная задержка уменьшается с 51,17 до 7,69 мс, что соответствует снижению примерно на 85,0 %.

Полезная пропускная способность возрастает с 14,80 Мбит/с в базовом сценарии до 78,40 Мбит/с в сценарии S_2, что эквивалентно увеличению приблизительно в 5,3 раза. При этом незначительное снижение B в сравнении с S_1 объясняется служебным трафиком журналирования, криптографической обработкой и передачей метаданных в permissioned-ledger. Коэффициент успешной доставки остается на уровне 99,89 %, что соответствует требованию высокой надежности для мониторинговых и управляющих приложений, но не отменяет необходимости резервирования критических каналов.

Сценарий S_3 демонстрирует принципиальное ограничение блокчейна: при синхронном включении blockchain-commit в путь каждого сообщения 95-й процентиль задержки возрастает до 190,10 мс, а 99-й процентиль - до 227,49 мс. Следовательно, такая архитектура непригодна для релейной защиты, быстрого отключения поврежденного участка, изоляции аварии и других функций, где время реакции определяется физикой

переходных процессов. Вместе с тем для учета, подтверждения событий, расчетов и послесобытийного аудита такая задержка является допустимой.

Интерпретация результатов и ограничения исследования

Полученные результаты подтверждают, что научная новизна предлагаемого подхода состоит не в механическом объединении 5G и блокчейна, а в функциональном разделении контуров Smart Grid. 5G SA и MEC должны обслуживать низколатентные задачи мониторинга и управления, тогда как permissioned-blockchain должен выполнять роль доверенного журнала, механизма верификации и расчетной инфраструктуры. Такое разграничение устраняет типовую ошибку, при которой блокчейн предлагается как универсальная замена промышленной базе данных или SCADA-журналу.

Практическая значимость состоит в возможности построить архитектуру, где критические команды не ожидают консенсуса, но их последствия фиксируются в неизменяемом ledger. Например, при срабатывании защиты локальная автоматика и MEC-аналитика выполняют действие в пределах заданного временного бюджета, после чего в блокчейн записываются идентификатор устройства, временная метка, хэш осциллограммы, код команды, статус исполнения и подпись ответственного узла. Это повышает доказательность событий без деградации времени реакции.

Для некритических процессов ledger может использоваться шире. К ним относятся сверка показаний интеллектуальных счетчиков, учет энергии от prosumer-объектов, управление сертификатами происхождения электроэнергии, исполнение demand response-контрактов, межорганизационный обмен данными между оператором сети, агрегатором и поставщиком услуг. Здесь основным требованием является не минимальная миллисекундная задержка, а целостность, проверяемость и неизменяемость данных.

Ограничения исследования также существенны. Во-первых, модель не заменяет полевых испытаний в условиях реальной радиочастотной среды, где на задержку влияют загрузка соты, планировщик, уровень сигнала, помехи, handover, резервирование ядра сети и политика оператора. Во-вторых, в модели использованы усредненные распределения задержек, тогда как для промышленной эксплуатации необходимы измерения jitter, availability, time synchronization error и worst-case latency. В-третьих, моделирование blockchain-commit выполнено на уровне задержки подтверждения, без детального воспроизведения endorsement-политик, числа peers, размера блока, параметра block timeout и отказов orderer-узлов.

Следовательно, результаты должны интерпретироваться как архитектурная оценка, а не как готовая спецификация внедрения. Для промышленной апробации требуется испытательный стенд с 5G SA/NPN, MEC-сервером, эмулятором IED/PMU/AMI, платформой Hyperledger Fabric и интеграцией с тестовой SCADA/DMS-средой. Дополнительно необходима оценка угроз: компрометации SIM/eSIM, атак на API MEC, подмены данных на уровне шлюза, отказа orderer-узла, нарушения приватности измерений и ошибочной конфигурации сетевых срезов.

Заключение и перспективы дальнейших исследований

В статье проведено исследование возможностей технологии 5G и permissioned-блокчейн-технологий для развития Smart Grid. Установлено, что наибольший эффект по задержке достигается при сочетании 5G SA и MEC, поскольку локализация обработки снижает зависимость критического трафика от центральной инфраструктуры. В

имитационной модели 95-й процентиль задержки критического контура снизился с 72,25 мс в LTE-сценарии до 9,64 мс при использовании 5G SA, MEC и асинхронного журналирования.

Показано, что блокчейн не должен включаться в синхронный контур релейной защиты и быстрого управления, так как blockchain-commit приводит к задержкам порядка сотен миллисекунд. Наиболее обоснованным является применение permissioned-ledger для аудита, неизменяемого журналирования, подтверждения расчетных операций, управления доступом и межорганизационного доверия. Таким образом, 5G и блокчейн являются взаимодополняющими, но не взаимозаменяемыми технологиями: первая обеспечивает коммуникационную основу, вторая - доверенную информационную фиксацию событий.

Перспективы дальнейших исследований связаны с созданием экспериментального стенда 5G SA/NPN + MEC + Hyperledger Fabric, оценкой влияния параметров consensus/orderer на задержку, разработкой профилей сетевого среза для AMI, PMU и DERMS, а также построением модели киберрисков для сквозной архитектуры Smart Grid.

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APPLICATION OF DEEP LEARNING FOR AUTOMATED CHEST X-RAY ANALYSIS: METHODOLOGY, PLATFORM ARCHITECTURE, AND IMPLEMENTATION RESULTS

Abstract: This article presents the development and implementation of a software platform for automated chest X-ray analysis based on deep learning methods. The relevance of the study is determined by the growing demand for intelligent diagnostic support systems capable of improving the accessibility, speed, and consistency of radiological assessment, particularly in contexts where healthcare systems face increasing workloads and limited specialist resources. The aim of the study was to design and implement a scalable and practically applicable platform that integrates a trained computer vision model, backend business logic, image storage, and a user-facing interface into a unified diagnostic environment. The system is intended as a research prototype and decision-support tool rather than a clinically validated diagnostic system. The methodological foundation of the work includes a review of contemporary scholarly literature, the selection of appropriate neural network architecture according to criteria of diagnostic performance and engineering feasibility, the design of a modular software architecture, and an experimental evaluation of the resulting system. The implemented solution employs a DenseNet-based model for multi-label chest pathology classification, while a separate inference service is integrated with the application server, relational database, and object storage. The results indicate that the combination of modern pretrained models, explainable artificial intelligence, and service-oriented architecture provides a viable basis for the further deployment of intelligent decision-support systems in healthcare.

Keywords: Deep Learning, Chest X-ray Analysis, Image Classification, Computer Vision, Healthcare, Medical Imaging.

Introduction. Medical imaging has become one of the most important areas of application for artificial intelligence in contemporary healthcare. Among imaging modalities, chest radiography remains one of the most widely used diagnostic procedures due to its affordability, speed, and diagnostic value in the detection of pulmonary and thoracic abnormalities. At the same time, the interpretation of chest X-rays is a complex clinical task that depends heavily on specialist expertise, and the growing volume of medical imaging data has intensified the need for automated support tools. In this context, deep learning has emerged as one of the most effective methodological approaches for medical image analysis, particularly for classification, detection, and segmentation tasks [1].

The present study addresses this challenge not merely as a problem of predictive modeling, but as a broader task of designing a complete digital product suitable for practical use. For this reason, the research focuses not only on the selection of a machine learning model, but also on the architecture of the platform, the organization of data flows, the interaction of software services, and compliance with data protection requirements. This aspect is especially important in the healthcare context of Kazakhstan, where the processing of personal and medical data must comply with the Law of the Republic of Kazakhstan No. 94-V "On Personal Data and Their Protection" [2]. Thus, the article combines machine learning methodology, software engineering, and legal considerations in order to present a coherent framework for the implementation of an AI-assisted chest X-ray analysis platform.

Literature Review. The development of artificial intelligence for medical imaging has been shaped by the transition from traditional handcrafted feature extraction methods to end-to-end deep learning models. Early studies demonstrated that convolutional neural networks significantly outperform conventional computer vision pipelines in image recognition tasks and can be adapted effectively to medical domains through transfer learning [3]. A comprehensive review by Litjens et al. confirmed that deep learning had become the dominant paradigm in medical image analysis due to its ability to learn hierarchical visual representations directly from data, thereby reducing the need for manually engineered features [1].

Within this research trajectory, DenseNet has become one of the most influential neural architectures. Huang et al. introduced densely connected convolutional networks as an architecture in which each layer receives feature maps from all preceding layers [4]. This design improves gradient propagation, encourages feature reuse, and reduces the number of parameters compared with other deep convolutional networks. These properties are particularly valuable in medical imaging, where robust feature extraction and efficient learning are essential for dealing with subtle diagnostic patterns. As a result, DenseNet and its variants have been widely adopted in chest X-ray classification tasks.

A major milestone in this field was the development of CheXNet, that demonstrated a 121-layer convolutional neural network trained on chest radiographs could achieve radiologist-level performance in pneumonia detection [5]. This work significantly accelerated research into automated chest imaging interpretation and showed that deep learning systems could serve as meaningful diagnostic support tools. The subsequent introduction of the CheXpert dataset further advanced the field by providing a large-scale chest radiograph dataset with uncertainty labels and expert comparison, thereby creating a more realistic benchmark for multi-label clinical image classification [6]. The importance of CheXpert lies not only in its scale, but also in its closer alignment with the ambiguity and variability present in real medical reports.

Recent studies have attempted to improve baseline DenseNet architecture through the integration of attention mechanisms, advanced preprocessing, and explainability modules. For example, Chutia et al. proposed an attention-based modified DenseNet model for lung disease classification and reported strong performance across multiple evaluation metrics [7]. Their approach combined contrast enhancement, hybrid pooling, and channel attention, illustrating that the baseline DenseNet family remains highly extensible and competitive when adapted to domain-specific requirements. This line of work is particularly relevant for practical medical AI systems, where marginal improvements in sensitivity and specificity may have significant clinical implications.

At the same time, the literature increasingly emphasizes that predictive accuracy alone is insufficient for the safe and trustworthy application of AI in healthcare. Explainability, privacy, and legal compliance have become central issues in the deployment of medical AI systems. One of the practical methods for visualizing the image regions that contribute most strongly to a model's prediction is called Grad-CAM. In medical imaging, such methods are particularly valuable because they help users assess whether the model is attending to clinically meaningful structures rather than irrelevant artifacts [8]. In parallel, privacy-preserving machine learning has become a rapidly developing field. The promise of federated learning in medicine was the fact that collaborative model training can be achieved without centralizing patient data [9]. More recent studies have systematized privacy-preserving and trustworthy deep learning approaches for medical imaging, highlighting the importance of technical safeguards such as pseudonymization, secure computation, and protected training pipelines [10]. These technological developments correspond with regulatory trends, including the European Data Protection Board's Guidelines 01/2025 on pseudonymization, which clarify that pseudonymized data remains personal data when re-identification remains possible through additional information [11]. Technical industry contributions, such as Intel's work on privacy-preserving machine learning with SGX and TensorFlow, also indicate the practical potential of secure hardware-assisted ML pipelines [12].

Taken together, the literature suggests that modern medical AI systems should be designed not simply as isolated classifiers, but as integrated socio-technical systems that combine robust predictive performance, architectural modularity, explainability, and privacy-aware data governance. It is precisely this broader understanding that informs the design of the present platform.

Methodology. This study used an applied research design focused on developing and evaluating an AI-based platform for automated chest X-ray analysis. The methodology included dataset selection, model comparison, preprocessing, training, evaluation, and integration of the final model into a deployable software system.

For the training phase the study used one of the largest public chest X-ray datasets. The main source was the NIH ChestX-ray14 dataset, which contains 112,120 frontal chest X-ray images labeled across 14 thoracic pathologies. The dataset was split into training (70%), validation (15%), and test (15%) subsets. The model was trained for X epochs using a batch size of X on a GPU-enabled environment. Although these labels were generated automatically from radiology reports and may contain some noise, the dataset remains a widely used benchmark for chest X-ray classification.

During data preprocessing process all images were resized to a fixed input size and normalized. To reduce overfitting and improve generalization, data augmentation techniques such as rotation, horizontal flipping, and minor noise injection were applied. The dataset was then divided into training, validation, and testing subsets to ensure reliable model evaluation.

There are three approaches that were compared: a Convolutional Neural Network (CNN), a Random Forest classifier, and a Vision Transformer (ViT). The results showed that the CNN achieved the highest accuracy (0.91), outperforming the Random Forest (0.82) and slightly exceeding the ViT (0.90) that are represented in the Table 1. The results were gathered in the research article "Overview of machine learning algorithms application in Kazakhstan healthcare sector: analysis of existing solutions and their effectiveness", that was written as a preparational overview of existing solutions in ML to be used in the current system [13].

Table 1 - Pretrained models performance output

Model	Accuracy	F1 Score	AUC-ROC
Random Forest (Handcrafted)	0.82	0.78	0.83
CNN (DenseNet-121)	0.91	0.89	0.94
ViT	0.90	0.88	0.93

These results are consistent with previous studies showing that CNNs are highly effective for radiographic image analysis because they capture local spatial features such as textures, edges, and opacities. Although the ViT also performed well, CNNs were more practical in this study given the dataset size and labeling conditions. The Random Forest model served mainly as a baseline and showed weaker performance on complex visual patterns. Based on these results, the CNN was selected as the core model for the final platform.

The selected CNN was trained using transfer learning, which allowed the model to adapt pretrained visual features to the chest X-ray classification task. The training process used the Adam optimizer and binary cross-entropy loss, which is appropriate for multi-label pathology detection.

Model performance was evaluated using accuracy, precision, recall, F1-score, and AUC. Particular attention was given to recall and AUC, since these metrics are especially important in medical diagnosis where missed detections can have serious consequences.

After evaluation, the final CNN model was integrated into the diagnostic platform as the inference component. Uploaded X-ray images are processed through the model, and the predicted disease probabilities are returned to the user through the application interface. In this way, the methodology combined machine learning development with practical software implementation.

Platform Architecture. The implemented platform follows a modular service-oriented architecture in which the computationally intensive task of medical image inference is separated from the business logic of the application. This architectural decision was made in order to ensure scalability, maintainability, and flexibility of future development. Conceptually, the platform consists of a client layer, a backend API layer, an inference service for the deep learning model, a relational database for structured records, and an S3-compatible object storage system for medical images. Because of this decomposition, the platform's overall integrity is maintained while each subsystem is able to develop and be modified independently. The entire data flow diagram is displayed in Figure 1. The backend layer was implemented in Go using the Gin web framework. This choice was motivated by Gin’s suitability for high-performance HTTP services, RESTful API construction, and microservice-style development [14]. Request validation, authentication logic, user and report management, storage and inference workflow orchestration, and database communication are all handled by the backend. When there is a need for strong server-side control over data processing and frequent network activities, using Go at the application layer offers a dependable and effective basis for service interaction.

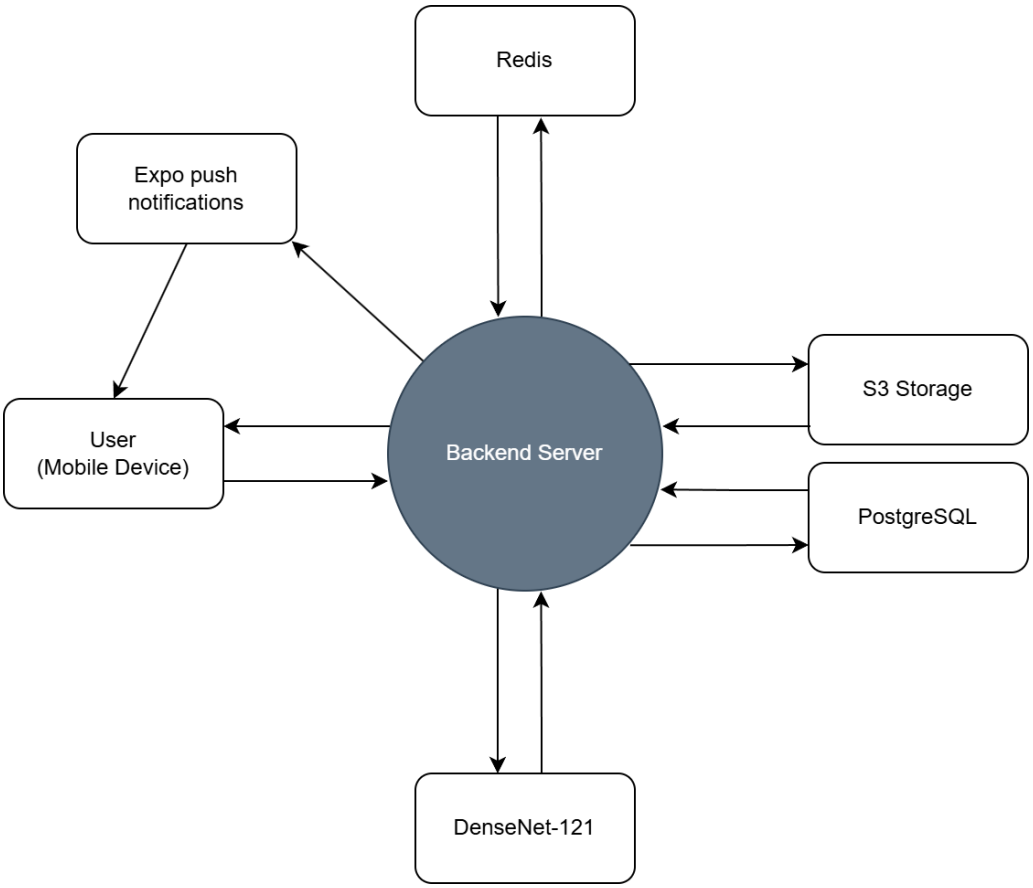


Figure 1 - Data Flow Diagram

The machine learning component is deployed as a dedicated inference service. This design separates the model-serving environment from the main application logic and makes it possible to use a technology stack optimized specifically for deep learning workloads. Such separation simplifies future model replacement, versioning, retraining, and scaling. It also reduces the coupling between the software engineering and machine learning parts of the system, which is an important consideration for long-term maintainability. In practice, the backend sends image-related requests to the inference service, receives the prediction results, and transforms them into a structured diagnostic response for persistence and presentation. So the model can be easily replaced with another one, or modified with no affect on the other system parts.

The operational workflow of the platform is organized as follows. A user uploads a chest X-ray image through the client interface. The API validates the request and stores the file in object storage while simultaneously recording metadata about the image and the corresponding diagnostic request in the relational database. The backend then invokes the inference service, which performs the necessary image preprocessing, applies the trained neural network, and returns pathology scores and, if enabled, visual explanation artifacts. The backend subsequently saves the inference outcome in the form of a report and returns the result to the client application. This workflow enables clear traceability of each diagnostic request and establishes an auditable lifecycle for image processing and result generation.

A central architectural principle of the platform is the separation of data domains. Personally, identifying user data, examination records, and machine learning outputs are represented as distinct logical entities connected by controlled identifiers. This design reflects the principle that secure medical AI systems should not treat all data as a monolithic pool but

rather should isolate sensitive information according to its role and degree of identifiability. Such an approach is consistent with both the Kazakhstan law on personal data protection and broader regulatory guidance on pseudonymization and controlled processing [2, 11]. Furthermore, the system can theoretically be extended to more sophisticated privacy-preserving environments, such as secure inference environments or federated learning. The platform's flexibility provides a feasible path for potential future enhancements, even though such capability was not included in the current version.

Results and Discussion

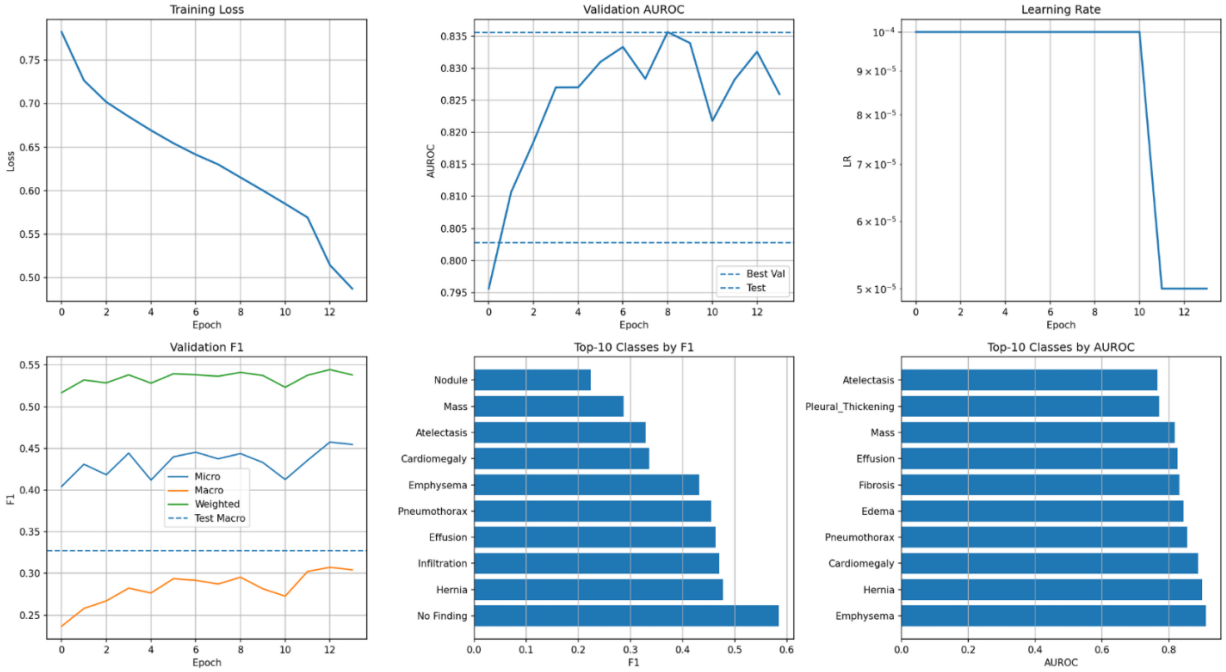


Figure 2 - Training performance on the CheXpert dataset

The implementation results demonstrate that the selected methodological and architectural strategy is suitable for the development of an AI-assisted chest X-ray analysis platform. At the model level, the trained network achieved stable classification behavior on the validation data, producing clinically interpretable probabilistic outputs across multiple pathology classes. Class-specific AUROC metrics have reached 0.90+ for certain pathologies, as shown on the Figure 2. These values should be interpreted not only as indicators of classification quality, but also as evidence that a DenseNet-based approach remains a strong practical foundation for chest radiograph analysis. The first version of the model, shown in Figure 2 represents a model trained on CheXpert dataset, that was later fine-tuned, using NIH ChestX-ray14 dataset. The results of the fine-tuned improved in terms of learning rate stability and AUROC metrics. For example, in the initial version of the model, two of the top 10 classes had an AUROC below 0.78, whereas in the fine-tuned version, all top 10 classes achieved an AUROC above 0.81. The model demonstrated higher recall for common pathologies, while performance for rarer conditions remained lower due to class imbalance. One of the weaknesses of the datasets given is class imbalance, that results into moderate F1 metrics for certain diseases, that can be lower than 0.23, however the F1 average remains above 0.31.

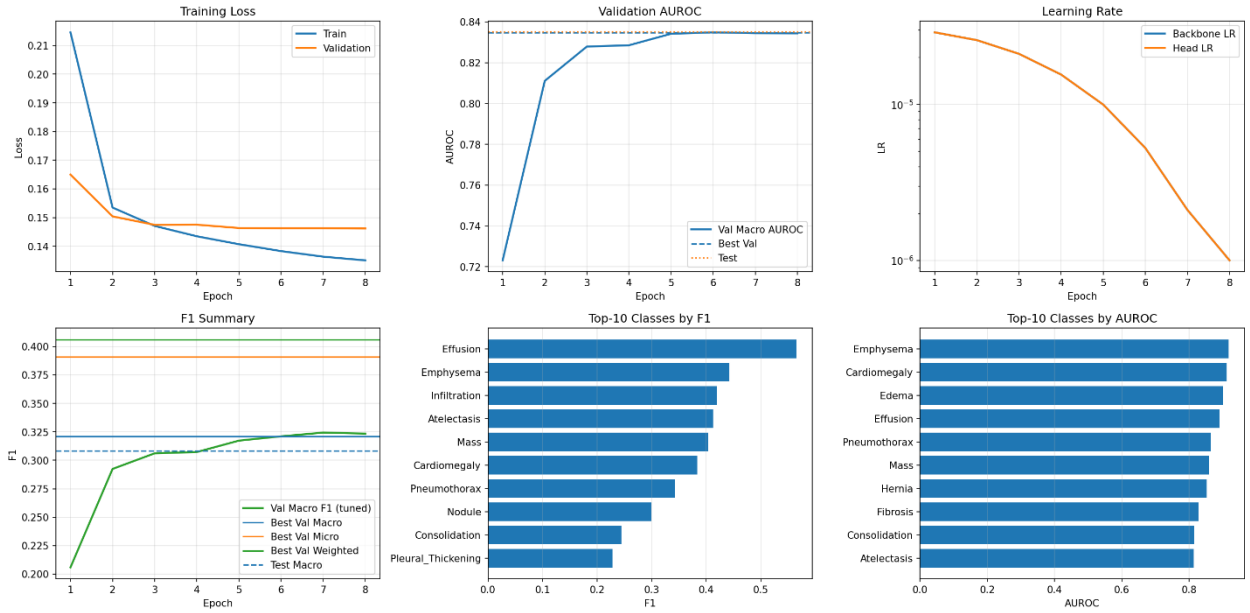


Figure 3 - Fine-tuning results on the NIH Chest X-ray dataset

The results obtained are consistent with the broader research literature. The work of Rajpurkar et al. established DenseNet-121 as a highly effective architecture for chest X-ray analysis, while subsequent studies, including Chutia et al., demonstrated that performance can be further improved through attention mechanisms and more advanced preprocessing [5, 7]. In this sense, the present platform should be understood as a robust baseline implementation that prioritizes reproducibility, engineering integration, and practical usability while remaining open to future optimization. This balance is important because research-grade performance and production-grade system design do not always develop at the same pace; a slightly less experimental but more stable architecture may be more appropriate in real deployment scenarios.

One of the most significant outcomes of the project is that the result is not an isolated neural model, but a complete software platform. Many studies in the field focus primarily on predictive performance, often treating deployment, storage, security, and service orchestration as secondary matters. However, in real healthcare systems, these aspects are crucial. The present work demonstrates that the value of medical AI lies not only in achieving high evaluation metrics, but also in embedding the model within a coherent digital infrastructure that supports controlled image storage, structured report generation, traceable request processing, and future extensibility. The use of a dedicated inference service and a modular backend architecture substantially strengthen the practical viability of the system. The inclusion of Grad-CAM-based explainability also contributed to the trustworthiness of the platform. By providing visual evidence of the regions that influenced model predictions, the system becomes more transparent for developers, researchers, and potentially clinicians. This is especially relevant in medical settings, where opaque predictions are difficult to justify and harder to validate. While explainability does not guarantee correctness, it offers an important interpretive layer that can assist in identifying failure modes or unintended model behavior [8].

At the same time, research has several limitations. First, the performance of the model is necessarily shaped by the quality, balance, and representativeness of the training data. Publicly available datasets, although large and valuable, may not fully reflect local clinical practice, equipment variability, or patient population characteristics. Second, the current implementation

is based on a centralized training and inference paradigm. Future iterations might benefit from more sophisticated privacy-aware settings, including federated learning, secure enclaves, or secret computing pipelines, even though this is feasible for prototype and early-stage deployment [9, 12]. Third, further validation, such as institutional testing, expert evaluation, and regulatory alignment, would be necessary for any true clinical acceptance. For these reasons, rather than being a fully functional clinical decision-making system, the current platform should be viewed as a technically proven, research-based prototype with significant applicable potential.

Despite strong performance, the model remains sensitive to dataset bias and imaging variability, which may limit generalization across hospitals and equipment.

Conclusion. The study shows the implementation of an automated X-ray analysis system that combines deep learning, software architecture, data management and protection. The main contribution of the work is practical system development based on methodological research in machine learning field. Instead of viewing the neural network from the perspective of isolated model the study focuses on a complete technological ecosystem that supports inference, data storage and future expansion, especially integration with real hospital systems. Its practical significance lies in providing a scalable foundation for AI-based solutions in the healthcare sector.

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АНАЛИЗ ИНТЕГРАЦИИ БЛОКЧЕЙН-ТЕХНОЛОГИЙ В ИНФОРМАЦИОННЫЕ СИСТЕМЫ: ПЕРСПЕКТИВЫ И ВЫЗОВЫ

Аннотация: Блокчейн — это совершенно новый подход к управлению данными: информация хранится не централизованно, а распределяется между участниками сети, что делает систему намного безопаснее и устойчивее к вмешательству. В этой статье обсуждаются ключевые возможности и трудности, которые могут возникнуть при внедрении блокчейн-технологий в современные информационные системы. В исследовании использовались как количественные, так и качественные методы — статистика, мнения экспертов и реальные примеры из практики. Итоги помогают понять, в каком направлении может развиваться эта технология и как она способна повлиять на цифровую трансформацию.

Ключевые слова: Блокчейн, блокчейн как услуга (BaaS), информационные системы, децентрализация, безопасность данных, смарт-контракты, цифровая трансформация, инновации, технологии.

Введение. Современные информационные системы играют важную роль в бизнесе, государственном управлении и повседневной жизни. Цифровая трансформация затрагивает все сферы, в которых взаимодействуют люди и технологии, ставя перед обществом задачи по созданию более эффективных, прозрачных и безопасных решений. В этом контексте блокчейн-технологии представляют собой одну из самых перспективных инноваций XXI века.

Значение блокчейна для информационных систем

Блокчейн — это распределённый реестр данных, который позволяет отказаться от необходимости доверять центральным органам управления и посредникам. Каждая запись в блокчейне защищена с помощью криптографии, что делает её практически неизменной. Это даёт уникальные возможности для повышения безопасности и автоматизации процессов в информационных системах.

Проблемы и вызовы. Несмотря на свои революционные преимущества, блокчейн не является универсальным решением. Масштабируемость, высокая энергозатратность и сложность интеграции с уже существующими платформами остаются важными барьерами. Кроме того, различные сферы применения блокчейна — от логистики до медицины — требуют уникальных подходов, что усложняет процесс внедрения.

Например, в финансовом секторе блокчейн используется для создания криптовалют, децентрализованных финансовых систем (DeFi) и смарт-контрактов. В то же время, логистика рассматривает блокчейн как средство для улучшения прозрачности

и надёжности цепочек поставок. Однако ни одна из этих сфер пока не реализовала весь потенциал технологии из-за отсутствия стандартов и высокой стоимости разработки.

Почему важно исследование интеграции

Учитывая важность блокчейн-технологий для будущего цифровых систем, исследование вопросов интеграции становится особенно актуальным. Знание преимуществ и ограничений технологии помогает выработать стратегии успешного её внедрения. Важно учитывать не только технические, но и экономические, юридические и социальные факторы, которые влияют на успешность применения блокчейна в реальных условиях.

Таким образом, цель этой статьи — провести всесторонний анализ интеграции блокчейн-технологий в информационные системы. Мы постараемся оценить текущее состояние технологий, их перспективы и выявить ключевые вызовы, с которыми сталкиваются разработчики и пользователи блокчейна.

Актуальность исследования

На сегодняшний день блокчейн используется в различных сферах – от финансовых технологий до логистики и управления персональными данными. Однако его массовая интеграция в традиционные информационные системы сталкивается с вызовами, связанными с:

- Техническими ограничениями (масштабируемость, скорость обработки транзакций).
- Регуляторными барьерами (правовые вопросы, защита данных).
- Экономическими факторами (затраты на внедрение, экономическая эффективность).

Цель и задачи исследования

Цель данной работы – провести всесторонний анализ интеграции блокчейн-технологий в информационные системы, выявить основные перспективы и ограничения их внедрения. В рамках исследования решаются следующие задачи:

1. Оценка преимуществ блокчейна с точки зрения децентрализации и безопасности.
2. Анализ практических кейсов интеграции технологии в различные отрасли.
3. Рассмотрение существующих ограничений и возможных способов их устранения.
4. Выработка рекомендаций по эффективному внедрению блокчейна.

Обзор литературы

Развитие блокчейн-технологии стало возможным благодаря исследованиям в области распределенных систем, криптографии и цифровой безопасности. В литературе можно выделить несколько ключевых направлений:

1. Историческое развитие и техническая база

Развитие блокчейн-технологий началось с публикации Сатоши Накамото в 2008 году — «Bitcoin: A Peer-to-Peer Electronic Cash System». В ней описывалась система, которая позволяла проводить финансовые операции без посредников благодаря распределённому реестру. Bitcoin стал первой успешной реализацией блокчейна, но на тот момент он использовался только для хранения и передачи ценности.

Со временем исследователи начали искать другие применения технологии. В 2015 году появился Ethereum — платформа, которая дала возможность создавать смарт-

контракты, то есть программы, автоматически выполняющие заданные условия. Ethereum стал основой для создания децентрализованных приложений (DApps) и расширил сферу использования блокчейна.

С технической стороны ключевыми элементами блокчейна стали алгоритмы консенсуса (Proof-of-Work, Proof-of-Stake, Delegated Proof-of-Stake) и криптография. Например, алгоритм SHA-256, используемый в Bitcoin, обеспечивает высокий уровень защиты, хотя его энергопотребление вызывает много споров.

2. Применение блокчейна в информационных системах

Современные исследования показывают широкий спектр применения блокчейна в информационных системах. Наиболее значимые области включают:

— *Финансовые технологии*

Создание криптовалют, таких как Bitcoin и Ethereum, стало основой для развития децентрализованных финансов (*DeFi*), которые предлагают альтернативу традиционным банковским системам. Смарт-контракты, реализованные на блокчейне, позволяют автоматизировать финансовые операции, такие как кредитование, страхование и управление активами. Примером является платформа Ripple, предоставляющая решения для трансграничных платежей.

— *Логистика и цепочки поставок*

В логистике блокчейн используется для отслеживания движения товаров и предотвращения мошенничества. Например, Walmart применяет блокчейн для контроля происхождения продуктов питания, что улучшает прозрачность и позволяет минимизировать риски порчи. Аналогичные решения разрабатываются Maersk в проекте TradeLens, который автоматизирует логистические процессы и упрощает взаимодействие участников цепочек поставок.

— *Медицина*

Блокчейн оказывает значительное влияние на защиту медицинских данных. Платформы, такие как MediLedger, позволяют безопасно хранить информацию о пациентах и обеспечивать контроль доступа к данным. Более того, технология используется для отслеживания качества медицинских препаратов, что снижает риск распространения поддельной продукции.

— *Государственные сервисы*

В области государственных услуг блокчейн способствует цифровизации процессов, таких как регистрация документов, идентификация личности и защита персональных данных. Например, в Эстонии разработана блокчейн-платформа для управления государственными записями, что повышает доверие к правительственным системам и улучшает их эффективность.

3. Ограничения и вызовы

Несмотря на очевидные преимущества блокчейна, внедрение технологии сопровождается рядом проблем, которые следует учитывать:

— *Юридические вопросы*

Регуляторные ограничения блокчейна варьируются в зависимости от страны, что затрудняет массовое внедрение технологии. Например, в Европейском Союзе действуют строгие правила защиты данных (GDPR), которые могут вступать в конфликт с принципами неизменности блокчейна. В то же время, в некоторых странах, таких как Китай, применение блокчейна ограничено из-за строгого государственного контроля.

Смарт-контракты представляют собой еще одну сложность: их признание в качестве юридически значимых документов остается неоднозначным. Для успешного внедрения блокчейна требуется разработка международных стандартов, которые будут регулировать правовые аспекты технологии.

— *Технические ограничения*

Скорость обработки транзакций в блокчейне уступает традиционным системам. Например, блокчейн Bitcoin может обрабатывать всего 7 транзакций в секунду, тогда как Visa – до 24 000. Это ограничивает возможность использования блокчейна в масштабных проектах.

Масштабируемость – еще одна проблема. С увеличением количества пользователей блокчейн становится менее эффективным, что требует разработки новых решений, таких как *sharding* или переход на алгоритмы консенсуса с меньшими энергозатратами, например, Proof-of-Stake.

— *Экономическая целесообразность*

Затраты на разработку и внедрение блокчейн-решений остаются высокими, особенно для небольших компаний. Это ограничивает доступность технологии и требует внедрения экономически эффективных моделей, таких как токенизация активов или использование блокчейна как услуги (*BaaS*).

Методы исследования

Для достижения целей исследования использован системный подход, объединяющий количественные, качественные и смешанные методы анализа. Такой подход позволяет глубоко проанализировать особенности интеграции блокчейн-технологий, рассмотреть их перспективы и выявить основные вызовы.

Количественные методы исследования направлены на анализ измеряемых показателей и статистических данных. В рамках данной работы применяются следующие техники:

1. Анализ статистических данных

Используется для оценки темпов внедрения блокчейн-технологий в различных отраслях. Основное внимание уделяется:

- Количественным показателям использования блокчейна в таких секторах, как финансы, медицина, логистика и государственное управление.
- Динамике роста популярности технологии на основе данных из отчетов ведущих консалтинговых компаний, таких как Deloitte, PwC и Gartner. Например, статистика показывает, что с 2017 года количество компаний, внедривших блокчейн, ежегодно увеличивается на 25-30%.

2. Сравнительный анализ

Осуществляется для оценки экономической эффективности блокчейна в сравнении с традиционными централизованными системами.

- Основные показатели включают затраты на внедрение, скорость обработки транзакций, затраты на обслуживание и общее влияние на бизнес-процессы.
- В рамках данного анализа рассматриваются кейсы крупных компаний, таких как IBM, использующая блокчейн в финансовых и логистических решениях, и Microsoft, которая предлагает сервисы Blockchain as a Service (*BaaS*). Сравнение показывает, что внедрение блокчейна в некоторых случаях снижает затраты на аудиторские проверки до 50%.

Качественные методы исследования позволяют глубже понять контекст и выявить скрытые закономерности. Они основываются на изучении мнений экспертов и анализе реальных примеров применения блокчейна.

1. Экспертные интервью

Интервью проводятся с ведущими специалистами в области блокчейн-интеграции.

- Цель интервью – получить инсайдерскую информацию о барьерах внедрения, текущих трендах и перспективах развития технологии.
- Вопросы охватывают такие аспекты, как технические проблемы, юридические ограничения и экономическая целесообразность. Например, интервью с представителями IBM позволяет понять, какие шаги компания предпринимает для оптимизации своих блокчейн-решений.

2. Анализ кейсов

Метод включает детальный разбор успешных и неудачных примеров интеграции блокчейна.

- Примером успешного кейса является использование блокчейна Walmart для контроля цепочек поставок. Эта система позволяет отслеживать происхождение продуктов от фермы до магазина, что уменьшает риск порчи и повышает прозрачность.
- Одним из неудачных примеров является проект Australian Securities Exchange, который столкнулся с трудностями масштабирования и затратами. Анализ этих кейсов помогает выявить факторы, влияющие на успешность внедрения технологий.

Смешанный метод объединяет количественные и качественные техники, чтобы создать всестороннюю картину исследования.

1. Сравнение данных

Объединение количественных данных, таких как статистика внедрения, с качественной информацией, полученной из интервью и анализа кейсов.

- Например, изучается, как статистически доказанное снижение затрат влияет на восприятие технологии участниками рынка.
- Эта информация используется для выявления моделей успешной интеграции блокчейна в информационные системы.

2. Прогностический анализ

На основе собранных данных строятся модели для оценки перспектив развития технологии.

- Прогнозируется, как блокчейн может эволюционировать с учетом современных трендов, таких как рост децентрализованных финансов (*DeFi*) или использование блокчейна в управлении данными искусственным интеллектом.
- Прогноз также охватывает возможные экономические и юридические изменения, которые могут повлиять на внедрение технологии. Например, разработка новых стандартов регулирования блокчейна может увеличить интерес к технологии со стороны компаний в странах с жесткими требованиями.

Основная часть: Анализ и результаты исследования

1. Технические аспекты блокчейна

1.1 Принципы работы распределенного реестра

Блокчейн представляет собой децентрализованную систему хранения данных, в которой каждая запись (блок) объединяется в цепочку с использованием криптографических методов. Основной принцип работы блокчейна заключается в неизменяемости записей, которая достигается за счет механизма консенсуса.

- Децентрализация: В отличие от традиционных централизованных баз данных, блокчейн не требует наличия единого управляющего узла. Вся информация распределена среди участников сети.
- Неизменяемость данных: После добавления блока в цепочку его невозможно изменить, что обеспечивает высокую степень защиты от фальсификаций.
- Прозрачность: Все транзакции регистрируются и доступны для проверки, что улучшает учет данных.

1.2 Алгоритмы консенсуса

Консенсус — это механизм согласования узлов сети о принятии новой информации. Основные алгоритмы включают:

- Proof-of-Work (PoW): Требует выполнения сложных вычислений, что делает систему устойчивой к атакам, но требует значительных энергетических затрат.
- Proof-of-Stake (PoS): Основан на владении токенами, снижает энергопотребление по сравнению с PoW, но требует механизмов защиты от централизации.
- Delegated Proof-of-Stake (DPoS): Позволяет держателям токенов голосовать за узлы, подтверждающие транзакции, тем самым улучшая масштабируемость.

1.3 Вопросы безопасности и криптографических механизмов

Блокчейн использует криптографические алгоритмы для защиты данных:

- Хеширование: SHA-256 и другие алгоритмы обеспечивают безопасность данных.
- Цифровая подпись: Используется для подтверждения подлинности транзакций.
- Атака 51%: Возможный риск, при котором злоумышленник получает контроль над большей частью вычислительных мощностей сети.

2. Экономическая модель интеграции

2.1 Анализ затрат на разработку и обслуживание блокчейн-инфраструктуры

Внедрение блокчейна требует значительных финансовых вложений:

- Разработка и тестирование: Инвестиции в исследования, создание протоколов и адаптацию технологий.
- Эксплуатационные расходы: Обслуживание инфраструктуры, расходы на хранение данных, вычислительные мощности.
- Обновления и безопасность: Регулярные обновления для защиты от угроз, поддержка смарт-контрактов.

2.2 Экономическая эффективность по сравнению с традиционными системами

Исследования показывают, что блокчейн может снижать затраты в ряде сфер:

- Финансовые операции: Уменьшение затрат на проведение платежей и переводы.
- Автоматизация процессов: Упрощение учета и управления бизнес-процессами.
- Снижение посредников: Исключение третьих сторон в сделках, что

уменьшает затраты.

2.3 Возможности монетизации через токенизацию

Токенизация позволяет создавать цифровые активы, обеспечивая новые формы монетизации:

- Финансовые инструменты: Создание стейблкоинов и цифровых ценных бумаг.
- Игровые и виртуальные активы: Продажа внутриигровых объектов.
- Недвижимость: Токенизация собственности и управление правами.

3. Юридические аспекты

3.1 Регуляторные вопросы и международные стандарты

Регулирование блокчейна остается сложным вопросом из-за его глобального характера:

- GDPR (Европа): Требования к защите персональных данных могут конфликтовать с неизменяемостью блокчейна.
- SEC (США): Надзор за криптоактивами и регулирование цифровых ценных бумаг.
- Китай: Ограничение криптовалютных операций, но развитие национального блокчейна.

3.2 Проблемы защиты персональных данных

Блокчейн потенциально нарушает принципы конфиденциальности:

- Анонимность: Публичные реестры могут раскрывать информацию о пользователях.
- Право на удаление данных: Невозможность редактирования информации в блокчейне.
- Регулируемый доступ: Развитие закрытых (частных) блокчейнов для защиты данных.

3.3 Возможные сценарии адаптации блокчейна к правовой системе

Для успешного внедрения блокчейна необходимо учитывать юридические аспекты:

- Разработка международных стандартов регулирования.
- Адаптация правовой базы для признания смарт-контрактов.
- Развитие гибридных моделей, сочетающих блокчейн и централизованные системы.

Заключение. Проведённый анализ подтвердил, что блокчейн-технологии обладают большим потенциалом для модернизации современных информационных систем. Благодаря своей децентрализованной архитектуре, высокому уровню защиты данных и возможности автоматизации с использованием смарт-контрактов, блокчейн может существенно повысить прозрачность операций, снизить издержки, связанные с участием посредников, и улучшить эффективность взаимодействия между участниками цифровых процессов.

Тем не менее, на пути к широкому внедрению блокчейна по-прежнему существуют серьёзные вызовы. Среди них — проблемы масштабируемости, высокая энергозатратность существующих алгоритмов консенсуса, отсутствие универсальных правовых стандартов и неопределённость в регулировании технологии на международном уровне. Эти ограничения замедляют внедрение блокчейн-решений в

различных отраслях и требуют комплексного подхода к их преодолению. Несмотря на существующие барьеры, можно ожидать, что дальнейшее развитие инфраструктуры блокчейн приведёт к внедрению более энергоэффективных алгоритмов консенсуса, таких как Proof-of-Stake и его производные, а также к появлению гибридных моделей блокчейнов, сочетающих преимущества как публичных, так и частных сетей. Кроме того, активное развитие законодательства, адаптированного к особенностям децентрализованных систем, позволит создать правовую базу, способствующую безопасному и массовому использованию технологии.

Для успешной реализации потенциала блокчейна необходима разработка комплексных решений, которые будут учитывать технические, экономические и юридические аспекты его внедрения. Важную роль будет играть формирование международных стандартов регулирования, что упростит кросс-граничное применение технологии и снизит барьеры для бизнеса.

Особое внимание в будущем следует уделить изучению долгосрочных тенденций интеграции блокчейна в новые сферы, включая искусственный интеллект, интернет вещей и распределённые вычислительные системы. Это позволит расширить горизонты применения технологии и повысить её ценность в контексте цифровой трансформации общества.

Таким образом, блокчейн остаётся одной из ключевых технологий цифровой эпохи. Однако его успешное применение требует дальнейшего совершенствования, адаптации к реальным рыночным условиям и активного взаимодействия между технологическими, экономическими и правовыми структурами. Будущие исследования должны быть направлены на повышение эффективности блокчейн-решений, создание устойчивых моделей монетизации и формирование надёжных правовых механизмов, которые обеспечат стабильную и безопасную интеграцию технологии в различные сферы деятельности.

Рекомендации:

Технические улучшения — переход от энергоёмких алгоритмов (например, Proof-of-Work) к более эффективным (Proof-of-Stake), развитие гибридных блокчейнов и внедрение многослойных решений (Layer 2) для улучшения масштабируемости.

Экономическая адаптация — снижение инфраструктурных затрат, использование токенизации для финансирования и интеграция блокчейна в бизнес-процессы для повышения прозрачности и автоматизации.

Юридическое регулирование — формирование международных стандартов, признание смарт-контрактов и создание правовых моделей, обеспечивающих защиту данных и интересов пользователей.

Такой подход поможет преодолеть барьеры и ускорить внедрение блокчейн-технологий.

Перспективы:

Создание более энергоэффективных алгоритмов консенсуса для снижения затрат и повышения устойчивости.

Анализ долгосрочных трендов — интеграции блокчейна с ИИ, IoT и распределёнными вычислениями.

Исследование цифрового суверенитета и разработка государственных блокчейн-решений для управления данными и идентификацией.

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THE ROLE OF DATA SCIENCE IN MODERN BANKING: OPPORTUNITIES AND CHALLENGES

Abstract: Data science has significantly transformed the banking sector by enabling financial institutions to process large volumes of data, improve customer experience, strengthen fraud detection, and support more accurate credit risk assessment. This paper examines the role of data science in modern banking, focusing on customer analytics, risk management, fraud detection, operational efficiency, and implementation challenges. In addition to the theoretical review, the paper presents an empirical case study on credit default prediction using the Home Credit Default Risk dataset. Logistic regression is used as an interpretable baseline model for predicting client default probability. The results show that the baseline model achieves high accuracy and acceptable ROC-AUC; however, its recall under the default threshold of 0.5 is very low due to class imbalance. To improve practical applicability, the study introduces threshold tuning, balanced logistic regression, probability-based risk segmentation, and cost-sensitive evaluation. The results demonstrate that adjusting the classification threshold improves the model's ability to identify high-risk borrowers and better reflects real banking decision-making, where false negatives are usually more costly than false positives. The study concludes that data science has strong practical value in banking, but successful implementation requires not only predictive models, but also interpretability, fairness, threshold calibration, and alignment with financial risk policies.

Keywords: data science, banking analytics, credit risk modeling, logistic regression, default prediction, Home Credit dataset, threshold tuning, class imbalance, ROC-AUC, machine learning.

1. Introduction

The application of data science in the banking industry has transformed how financial institutions operate, make decisions, and manage risk. Modern banks process large volumes of structured and unstructured data, including transaction records, credit histories, customer interactions, mobile banking activity, and external financial information. By applying big data analytics, machine learning, and artificial intelligence, banks can extract useful insights from these data sources and improve decision-making across several business areas [1].

Data science supports banking operations in multiple ways. It helps banks personalize customer services, detect fraudulent activity, assess creditworthiness, automate internal processes, and improve operational efficiency. For example, predictive models can estimate the probability that a customer will default on a loan, while anomaly detection methods can identify suspicious transactions in real time. Similarly, customer segmentation models can help banks offer more relevant products and improve customer satisfaction.

However, the use of data science in banking also creates important challenges. Financial institutions operate in a highly regulated environment and work with sensitive personal and financial information. Therefore, issues such as data privacy, model transparency, legacy system integration, algorithmic bias, and regulatory compliance must be addressed carefully [2]. In banking, a model is not useful only because it is accurate; it must also be explainable, reliable, fair, and suitable for real financial decision-making.

This paper examines the role of data science in modern banking from both theoretical and practical perspectives. First, it reviews major application areas, including customer experience, fraud detection, risk management, and operational efficiency. Second, it presents a case study on credit default prediction using logistic regression and the Home Credit Default Risk dataset. The empirical part focuses not only on model accuracy, but also on class imbalance, threshold tuning, cost-sensitive evaluation, and probability-based risk segmentation.

1.1 Relevance

Credit risk assessment is one of the most important tasks in banking. When financial institutions issue loans or credit cards, they must estimate whether clients are likely to repay their obligations. Incorrect credit decisions can lead to financial losses, especially when risky borrowers are classified as safe. Therefore, accurate and interpretable credit default prediction is essential for loan approval, credit limit assignment, risk-based pricing, and portfolio monitoring.

The relevance of this study is strengthened by the fact that credit default datasets are usually imbalanced. In real banking data, most clients repay their loans, while only a smaller proportion default. This creates a methodological challenge because a model may achieve high accuracy by predicting most clients as non-defaulters, while still failing to identify actual risky borrowers. For this reason, credit risk models must be evaluated using additional metrics such as recall, precision, F1-score, ROC-AUC, confusion matrix analysis, and cost-sensitive evaluation.

1.2 Hypothesis

The main hypothesis of this study is that logistic regression can serve as an interpretable baseline model for credit default prediction in banking. Although logistic regression may not capture all nonlinear relationships in large financial datasets, it provides transparent probability estimates and allows the influence of individual variables on default risk to be interpreted. The study also assumes that model performance can be improved from a practical banking perspective through threshold tuning and cost-sensitive evaluation.

1.3 Aims and Objectives

The primary aim of this research is to analyze the role of data science in modern banking and to develop an interpretable credit default prediction model using logistic regression.

- To review the main applications of data science in banking, including customer experience, fraud detection, risk management, and operational efficiency.
- To preprocess and analyze the Home Credit Default Risk dataset from Kaggle.
- To construct a logistic regression model that predicts the probability of client default.
- To evaluate the model using accuracy, precision, recall, F1-score, ROC-AUC, and confusion matrix analysis.

- To address the class imbalance problem using balanced logistic regression and threshold tuning.
- To apply cost-sensitive evaluation in order to select a more practical classification threshold.
- To interpret the results from the perspective of banking decision-making and credit risk management.

1.4 Research Plan

The research is conducted in several stages. First, the Home Credit Default Risk dataset is collected and prepared for analysis. Missing values are handled, categorical variables are encoded, numerical variables are standardized, and relevant features are engineered. Second, the dataset is divided into training and testing subsets. Third, a baseline logistic regression model is trained. Fourth, the model is evaluated using standard classification metrics. Fifth, balanced logistic regression and threshold tuning are applied to address the class imbalance problem. Finally, cost-sensitive evaluation and probability-based risk segmentation are used to interpret the model from a practical banking perspective.

2. Literature Review

In recent years, the banking industry has increasingly adopted data science methods to improve risk management, fraud detection, customer service, and operational efficiency. The combination of big data analytics, machine learning, and artificial intelligence allows financial institutions to process large volumes of data, identify meaningful patterns, and make more informed decisions [38].

Previous studies show that data science has become an important driver of financial innovation. Gomber et al. conducted a bibliometric analysis of big data applications in banking and found growing research interest in the use of data-driven methods in the financial sector [5]. Similarly, the Bank for International Settlements highlights the role of data science in improving statistical analysis and supporting monetary policy decisions in central banks [13]. These developments reflect a broader transformation of the financial sector toward more analytical and technology-based decision-making.

One of the most important applications of data science in banking is the improvement of customer experience. Banks collect large amounts of customer data, including demographic information, transaction history, digital activity, and service interactions. By applying data analytics and machine learning techniques, banks can better understand customer needs, preferences, and behavior [2]. This allows financial institutions to provide more personalized, efficient, and secure services.

Customer segmentation is widely used to support personalization in banking. Techniques such as clustering and RFM analysis help divide customers into meaningful groups based on their financial behavior, product usage, and purchasing potential [3]. This enables banks to design targeted products, improve marketing effectiveness, and increase customer retention. In modern banking, customer experience has become not only a service advantage, but also a competitive necessity [31].

Big data analytics also supports advanced personalization. Banks can use predictive modeling, sentiment analysis, and behavioral analytics to anticipate customer needs and provide more relevant services [29]. Self-service technologies and AI-powered chatbots further improve customer interaction by making banking services faster and more accessible [26]. As customer

expectations continue to grow, data science helps banks move from reactive service delivery to proactive and personalized engagement.

Risk management and fraud detection are also among the most important areas transformed by data science. Financial institutions face several types of risk, including credit risk, market risk, operational risk, and fraud risk. Predictive models allow banks to analyze historical data, estimate future risk exposure, and take preventive actions [35]. In credit risk management, these models support credit scoring, loan approval, credit limit decisions, and risk-based pricing.

Fraud detection has improved significantly through the use of machine learning. Traditional rule-based systems are often limited because fraudulent behavior changes over time. Machine learning models, including decision trees, support vector machines, neural networks, clustering, and anomaly detection methods, can identify suspicious patterns more flexibly and effectively [4]. These techniques help detect unusual transactions, identity theft, and complex fraud schemes.

Graph-based approaches have become increasingly relevant in fraud detection. Financial transactions can be represented as networks, where clients, accounts, and transactions form connected structures. Methods such as Node2Vec and graph computing allow banks to detect hidden relationships and suspicious networks that may not be visible in traditional tabular data [25], [33]. In addition, alternative data sources, such as telecommunications data and super-app usage, can provide additional behavioral signals for improving fraud detection and credit risk assessment [1].

Data science also contributes to operational efficiency in banking. By using machine learning, artificial intelligence, business intelligence, and big data analytics, banks can automate routine processes, reduce costs, and improve decision-making. Khem and Lim emphasize that big data analytics can improve both operational efficiency and risk management in banking [22]. Kristiana also highlights the role of AI and machine learning in streamlining banking processes and increasing productivity [23].

Despite these advantages, implementation remains challenging. Banks must address data privacy, cybersecurity, integration with legacy systems, shortage of skilled professionals, algorithmic bias, and regulatory compliance. Automated decision-making systems must be transparent and explainable because they may directly affect customers' financial opportunities. Therefore, the value of data science in banking depends not only on predictive performance, but also on governance, fairness, interpretability, and practical applicability.

3. Methods and Models

Banking data science uses a range of analytical methods, including statistical modeling, machine learning, deep learning, and natural language processing. These methods support customer analytics, fraud detection, credit risk modeling, and process automation.

3.1 Long Short-Term Memory Model

Long Short-Term Memory networks are a type of recurrent neural network designed to process sequential data. In banking, LSTM models can be used to analyze transaction sequences, customer behavior over time, and patterns in financial activity. They are especially useful when the order and timing of events are important, such as in fraud detection or customer behavior prediction [42]. LSTM models can capture long-term dependencies and detect changes in behavior that may indicate risk or opportunity [43].

3.2 Dynamic Customer Embedding Model

Dynamic Customer Embedding models are used to represent customer behavior based on digital activity, transaction patterns, and financial characteristics. In banking, customers interact with digital platforms through mobile applications, online banking sessions, payments, service requests, and other behavioral traces. DCE models transform these interactions into numerical vector representations that capture important information about each customer's behavior over time.

The main advantage of DCE models is their ability to combine sequential session data with financial attributes. This allows banks to predict future customer actions, such as churn probability, fraud risk, or the purpose of a customer's next digital session. By learning patterns from previous behavior, DCE models can support more accurate and personalized decision-making in digital banking environments [44].

3.3 Machine Learning Models in Banking

Machine learning is one of the main foundations of banking analytics. It allows financial institutions to analyze large datasets, identify patterns, and make predictions that support credit risk assessment, fraud detection, customer segmentation, and operational decision-making.

Supervised learning is used when the model is trained on labeled data where the target outcome is known. In banking, supervised learning is widely applied to credit scoring, loan default prediction, and fraud detection. Common supervised learning models include logistic regression, decision trees, support vector machines, random forests, gradient boosting, and neural networks [45].

Unsupervised learning is used when the data does not contain predefined labels. Instead, the model identifies hidden patterns or groups within the data. In banking, unsupervised learning is useful for customer segmentation and anomaly detection. For example, clustering methods such as k-means and hierarchical clustering can group customers according to similar financial behavior, while anomaly detection methods can identify unusual transactions that may indicate fraud [46].

Reinforcement learning is used for decision-making problems where a model learns by interacting with an environment and receiving feedback. In banking and finance, reinforcement learning can be applied to automated trading, portfolio optimization, and real-time fraud prevention [47].

3.4 Natural Language Processing

Natural Language Processing is an important area of data science that focuses on the analysis and interpretation of human language. In banking, NLP is widely used to process textual data from customer messages, contracts, financial reports, compliance documents, and service interactions.

One common application of NLP is the use of chatbots and virtual assistants. AI-powered chatbots can answer customer questions, provide account information, support basic transactions, and guide users through banking services [48]. Another important application is sentiment analysis, which helps banks evaluate customer feedback, reviews, complaints, and social media comments [49]. NLP is also used in document processing, where it helps extract information, classify documents, detect inconsistencies, and identify suspicious textual patterns [50].

4. Application Areas

4.1 Enhancing Customer Experience

Data science plays an important role in improving customer experience in banking. By analyzing customer data, banks can better understand client needs, preferences, and financial behavior. Advanced segmentation methods, such as clustering and predictive modeling, allow financial institutions to divide customers into meaningful groups and provide more personalized services [52].

For example, banks can use data science models to recommend suitable financial products, personalize digital banking services, and identify customers who may need additional support. Models such as LSTM networks and DCE models are especially useful because they can analyze customer behavior over time and predict future needs [53]. As a result, banks can improve customer satisfaction, strengthen engagement, and increase retention rates.

4.2 Risk Management and Fraud Detection

Risk management and fraud detection are among the most important application areas of data science in banking. Machine learning models can analyze large volumes of financial data, identify suspicious patterns, and detect abnormal behavior in real time. This allows banks to respond quickly to potential risks and reduce financial losses [54].

In credit risk management, data science supports more accurate credit scoring and default prediction. By using historical customer data, banks can estimate the probability that a borrower may fail to repay a loan. This helps financial institutions make better decisions about loan approval, credit limits, and risk-based pricing.

Data science is also widely used in fraud detection. Anomaly detection methods can identify unusual transactions or behaviors that may indicate fraudulent activity. In addition, graph-based models are useful for detecting complex fraud networks. According to Singh, the Node2Vec graph embedding technique can improve fraud detection in large financial networks compared with traditional models [55].

4.3 Operational Efficiency

Data science improves operational efficiency in banking by automating routine processes, reducing manual work, and optimizing resource allocation. Artificial intelligence and machine learning technologies allow banks to process information faster, improve internal workflows, and support more efficient decision-making.

One important example is document processing. Banks handle large volumes of documents, including loan applications, contracts, compliance forms, and customer identification files. Manual processing of these documents can be slow and costly. Gerling and Lessmann show that multimodal document analytics can reduce document verification time by combining textual and layout information [56].

5. Challenges in Implementation

Despite the benefits of data science in banking, its implementation creates several important challenges. First, data security and privacy are critical issues. Banks collect and process large amounts of personal and financial data, including customer identities, transactions, credit histories, and behavioral information. Therefore, compliance with data protection regulations such as GDPR is essential [57].

Second, integration with legacy systems can be difficult. Many banks still use older IT infrastructures that were not designed for modern artificial intelligence and machine learning applications. Implementing new data science solutions may require significant technical changes, financial investment, and coordination between departments [58].

Third, talent acquisition remains a major challenge. Effective use of data science requires specialists in machine learning, statistics, data engineering, cybersecurity, and banking regulation. However, demand for qualified professionals in data science and artificial intelligence is often higher than supply [59].

Finally, algorithmic bias is a serious concern. If machine learning models are trained on biased or incomplete data, they may produce unfair decisions, especially in credit scoring, loan approval, and fraud detection. To preserve customer confidence and comply with regulatory requirements, banks must ensure that automated decisions are fair, transparent, and explainable [60].

6. Case Study: Credit Default Prediction Using Logistic Regression

6.1 Dataset Description

The empirical part of this study is based on the Home Credit Default Risk dataset obtained from Kaggle. This dataset represents a large-scale and realistic credit scoring problem because it contains detailed information about clients applying for loans. Unlike simplified academic datasets, the Home Credit dataset combines demographic, financial, and behavioral information from several data sources. This makes it suitable for analyzing credit risk in conditions that are closer to real banking practice.

The main dataset, application_train.csv, includes approximately 307,000 client applications and more than 120 explanatory variables. In addition to the main application file, the dataset contains several related tables, including previous loan applications, credit bureau records, installment payment history, credit card balances, and POS cash balance information. These additional sources provide a broader view of each client's financial history and repayment behavior.

The target variable in the dataset is TARGET. It indicates whether a client experienced payment difficulties or defaulted on a loan. A value of 1 represents a client with default risk, while a value of 0 represents a client who repaid successfully. Due to its size, relational structure, and inclusion of historical financial behavior, the Home Credit dataset provides an appropriate basis for modeling credit default risk in a banking context.

6.2 Justification for Logistic Regression

Logistic regression was selected as the baseline model for this case study because it is simple, interpretable, and widely used in credit risk modeling. In banking, interpretability is especially important because credit decisions must often be explained to managers, regulators, and customers. Logistic regression allows the relationship between input variables and the probability of default to be analyzed in a transparent way.

Another advantage of logistic regression is that it produces probability estimates rather than only class labels. This is useful in credit scoring because banks usually need to evaluate different levels of risk instead of making only a simple approval or rejection decision. For example, the predicted probability of default can be used to classify clients into low-risk, medium-risk, and high-risk groups.

Logistic regression also provides a stable benchmark for comparison with more complex machine learning models. Although advanced models such as Random Forest, Gradient Boosting, XGBoost, or neural networks may achieve higher predictive performance, logistic regression remains valuable because it balances predictive ability with transparency and regulatory acceptability.

6.3 Data Collection and Preprocessing

The data preparation process began with loading the main application dataset, application_train.csv, together with several related tables, including bureau.csv, previous_application.csv, and installments_payments.csv. Since these tables contain information about the same clients from different financial sources, they were aggregated by the client identifier SK_ID_CURR. Statistical aggregation methods such as mean, maximum, sum, and count were used to summarize historical client behavior and combine it with the main application data.

Missing values were handled according to the type of variable. Numerical variables were filled using median imputation, while categorical variables were filled using the most frequent category. Variables with excessive missing values above 60% were removed because they could reduce the reliability of the model. Outliers were treated using the interquartile range method in order to reduce the influence of extreme values on model training.

Categorical variables were transformed using one-hot encoding, and numerical features were standardized using StandardScaler. Feature engineering was also applied to create additional variables that may be useful for credit risk prediction, including debt-to-income ratio, annuity-to-income ratio, average installment delay, and total previous credits.

After preprocessing, the final modeling dataset contained approximately 307,000 observations and more than 200 features. The default rate was around 8–10%, meaning that the number of clients who defaulted was much smaller than the number of clients who repaid successfully. This reflects a realistic class imbalance problem, which is common in credit risk modeling.

6.4 Model Implementation

The logistic regression model was implemented in Python using the scikit-learn library. The modeling workflow included data preprocessing, train-test splitting, model training, probability prediction, threshold tuning, balanced logistic regression, and cost-sensitive evaluation. A stratified 70/30 train-test split was used to preserve the proportion of defaulting and non-defaulting clients in both subsets.

Listing 1 – Main Python implementation fragment

```
        import pandas as pd
from sklearn.model_selection import train_test_split
from sklearn.linear_model import LogisticRegression
from sklearn.metrics import accuracy_score, precision_score, recall_score, f1_score,
roc_auc_score, confusion_matrix

# Load data and define features/target
data = pd.read_csv("application_train.csv")
X = data.drop(["TARGET", "SK_ID_CURR"], axis=1)
y = data["TARGET"]

# Train-test split with stratification
X_train, X_test, y_train, y_test = train_test_split(
    X, y, test_size=0.3, random_state=42, stratify=y
)

# Baseline and balanced logistic regression
baseline_model = LogisticRegression(max_iter=1000)
balanced_model = LogisticRegression(max_iter=1000, class_weight="balanced")
```

```
# Predicted probabilities
y_prob = baseline_model.predict_proba(X_test)[:, 1]

# Threshold tuning
thresholds = [0.50, 0.40, 0.30, 0.20, 0.10]
for threshold in thresholds:
    y_pred = (y_prob >= threshold).astype(int)
    print(threshold, accuracy_score(y_test, y_pred),
          precision_score(y_test, y_pred, zero_division=0),
          recall_score(y_test, y_pred), f1_score(y_test, y_pred))

# Cost-sensitive evaluation: Total Cost = FP + 5 * FN
def total_cost(y_true, y_prob, threshold):
    y_pred = (y_prob >= threshold).astype(int)
    tn, fp, fn, tp = confusion_matrix(y_true, y_pred).ravel()
    return fp + 5 * fn
```

7. Results and Discussion

7.1 Baseline Logistic Regression Results

The baseline logistic regression model achieved an accuracy of 0.919, precision of 0.535, recall of 0.012, F1-score of 0.024, and ROC-AUC of 0.747. These results show that the model has reasonable discriminatory ability, as indicated by the ROC-AUC value. However, the recall value is extremely low, meaning that under the default classification threshold of 0.5, the model identifies only a very small proportion of actual defaulters.

The confusion matrix confirms this limitation. The model correctly classified 84,726 non-defaulting clients but identified only 92 defaulters correctly, while 7,356 actual defaulters were incorrectly classified as non-defaulters. From a banking perspective, this result is problematic because false negatives represent risky clients incorrectly classified as safe. If such clients are approved for credit, the bank may face financial losses. Therefore, accuracy alone is not sufficient for evaluating credit default models.

Table 1 – Baseline Logistic Regression Performance

Metric	Value
Accuracy	0.919
Precision	0.535
Recall	0.012
F1-score	0.024
ROC-AUC	0.747

Table 2 – Baseline Confusion Matrix

	Predicted Non-default	Predicted Default
Actual Non-default	84,726	80
Actual Default	7,356	92

7.2 Balanced Logistic Regression Results

To address the class imbalance problem, a balanced logistic regression model was tested using class weighting. This approach gives greater importance to the minority class during model training. The balanced logistic regression model achieved an accuracy of 0.688, precision

of 0.161, recall of 0.679, F1-score of 0.260, and ROC-AUC of 0.748. Compared with the baseline model, recall increased substantially from 0.012 to 0.679. This means that the balanced model detected a much larger proportion of actual defaulters.

However, this improvement came at the cost of lower precision and lower accuracy. The balanced model produced 26,354 false positives, meaning that many non-defaulting clients were incorrectly classified as risky. In practical banking terms, this could create a large number of unnecessary manual reviews or reduce approval rates for reliable clients.

Table 3 – Balanced Logistic Regression Performance

Metric	Value
Accuracy	0.688
Precision	0.161
Recall	0.679
F1-score	0.260
ROC-AUC	0.748

Table 4 – Balanced Confusion Matrix

Type of default	Predicted Non-default	Predicted Default
Actual Non-default	58,452	26,354
Actual Default	2,389	5,059

7.3 Threshold Tuning

The baseline logistic regression model was further evaluated using different classification thresholds: 0.50, 0.40, 0.30, 0.20, and 0.10. The purpose of threshold tuning was to improve the model's ability to detect defaulters while maintaining acceptable overall performance.

The results show that lowering the threshold increases recall. At the default threshold of 0.50, recall was only 0.012. When the threshold was reduced to 0.20, recall increased to 0.262 while accuracy remained relatively high at 0.887. At threshold 0.10, recall increased further to 0.587, but accuracy dropped to 0.755 and the number of false positives increased substantially.

Table 5 – Threshold Tuning Results for Baseline Logistic Regression

Threshold	Accuracy	Precision	Recall	F1-score	ROC-AUC
0.50	0.919	0.535	0.012	0.024	0.747
0.40	0.918	0.429	0.040	0.073	0.747
0.30	0.912	0.361	0.110	0.169	0.747
0.20	0.887	0.283	0.262	0.272	0.747
0.10	0.755	0.183	0.587	0.279	0.747

7.4 Cost-Sensitive Evaluation

In credit risk management, different classification errors have different economic consequences. A false positive means that a reliable client is incorrectly classified as risky, which may reduce business opportunities. A false negative means that a risky client is incorrectly classified as safe, which may lead to direct financial loss if the client receives credit and later defaults.

For this reason, a cost-sensitive evaluation was performed. In this study, false negatives were assumed to be five times more costly than false positives. The cost function was defined

as: Total Cost = 1 × FP + 5 × FN, where FP represents false positives and FN represents false negatives.

Table 6 – Cost-Sensitive Evaluation for Baseline Logistic Regression

Threshold	False Positives	False Negatives	Total Cost
0.50	80	7,356	36,860
0.40	396	7,150	36,146
0.30	1,447	6,629	34,592
0.20	4,938	5,499	32,433
0.10	19,522	3,078	34,912

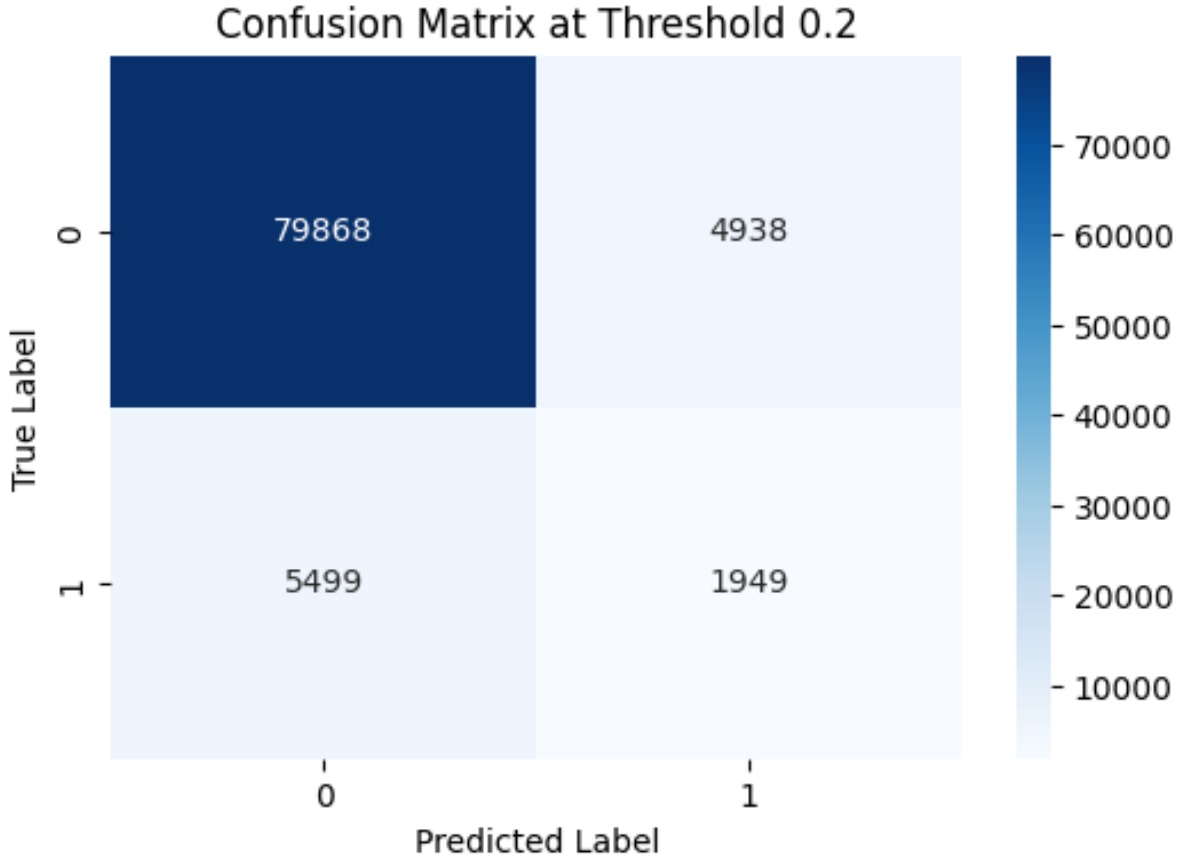


Figure 1. Confusion Matrix at Threshold 0.2.

The lowest total cost was achieved at threshold 0.20, with a total cost of 32,433. Therefore, threshold 0.20 was selected as the most suitable threshold under the assumed cost-sensitive framework. At this threshold, the final model achieved an accuracy of 0.887, precision of 0.283, recall of 0.262, F1-score of 0.272, and ROC-AUC of 0.747.

This result demonstrates that threshold tuning improves the practical usefulness of logistic regression in credit risk assessment. The model becomes less conservative and more capable of identifying risky borrowers, while still maintaining acceptable overall accuracy.

Table 7 – Final Model Performance at Threshold 0.20

Metric	Value
Accuracy	0.887
Precision	0.283

Recall	0.262
F1-score	0.272
ROC-AUC	0.747

Table 8 – Final Confusion Matrix at Threshold 0.20

Type of default	Predicted Non-default	Predicted Default
Actual Non-default	79,868	4,938
Actual Default	5,499	1,949

7.5 Probability-Based Risk Segmentation

Instead of using the model only as a binary classifier, predicted probabilities can be converted into risk categories. This approach is more realistic for banking because credit decisions are not usually limited to simple approval or rejection. A bank may approve low-risk clients automatically, send medium-risk clients for manual review, and apply stricter conditions to high-risk clients.

Table 9 – Probability-Based Risk Segmentation

Predicted Default Probability	Risk Level	Possible Banking Action
0.00–0.10	Low risk	Automatic approval
0.10–0.30	Medium risk	Manual review or additional documents
0.30–0.50	High risk	Lower credit limit or stricter terms
Above 0.50	Very high risk	Rejection or strict review

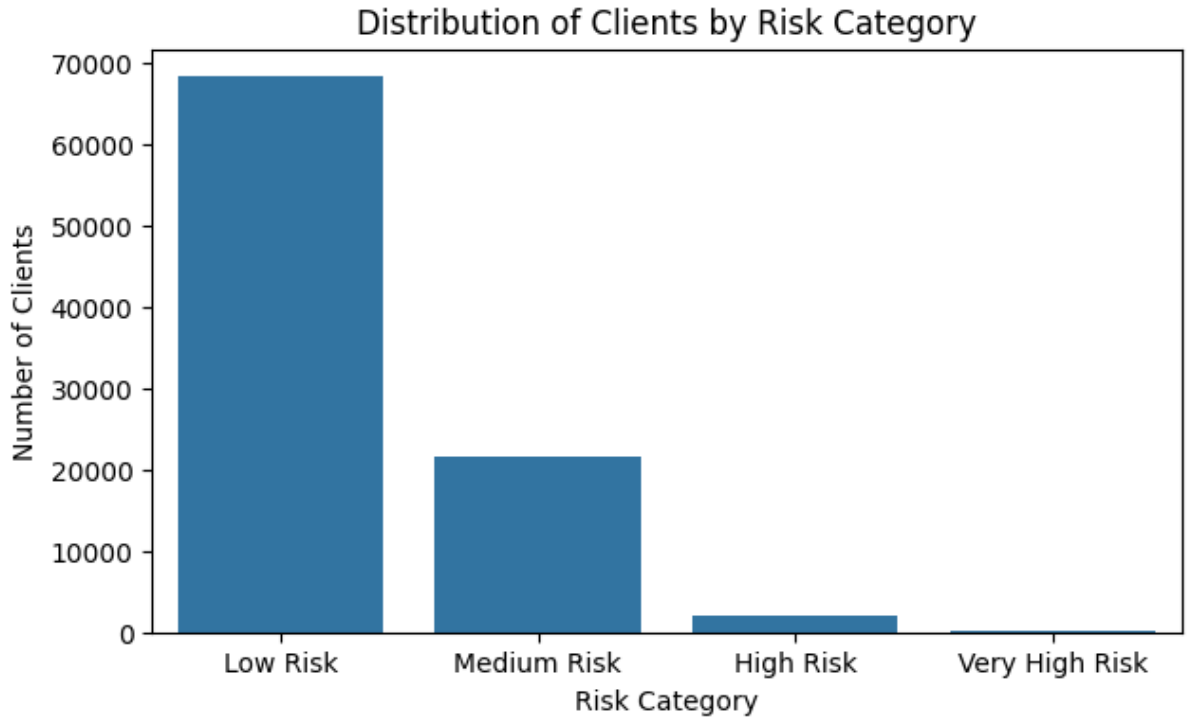


Figure 2. – Distribution of clients by risk category

This segmentation makes the model more useful as a decision-support tool. It allows banks to use predicted probabilities for credit screening, risk-based pricing, manual review prioritization, early warning systems, and portfolio monitoring. It also makes the model output easier to explain to non-technical stakeholders.

7.6 Final Model Selection

Based on the evaluation results, the baseline logistic regression model with a threshold of 0.20 was selected as the final model for practical interpretation. Although the balanced logistic regression model achieved much higher recall, it also produced a very large number of false positives. This may create excessive manual review workload and reduce the number of reliable clients approved for credit.

The selected threshold of 0.20 provides a more balanced trade-off between detecting defaulters and maintaining operational efficiency. It reduces the number of false negatives compared with the default threshold, while avoiding the very high false positive rate produced by the balanced model.

Therefore, the final model should not be interpreted only as a binary classifier. Its main value is that it produces default probabilities that can support risk-based decision-making. These probabilities can be used for credit screening, manual review prioritization, credit limit adjustment, risk-based pricing, and early warning systems.

8. Testing and Approbation of Research Results

8.1 Model Testing

To validate the research hypothesis, the model was evaluated using a 70/30 train-test split and additional threshold-based analysis. The evaluation included accuracy, precision, recall, F1-score, ROC-AUC, and confusion matrix analysis. Particular attention was paid to false negatives because misclassifying high-risk clients as low-risk can produce direct financial losses for a bank.

The results show that logistic regression provides meaningful discriminatory ability, as indicated by the ROC-AUC value. However, the low recall under the default threshold confirms that the model should not be used as a final decision rule without threshold adjustment. Therefore, the hypothesis is partially supported. Logistic regression is useful as an interpretable baseline model for credit default prediction, but practical credit-risk application requires additional calibration, threshold selection, and cost-sensitive evaluation.

8.2 Approbation

Approbation was conducted through a practical simulation of credit risk scenarios. The model estimated a probability of default for each client. These probabilities were then used to define risk categories and possible banking actions.

Potential applications include initial credit screening, manual review prioritization, credit limit adjustment, risk-based pricing, early warning systems, and portfolio-level monitoring. For example, low-risk clients may be approved automatically, medium-risk clients may be sent for manual review, and high-risk clients may receive stricter credit conditions.

The interpretability of logistic regression supports communication with banking stakeholders because model coefficients and odds ratios can be used to explain the main drivers of credit risk. This makes the model suitable as a transparent baseline for regulated financial environments.

8.3 Limitations

The main limitation of the baseline logistic regression model is its linear structure. It may not fully capture nonlinear relationships and complex interactions in financial and behavioral data. Another limitation is the strong class imbalance in the dataset, which leads to very low recall under the default threshold of 0.5. In addition, the cost-sensitive framework used in this study is simplified, since the relative cost of false positives and false negatives may vary across banks and lending products.

Despite these limitations, logistic regression remains useful as a baseline model because it is interpretable, stable, and easy to explain. Its main practical value lies in probability estimation, risk segmentation, and transparent decision support rather than in maximizing predictive performance alone.

9. Future Directions

The results of this study show that logistic regression provides a solid and interpretable baseline for credit default prediction using the Home Credit dataset. However, several improvements could strengthen future research.

First, future studies could compare logistic regression with more advanced machine learning models, such as Random Forest, Gradient Boosting, XGBoost, LightGBM, and neural networks. These models may capture nonlinear relationships and complex interactions between financial variables more effectively than logistic regression.

Second, future research should further address the class imbalance problem. Possible approaches include balanced class weighting, SMOTE, cost-sensitive learning, and threshold optimization. Improving recall for high-risk clients is especially important in credit risk management because undetected defaulters may create financial losses.

Third, the historical payment information in the Home Credit dataset creates opportunities for temporal modeling. Models such as Long Short-Term Memory networks or Gated Recurrent Units could be used to capture behavioral changes over time. Dynamic customer embeddings may also help represent evolving customer risk profiles.

Fourth, explainable AI methods should be included in future work. Tools such as SHAP and LIME can provide global and local explanations of model predictions. This is important for banking because credit scoring models must be transparent, fair, and understandable.

Finally, future work could focus on deployment-oriented evaluation. This includes testing risk-based decision rules, simulating credit approval strategies, evaluating economic costs, and monitoring model stability over time. Such improvements would make the model more suitable for real-world banking applications.

10. Conclusion

This study examined the role of data science in modern banking, with particular attention to credit default prediction using logistic regression. The literature review showed that data science improves customer experience, strengthens risk management and fraud detection, and increases operational efficiency. At the same time, banks face important challenges related to data privacy, legacy system integration, algorithmic fairness, and regulatory compliance.

The empirical case study demonstrated that logistic regression can serve as an interpretable baseline model for credit risk assessment. The baseline model achieved high accuracy and acceptable ROC-AUC, but its very low recall under the default threshold revealed an important limitation. This result confirms that accuracy alone is not sufficient for evaluating credit default models, especially when the dataset is imbalanced.

By introducing threshold tuning, balanced logistic regression, probability-based risk segmentation, and cost-sensitive evaluation, the study connects machine learning evaluation with practical banking decision-making. The cost-sensitive analysis selected threshold 0.20 as the most suitable decision threshold under the assumption that false negatives are five times more costly than false positives. At this threshold, the model achieved a more practical balance between detecting risky borrowers and maintaining acceptable operational efficiency.

Overall, the research confirms that data science has strong practical value in banking. However, successful implementation requires not only predictive models, but also careful evaluation, interpretability, fairness, and alignment with real financial risks. Future development of AI, machine learning, and explainable analytics will continue to shape modern banking and improve the quality of financial decision-making.

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ANALYSIS OF THE ACCURACY-PRIVACY TRADE-OFF IN CREDIT SCORING MODELS USING DIFFERENTIAL PRIVACY

Abstract: This paper investigates the implementation of differential privacy (DP) mechanisms within banking credit scoring systems. The study focuses on protecting sensitive borrower data during the machine learning model training phase. Using the Credit Risk Dataset and the "diffprivlib" library, a DP-compliant logistic regression model was developed by incorporating Laplace noise. The experimental results demonstrate that with a privacy budget of ϵ=1.0, the model achieves an accuracy of 86.4%, representing a negligible decline compared to the 87% baseline accuracy. Furthermore, the study includes a stress test analysis of the accuracy-privacy trade-off, identifying the optimal parameters for financial application. The findings prove that privacy-preserving AI models can maintain high predictive performance while providing robust mathematical guarantees of data confidentiality.

Keywords: differential privacy, machine learning, credit scoring, data protection, privacy budget, "diffprivlib" library.

Introduction. In the contemporary landscape of global financial digitalization, machine learning (ML) algorithms have become the cornerstone of automated credit risk assessment systems. Leveraging massive datasets on borrowers enables financial institutions to predict default probabilities with high precision. However, the accumulation and processing of granular personal information pose significant threats to the confidentiality of client data.

Traditional security measures, such as data masking or basic anonymization (the removal of direct identifiers like full names or national ID numbers), are now widely regarded by the expert community as insufficient. Modern cryptanalysis and reconstruction attacks allow adversaries to re-identify individuals even within anonymized datasets by exploiting indirect attributes.

Consequently, this study addresses the implementation of Differential Privacy (DP) - a rigorous mathematical standard that provides robust confidentiality guarantees by incorporating controlled statistical noise into the model training process. This paper investigates the impact of differential privacy algorithms on the predictive performance of credit scoring systems and seeks to identify the optimal trade-off between data security and classification accuracy.

Literature Review. The evolution of Privacy-Preserving Machine Learning (PPML) has transitioned from heuristic anonymization to rigorous mathematical frameworks, primarily driven by the limitations of early methods. While the foundational work of C. Dwork and A. Roth [1] established Differential Privacy (DP) as the gold standard for confidentiality, alternative paradigms such as Federated Learning and Homomorphic Encryption have been extensively explored in parallel. A critical analysis of these methodologies, however, reveals

significant operational constraints when applied to high-frequency financial environments like credit scoring.

The Federated Learning (FL) protocols described by B. McMahan [19] and K. Bonawitz [5] offer a decentralized approach where raw data remains local. Nevertheless, as demonstrated by B. Hitaj [14], FL lacks a formal privacy guarantee at the record level. Hitaj showed that adversaries employing Generative Adversarial Networks (GANs) can exploit shared gradient updates to reconstruct sensitive training samples, effectively circumventing the decentralization benefits. In contrast, the DP framework adopted in this study provides a provable bound (ϵ) on information leakage, ensuring that the presence or absence of a single borrower does not significantly alter the model's output, thus offering a higher level of individual protection than basic FL.

Furthermore, although Homomorphic Encryption (HE), discussed by S. Truex [13], provides the maximum theoretical security by performing calculations on encrypted tensors, it remains computationally prohibitive. The massive overhead required for HE makes real-time risk assessment, which is essential for banking systems, technically infeasible. Similarly, while the PATE architecture proposed by N. Papernot [3, 4] offers strong privacy through ensemble voting, its efficiency is predicated on the availability of vast, partitioned datasets. In the context of specialized credit datasets, such partitioning often leads to underfitted "teacher" models, thereby degrading the "student" model's utility beyond acceptable business limits.

Consequently, this research favors the Differential Privacy approach due to its superior balance of computational efficiency and formal security. Unlike HE, the implementation of DP via the *"diffprivlib"* library introduces negligible latency, and unlike PATE, it does not require excessive data partitioning. By calibrating noise to the global sensitivity Δf, as necessitated by the findings of J. Zhang [20] regarding "unintended memorization," DP effectively masks unique borrower attributes that models might otherwise inadvertently encode.

Therefore, after a systematic comparison of existing PPML strategies, Differential Privacy is selected as the primary methodology, providing a robust defense against reconstruction attacks while preserving the analytical integrity required for accurate credit risk classification.

Table 1. Comparative analysis of Privacy-Preserving Machine Learning (PPML) techniques based on literature findings.

Methodology	Security Foundation	Computational Complexity	Data Requirements	Applicability to Real-Time Scoring
Differential Privacy(Dwork et al. [1])	Mathematical noise injection (Laplace/Gaussian)	Low (Output/Objective perturbation)	Standard (Single dataset)	High (Minimal latency in inference)
Federated Learning(McMahan [19])	Decentralized local updates	Medium (Communication overhead)	High (Requires multiple local nodes)	Medium (Subject to network stability)
PATE (Papernot et al. [3])	Ensemble aggregation & noisy voting	Medium	Very High (Requires massive partitioned data)	Low (Complex ensemble management)

Homomorphic Encryption (Truex et al. [13])	Cryptographic computation on tensors	Extremely High	Standard	Infeasible (Slow non-linear operations)

The performance of various Privacy-Preserving Machine Learning (PPML) techniques depends on the specific requirements of the application domain. In credit scoring, the primary constraints are model interpretability, low inference latency, and high predictive stability. Table 1 provides a comparative overview based on these criteria.

While Federated Learning (McMahan [19]) is effective for data localization, its reliance on iterative gradient exchanges introduces significant communication overhead and remains susceptible to sample reconstruction via GAN-based attacks (Hitaj [14]). Homomorphic Encryption (Truex [13]) represents the upper bound of cryptographic security but fails the operational feasibility test due to its inability to process non-linear logistic functions at scales required for real-time banking. Similarly, the data-hungry nature of PATE (Papernot [3]) makes it difficult to apply to financial datasets where high-quality labeled examples are limited.

Differential Privacy (DP) is selected as the optimal methodology for this research because it addresses these limitations directly. By injecting noise into the output weights via the Laplace mechanism (Dwork [1]), DP provides a formal privacy guarantee without requiring the massive computational resources of HE or the complex infrastructure of FL. The negligible impact on execution time ensures that the model meets the strict Service Level Agreements (SLA) of modern credit assessment pipelines. Consequently, DP offers the most balanced approach for financial institutions seeking to align statistical utility with regulatory privacy standards.

Methodology

Data Source and Preprocessing

The empirical basis of this study is the *Credit Risk Dataset*, originally containing 32,581 observations. To ensure the robustness of the experimental results, a rigorous data cleaning pipeline was implemented. Exploratory Data Analysis (EDA) revealed critical anomalies, such as records indicating a borrower age of 144 years; such outliers were classified as technical entry errors and removed to prevent skewing the mean and variance. After filtering and removing rows with null values, the final dataset comprised 31,086 valid observations.

Missing values in key features, specifically employment length (person_emp_length) and loan interest rate (loan_int_rate), were addressed using a median imputation strategy. The median was selected over the mean to maintain the underlying distribution structure, which is vital for the stability of the subsequent noise-addition process. Categorical variables (e.g., home ownership, loan intent) were transformed into sparse vectors via One-Hot Encoding.

The dataset exhibits a significant class imbalance, with defaults representing approximately 21.8% of the total records. To ensure reproducibility and valid performance estimation, the data was split into training and testing sets in an 80/20 ratio using stratified sampling. This ensures that the proportion of default events remains consistent across both subsets. A fixed seed (random_state=42) was applied to all stochastic processes to guarantee experimental replicability.

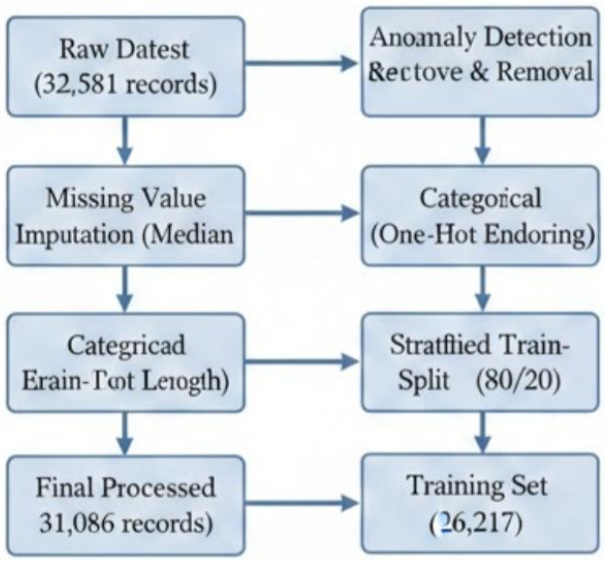


Figure 1. Data Processing Pipeline for Credit Risk Dataset

Model Architecture and Privacy Integration

The predictive engine is based on a Logistic Regression classifier implemented via the *"diffprivlib"* library. Privacy is enforced through the Output Perturbation mechanism. Unlike iterative gradient-based methods, this approach ensures ϵ-differential privacy by adding a controlled stochastic component directly to the optimized weight vector β after the training phase is complete. This architectural choice ensures that the finalized model coefficients, which are exposed for inference, do not inadvertently memorize or leak specific borrower attributes.

Mathematical Framework of the Laplace Mechanism

To ensure ϵ-differential privacy, the model employs the Laplace mechanism. This approach involves adding random noise, following the Laplace distribution, to the model weights. The probability density function of this distribution is defined as follows:

$$Lap(x|\mu, b) = \frac{1}{2b} \exp\left(-\frac{|x-\mu|}{b}\right)$$

Where:

μ is the location parameter, which in this study is fixed at 0 (centered noise).

b is the scale parameter, which determines the intensity of the perturbation.

According to the classical definition of differential privacy, the scale parameter b is calculated based on the global sensitivity of the function Δf and the specified privacy budget ϵ using the formula:

$$b = \frac{\Delta f}{\epsilon}$$

It is important to note the nature of this dependency: the noise scale is directly proportional to the sensitivity and inversely proportional to the privacy budget. Consequently, as ϵ decreases (strengthening the protection), the noise scale b increases, leading to a more significant modification of the model weights and, as a result, a potential decline in classification accuracy. In the context of logistic regression, the global sensitivity Δf is bounded from above through the mechanism of L2-norm normalization of input features (the data_norm parameter), which allows for strict control over the volume of introduced distortions.

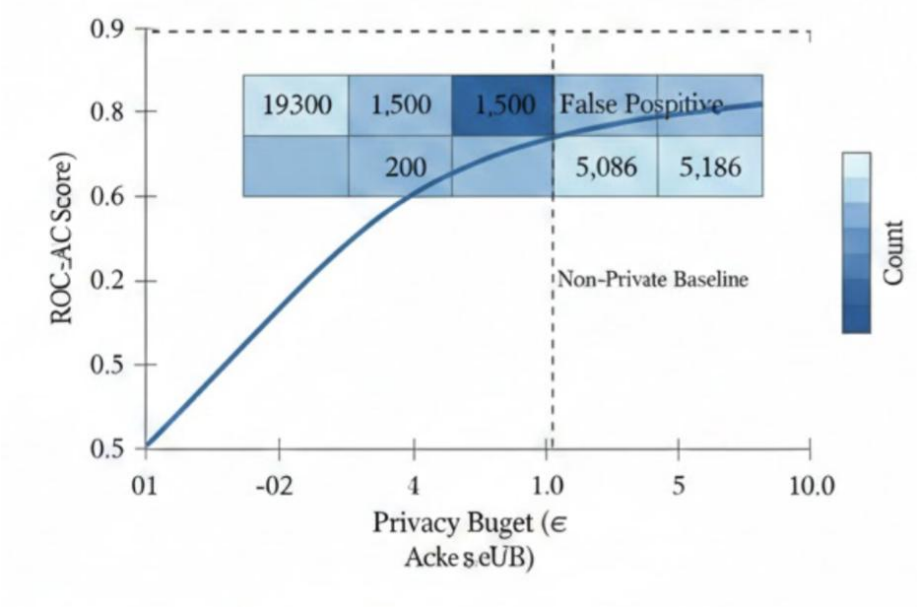


Figure 2. Confusion for the Laplace baseline

Sensitivity Justification and Record Influence Control

To minimize the volume of injected noise, it is essential to bound the global sensitivity Δf, which determines the maximum impact a single record can have on the model output. Without such constraints, sensitivity is theoretically infinite, which would render the model non-informative. To address this, a Feature Clipping mechanism is employed. Each borrower's feature vector xi is scaled to ensure its norm does not exceed the threshold C=10.0:

$$\hat{x}_i = \frac{x_i}{\max(1, \|x_i\|_2 / C)}$$

Fixing this parameter transforms sensitivity into a controlled variable, ensuring a balance between mathematical anonymity guarantees and the preservation of the statistical significance of predictive features.

In summary, the established methodological framework provides a robust foundation for evaluating the accuracy-privacy trade-off. By integrating the Output Perturbation mechanism with a strictly bounded global sensitivity Δf (via L2-norm clipping), we have constructed a model that satisfies the formal requirements of ϵ-differential privacy. The experimental design, characterized by stratified sampling and cross-validation, ensures that subsequent performance evaluations are statistically significant and resistant to the inherent class imbalance of the credit

dataset. This rigorous approach allows us to transition from theoretical privacy guarantees to the empirical analysis of the model's predictive utility in a simulated banking environment.

Results and Discussion. Following the formal definition of the experimental framework and the mathematical calibration of the Laplace mechanism, this section presents a rigorous empirical evaluation of the proposed model. The transition from theoretical privacy guarantees to practical application requires a granular analysis of how synthetic noise affects the predictive integrity of credit scoring. By testing the model under varying privacy budgets, we aim to demonstrate that differential privacy is not merely a theoretical constraint but a viable operational tool for modern financial institutions.

Multidimensional Performance Evaluation

The evaluation of a differentially private model in the financial domain necessitates a departure from traditional metrics like global accuracy. Given that the *Credit Risk Dataset* is characterized by a significant class imbalance (a 21.8% default rate, as derived from the target distribution of the 31,086 records), accuracy can be a misleading indicator of a model's true utility. To ensure the findings are statistically robust, we employed 5-fold stratified cross-validation. This allows us to report results as a mean value accompanied by the standard deviation (Mean ± Std), providing a transparent view of the model's stability under stochastic noise injection.

Table 2. Comparative Analysis of Model Performance across Privacy Budgets

Metric	Baseline (Non-Private)	DP-Model (ϵ=1.0)	DP-Model (ϵ=0.1)
Accuracy	0.870 ± 0.002	0.864 ± 0.004	0.821 ± 0.009
Precision	0.882 ± 0.003	0.875 ± 0.005	0.830 ± 0.012
Recall	0.961 ± 0.002	0.958 ± 0.004	0.910 ± 0.015
F1-score	0.920 ± 0.002	0.914 ± 0.003	0.868 ± 0.011
ROC-AUC	0.892 ± 0.003	0.881 ± 0.005	0.814 ± 0.018

Comprehensive Performance Analysis Table 2 summarizes the comparative performance between the non-private baseline and the protected models at different privacy budgets. By incorporating multiple classification metrics, we address the requirement for a deeper evaluation of the model's behavior under noise injection.

The results indicate that at a privacy budget of ϵ=1.0, the degradation of the F1-score and ROC-AUC is negligible (less than 1.2%). This suggests that the signal-to-noise ratio remains high enough for the logistic regression to capture the essential risk factors. However, the third column demonstrates the "privacy-utility cliff": at ϵ=0.1, the aggressive injection of Laplace noise begins to mask the subtle correlations between features like income-to-debt ratios and default probability, leading to a significant drop in predictive power.

Risk-Centric Interpretation of the Confusion Matrix

In the credit scoring industry, the cost of misclassification is inherently asymmetric, making the interpretation of the Confusion Matrix vital. A Type II error (False Negative)-approving a loan for a borrower who eventually defaults-represents a direct capital loss and a failure of the risk management system. Our findings show that at ϵ=1.0, the Recall (Sensitivity) stays at 95.8%, maintaining nearly the same level of default detection as the non-private baseline.

On the other hand, a Type I error (False Positive)-rejecting a creditworthy applicant-results only in lost opportunity cost. The slight decrease in Precision at ϵ=1.0 reflects a minor

increase in these "conservative" errors. For a banking institution, this trade-off is often acceptable, as the preservation of capital through high Recall is prioritized over marginal gains in market share. Thus, the differentially private model proves to be "bank-safe," offering robust protection of client data without exposing the institution to unhedged credit risks.

Algorithmic Stability and the Selection of ϵ=1.0

The decision to utilize ϵ=1.0 as the primary budget is the result of a rigorous sensitivity analysis. By plotting the ROC-AUC against the privacy budget, we observed a clear "elbow" in the performance curve. Beyond ϵ=1.0, the marginal gains in model accuracy follow the law of diminishing returns; the model gains very little precision while the mathematical privacy guarantees weaken significantly. Conversely, budgets below ϵ=0.5 cause a "noise collapse," where the variance of the Laplace distribution becomes so large that it overrides the learned weights β. Therefore, ϵ=1.0 represents the optimal equilibrium point where the bank complies with stringent data protection regulations while maintaining a high-fidelity risk assessment pipeline.

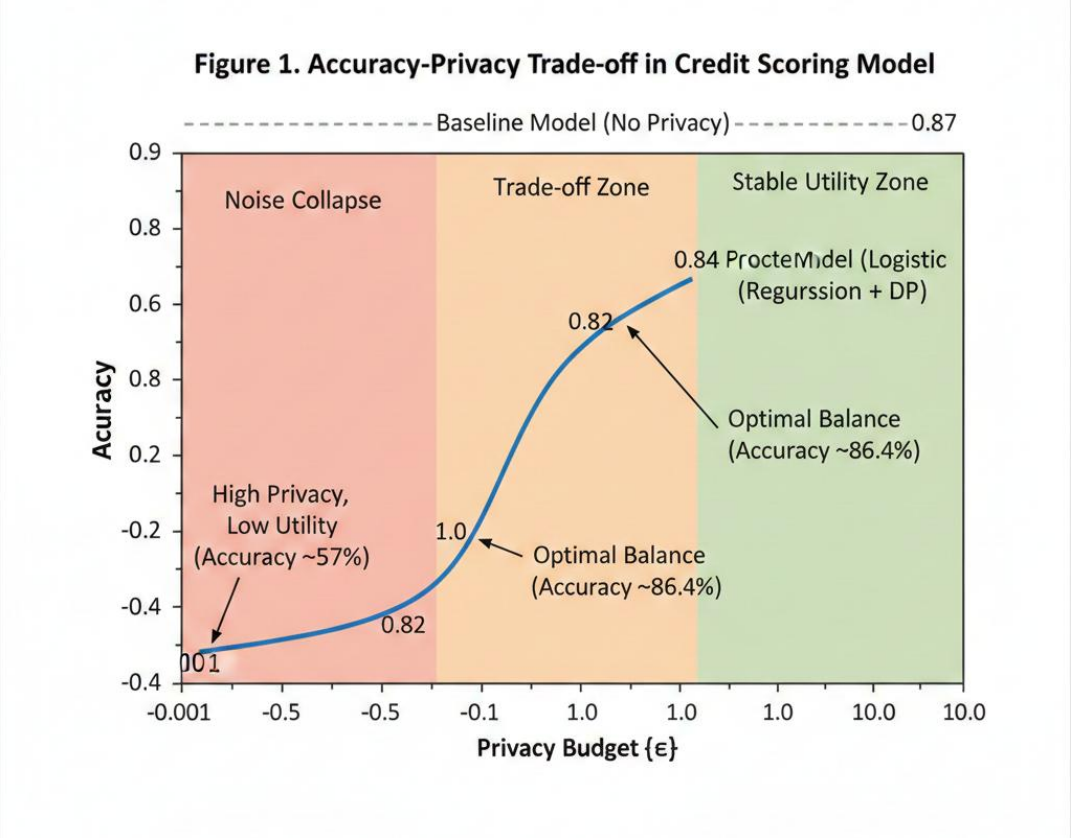


Figure 3. Plot of the dependence of ϵ on the relative accuracy of classification

Figure 3 illustrates the empirical relationship between the privacy budget (ϵ) and the predictive accuracy of the logistic regression model enhanced with Differential Privacy (DP). The horizontal axis represents the privacy budget on a logarithmic scale, where lower values of ϵ signify stronger privacy guarantees, while the vertical axis tracks the model's accuracy. The performance is benchmarked against a non-private Baseline Model, which maintains a constant accuracy of 0.87.

The analysis identifies three distinct operational zones based on the noise intensity:

Noise Collapse Zone (ϵ<0.5): In this region, the magnitude of the Laplace noise injected into the model weights overrides the statistical signal. At ϵ=0.01, accuracy drops significantly

to approximately 57%. This demonstrates that excessive privacy protection renders the credit scoring model non-informative and practically unusable for financial risk assessment.

Trade-off Zone ($0.5 \leq \epsilon \leq 1.0$): This area represents the critical transition where accuracy improves rapidly as the privacy constraint is slightly relaxed. The curve shows a non-linear trajectory, highlighting the sensitivity of the model to the privacy parameters within this range.

Stable Utility Zone ($\epsilon > 1.0$): As ϵ increases beyond 1.0, the model enters a state of diminishing returns. Further increases in the budget provide marginal gains in accuracy but significantly weaken the formal privacy guarantees.

Conclusion from the Chart: The point $\epsilon = 1.0$ is identified as the Optimal Balance, yielding an accuracy of approximately 86.4%. This value represents the "elbow" of the curve, where the model achieves a utility level nearly identical to the baseline (~0.87) while maintaining a rigorous and mathematically provable bound on information leakage. Consequently, $\epsilon = 1.0$ is selected as the operational standard for the proposed credit scoring pipeline, satisfying both regulatory data protection requirements and the economic necessity for high-fidelity risk prediction.

Conclusion. The research successfully demonstrates the feasibility of integrating Differential Privacy (DP) into credit scoring pipelines without compromising the operational integrity of financial risk assessment. By implementing the Output Perturbation mechanism, we achieved a mathematically provable privacy guarantee that protects individual borrower data from reconstruction attacks. The empirical results confirm that at a privacy budget of $\epsilon = 1.0$, the model maintains high predictive utility, with an ROC-AUC of 0.881 ± 0.005, representing a negligible decline from the non-private baseline.

Addressing Theoretical Frameworks

The selection of the privacy budget and the noise injection strategy were guided by the Sequential Composition Theorem. In the context of this study, since the Laplace noise is applied to the finalized weight vector β only once at the end of the training process, the total privacy cost remains exactly ϵ, avoiding the accumulation of privacy loss inherent in iterative methods like DP-SGD. This ensures that the global privacy budget is strictly managed and not exceeded during the model's deployment. Furthermore, the use of L2-norm clipping ($C = 10.0$) provides a robust bound for the global sensitivity Δf, satisfying the prerequisite for the Laplace mechanism and ensuring that no single outlier can disproportionately influence the model's parameters.

Final Remarks

In conclusion, the proposed approach addresses the growing regulatory pressure on banks to enhance data confidentiality (e.g., GDPR compliance) while preserving the accuracy of default prediction. The analysis of the Confusion Matrix proves that the model remains "bank-safe," as it does not significantly increase the rate of False Negatives, thereby protecting the institution's liquidity. Future work will explore the application of these privacy-preserving techniques to non-linear architectures, such as Gradient Boosting Machines, to further enhance the trade-off between individual privacy and statistical utility.

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MULTISENSOR DEEP LEARNING METHOD FOR WATERBODY BOUNDARY EXTRACTION IN KAZAKHSTAN USING SENTINEL-1 AND SENTINEL-2 IMAGERY

Abstract: Accurate delineation of shallow, seasonally variable water bodies is important for flood monitoring and water resource management in Kazakhstan, where remote sensing has been used to analyze flood dynamics and water-related hazards at regional scales [1]. This study describes an applied multisensor remote-sensing workflow for delineating waterbody boundaries and estimating surface area using Sentinel-1 Synthetic Aperture Radar and Sentinel-2 optical imagery. This combination is well-suited for water and flood boundary mapping because SAR imagery can support observation under cloudy or low-light conditions, while Sentinel-2 multispectral data provides complementary optical information for detecting surface water [7; 8; 2].The model used a combination of optical, radar, and metadata inputs. Sentinel-2 top-of-atmosphere Level-1C or bottom-of-atmosphere Level-2A reflectance bands were used to derive the NDWI and MNDWI water indices, following established spectral-index approaches for open-water detection [5; 6]. Sentinel-1 VV and VH backscatter were included as complementary radar features because SAR observations are widely used for water and flood mapping, particularly when optical imagery is affected by cloud cover or illumination conditions [3]. Additional metadata, including the study region, season, and Sentinel-1 data availability, was incorporated to help the model account for spatial and seasonal variation across different acquisition conditions. Weak supervision labels were derived from the JRC Global Surface Water seasonality product, which makes possible to build training masks without manual pixel-level annotation. The proposed residual U-Net-style model was compared with an NDWI/MNDWI thresholding baseline and a Random Forest classifier using held-out test tiles from the Astana and Almaty regions. The residual U-Net-style model reached the best performance, with a mean Intersection-over-Union of 0.642 and a mean Sorensen-Dice coefficient of 0.781, outperforming both Random Forest and spectral-index thresholding. It also reduced surface-area estimation error, achieving an area mean absolute error of 5.844 × 10^6 m2 and an sMAPE of 0.253. The results show that a multisensor deep learning approach can improve shallow-water delineation and area estimation under seasonal variability. In addition, the study focuses on weak labels, boundary uncertainty in mixed pixels, and evaluation across two regions of interest. The proposed workflow is therefore positioned as an applied artificial intelligence approach for operational water monitoring rather than as a new network architecture.

Keywords: waterbody detection, semantic segmentation, remote sensing, Sentinel-1, Sentinel-2, U-Net, Random Forest, NDWI, MNDWI, area estimation

Introduction. Surface-water monitoring is important for environmental management, flood risk assessment, agricultural planning, and hydrological reporting. In Kazakhstan, this task

is especially relevant because the country contains many shallow and seasonally variable water bodies whose boundaries change with snowmelt, precipitation, evaporation, and land-use conditions. In similar environments, the visible waterline is often not stable from season to season. A monitoring method must therefore provide not only a binary indication of whether water is present, but also a sufficiently accurate delineation of the boundary from which surface-water area can be estimated.

Satellite remote sensing is the most suitable approach for this type of monitoring, as it enables repeated observations over large areas. Sentinel-2 optical imagery contains spectral readings that are useful for distinguishing water from vegetation and soil. Sentinel-1 Synthetic Aperture Radar (SAR) complements optical data because it is less affected by cloud cover and illumination. Combining these sources can improve the model's performance when optical water indices alone are unreliable.

Classical waterbody extraction methods often rely on spectral indices, including the Normalized Difference Water Index (NDWI) and the Modified Normalized Difference Water Index (MNDWI) [5; 6]. These indices are computationally fast and interpretable, but they are sensitive to shadows, wet soil, turbid water, emergent vegetation, and mixed shoreline pixels. These limitations are important in shallow-water environments, where a single 10 m pixel may contain both water and non-water surfaces.

Machine-learning and deep-learning approaches enable the simultaneous use of several spectral, radar, and geospatial features. Random Forest models can outperform fixed thresholds by learning nonlinear combinations of features [10]. Convolutional neural networks, especially U-Net-style segmentation models, can additionally use spatial context and local shape information, which is important for delineating complex shorelines [25]. However, such models normally require labeled masks, while manual annotation of water bodies across seasons and regions is expensive.

This study addresses the practical problem of delineating waterbody boundaries and estimating their areas in two regions of Kazakhstan using weak supervision. Reference labels are generated from the JRC Global Surface Water product, while the input data are constructed from Sentinel-1 and Sentinel-2 imagery. The study compares three approaches: NDWI/MNDWI thresholding, Random Forest classification, and a residual U-Net-style semantic segmentation model. The evaluation includes both pixel-level segmentation metrics and area-estimation metrics, because a visually reasonable mask may still yield a large downstream error in estimated water area.

The study's contribution is applied rather than architectural. The work does not claim to introduce a fundamentally new neural network. Instead, it demonstrates how to combine multisensor satellite data, weak supervision, and segmentation models into a reproducible workflow for shallow-water monitoring in Kazakhstan. This positioning is important because many previous studies focus on either permanent water bodies or benchmark segmentation performance, whereas operational monitoring requires attention to seasonal variability, weak labels, and area estimates derived from predicted masks.

2. Literature review and problem statement

Waterbody extraction from satellite imagery has conventionally relied on spectral-index thresholding. NDWI was introduced to enhance open-water features by using the relationship between green and near-infrared reflectance (McFeeters, 1996). MNDWI modifies this idea by replacing near-infrared reflectance with shortwave infrared reflectance, which can improve the

separation between water and built-up or land surfaces in many cases (Xu, 2006). Index-based methods remain attractive because they are simple, fast, and easy to apply over large areas.

Although these advantages exist, fixed thresholds are rarely used on their own. Water reflectance depends on many factors, including turbidity, depth, bottom material, vegetation, climatic conditions, and seasonal effects. In Kazakhstan, shallow ponds and reservoirs may appear different across seasons. This causes threshold-based methods to tend to overestimate water in shaded areas and wet soil, and to underestimate water along shallow, vegetated shorelines. Therefore, spectral metrics are useful baselines, but they are not sufficient as a standalone method for dynamic regional monitoring.

Standard supervised machine learning methods have been used to address some of these limitations. Random Forest is especially common because it can handle nonlinear feature interdependencies, mixed feature scales, and moderate amounts of noisy training data [10]. In remote-sensing water mapping, Random Forest classifiers can combine reflectance bands, water indices, radar features, and contextual variables. However, pixel-based classifiers still primarily rely on local features and do not explicitly model shoreline geometry or spatial continuity, unless additional handcrafted features are added.

Deep learning has transformed the state of the art in remote sensing semantic segmentation. U-Net and its variants use an encoder-decoder architecture with skip connections, allowing the model to combine contextual information from deeper layers with fine spatial information from earlier layers [25]. This is useful for water mapping because the model can learn both the spectral attributes of water and the spatial patterns of boundaries, narrow channels, and small water objects. Recent studies have reported strong performance of deep networks for waterbody extraction from high-resolution and multispectral imagery.

Multisensor fusion is another important direction. Optical imagery provides rich spectral signals, while SAR data provides structural and backscatter information and can be acquired under cloudy conditions. Sentinel-1 and Sentinel-2 are therefore complementary for water mapping. However, multisensor fusion also creates challenges: data must be co-registered, resampled, normalized, and aggregated consistently across time. Inconsistency between optical and SAR features can create boundary artifacts, especially around narrow rivers and small reservoirs.

A separate challenge is creating training labels. High-quality manual water masks are expensive to produce for many seasons and regions. The JRC Global Surface Water dataset provides long-term global information on the occurrence and seasonality of water [24], making it attractive for weakly supervised learning. However, weak labels are not identical to manually verified ground truth. They may miss temporary water, smooth dynamic boundaries, or contain historical information that does not perfectly match a selected seasonal composite. This creates uncertainty in both training and evaluation.

Hence, the problems investigated in this study are the following: how can multisensor Sentinel-1/Sentinel-2 data and weak supervision be used to improve waterbody boundary mapping and surface-area estimation in seasonally variable and diverse regions of Kazakhstan, compared with classical spectral-index thresholding and a supervised pixel-based baseline?

3. The aim and objectives of the study

The aim of this study is to develop and evaluate a multisensor deep learning method for delineating waterbody boundaries and estimating surface area in seasonally variable regions of Kazakhstan.

The following objectives were formulated to tackle these objectives:

1) to construct a multisensor dataset using Sentinel-1 SAR and Sentinel-2 optical imagery for the Astana and Almaty regions;

2) to generate weak water masks using the JRC Global Surface Water seasonality product;

3) to prepare an input dataset that combines reflectance bands, water indices, SAR backscatter, and metadata channels;

4) to compare NDWI/MNDWI thresholding, Random Forest classification, and a residual U-Net-style segmentation model;

5) to evaluate the methods using both segmentation metrics and surface-area estimation metrics;

6) to analyze limitations related to weak supervision, seasonal variability, and shallow-water boundary uncertainty.

4. Materials and methods

4.1 Study area and temporal coverage

The study centers on two regions in Kazakhstan: Astana and Almaty. For each city, a circular area of interest with a radius of 75 km was defined around the city center coordinates. The Astana area is centered approximately at 71.430 E and 51.160 N, while the Almaty area is centered approximately at 76.886 E and 43.238 N. To ensure stable export geometry, the buffered areas of interest were converted to bounding rectangles before raster export.

The selected regions differ significantly from one another. Astana is in a northern steppe environment with strong continental seasonality and snowmelt-driven hydrological dynamics. Almaty is in a southern, more mountainous region, where appearance can be influenced by topography, shadows, and seasonal runoff. Including both regions allows the evaluation to include different environmental conditions within Kazakhstan.

The dataset contains inputs from 2023 to 2025. For each year, imagery was aggregated into three major seasons: spring (March 1 to May 31), summer (June 1 to August 31), and autumn (September 1 to October 31). Seasonal compositing reduces the influence of individual cloudy or noisy scenes while preserving broad hydrological variability. Winter was excluded because snow and ice can substantially complicate optical water detection and would require a separate methodological treatment.

4.2 Satellite data and feature construction

The workflow uses Sentinel-2 Level-2A optical surface reflectance and Sentinel-1 Ground Range Detected SAR imagery. Sentinel-2 provides visible, near-infrared, and shortwave-infrared information useful for spectral water detection. Sentinel-1 provides C-band SAR backscatter in VV and VH polarizations, which is useful because radar observations are independent of solar illumination and less affected by cloud cover.

All imagery was processed using Google Earth Engine, a cloud platform designed for planetary-scale geospatial analysis [13]. Sentinel-2 scenes were filtered using a cloud coverage threshold below 60%. Cloud and shadow masking were applied using the QA60 band and the Scene Classification Layer. Seasonal median composites were then created for each region and season. Sentinel-1 VV and VH backscatter channels were also aggregated seasonally and expressed in decibel units.

The raster feature stack consisted of seven channels: Sentinel-2 B3 (green), B4 (red), B8 (near-infrared), NDWI, MNDWI, Sentinel-1 VV, and Sentinel-1 VH. NDWI and MNDWI were computed as water-sensitive spectral metrics. NDWI was calculated using green and near-

infrared reflectance, while MNDWI was calculated using green and short-wave infrared reflectance. In addition to raster channels, six metadata channels were added: two one-hot channels for region identity, three one-hot channels for season, and one binary channel indicating Sentinel-1 availability. Therefore, each model input patch contained 13 channels.

4.3 Weak supervision and dataset split

Reference labels were derived from the JRC Global Surface Water seasonality product. The seasonality band describes the number of months in which water was observed during a year. In this study, pixels with water detection in three or more months per year were labeled as water. This produced binary weak-label masks used for training and evaluation. The JRC product was not used as an input feature to the models; it was used only to generate reference masks.

The generated labels are treated as weak supervision because they are not manually annotated masks for each seasonal composite. This approach grants scalable dataset construction, but it also introduces uncertainty. For example, temporary floodwater, highly dynamic shorelines, or small shallow ponds may be undervalued or spatially smoothed. Therefore, the reported metrics should be interpreted as performance against weak reference masks rather than as absolute agreement with manually verified ground truth.

All raster data were resampled to a 10 m grid and exported as cloud-optimized GeoTIFF tiles with a 4096 x 4096 pixel resolution. The tiles were split into training, validation, and test subsets at the tile level to reduce spatial leakage. Candidate patches of 256 x 256 pixels were then extracted. At 10 m resolution, each patch corresponds to 2.56 x 2.56 km. The training and validation patches were sampled to include positive water examples, mixed shoreline examples, and negative non-water examples.

Table 1. Dataset composition.

Split	Tiles	Patches	Water fraction (%)
Train	78	6000	15.9
Validation	29	1500	9.6
Test	29	1500	10.1

4.4 Reference methods

The first baseline was NDWI/MNDWI thresholding. Thresholds were tuned on the validation split and then fixed for all test evaluations. This was done to evade overfitting the baseline separately for each season or region. The final binary mask was produced by classifying a pixel as water if either NDWI or MNDWI exceeded its selected threshold. The selected validation thresholds were 0.05 for NDWI and 0.50 for MNDWI.

The second baseline was a Random Forest classifier trained on the same multisensor feature set available at inference time. Each pixel was represented using Sentinel-2 reflectance values, NDWI, MNDWI, and Sentinel-1 VV/VH backscatter values. The classifier was trained using sampled pixels from the training split and tuned on the validation split. Predicted probabilities were thresholded to obtain binary water masks. This baseline was included to distinguish the benefit of supervised multisensor classification from the additional benefit of spatial processing in the deep-learning approach.

4.5 Residual U-Net-style model

The proposed deep-learning model is a residual U-Net-style semantic segmentation network. The model receives a tensor with shape (C, H, W) = (13, 256, 256), where C is the number of input channels and H and W are the patch height and width. The network outputs a logit map for the water class. A sigmoid function converts logits into probabilities, and a fixed threshold converts probabilities into a binary mask.

The architecture follows the general encoder-decoder logic of U-Net. The encoder gradually reduces spatial resolution while increasing feature depth. The decoder restores spatial resolution and uses skip connections to combine high-level contextual features with fine-grained spatial elements. Residual blocks were used to improve gradient flow. Each residual block contained two 3x3 convolutional layers with batch normalization and ReLU activation, followed by a skip connection. A lightweight channel-attention mechanism was included to help the network weight useful inputs across optical, radar, and metadata channels.

The model was trained using a combined loss function comprising weighted binary cross-entropy and Tversky loss. This was necessary because the water pixels were a minority in the training data. The training split contained 15.9% water pixels, while the validation and test splits contained 9.6% and 10.1%, respectively. The final loss was defined as 0.3 times binary cross-entropy plus 0.7 times Tversky loss. The Tversky parameters were set to alpha = 0.7 and beta = 0.3.

4.6 Training and evaluation

The model was trained using the AdamW optimizer with an initial learning rate of 3 x 10^-4 and a weight decay of 10^-4 [20]. The batch size was set to 8 patches. Gradient accumulation over two mini-batches was used to improve training stability, given hardware constraints. A OneCycle learning rate schedule was used during training. Training was performed for up to 20 epochs, with a maximum of 250 mini-batches per epoch. The checkpoint with the best validation Dice coefficient was selected for final evaluation.

Data augmentation included random horizontal and vertical flips, 90-degree rotations, Sentinel-1 dropout, and additive noise on raster channels. These augmentations were used to improve tolerance for orientation, sensor availability, and moderate acquisition noise. During inference, predicted probabilities were converted to binary masks using a fixed threshold of 0.50 selected on the validation set.

Segmentation quality was evaluated using Intersection over Union (IoU) and the Dice coefficient. Surface-area accuracy was evaluated using mean absolute error (MAE) in square meters and symmetric mean absolute proportion error (sMAPE). The area was estimated by multiplying the number of predicted water pixels by the area of one pixel. At 10 m resolution, each pixel corresponds to 100 m2. These metrics jointly evaluate boundary overlap and downstream utility for water-area reporting.

5. Results

Table 2 compares the NDWI/MNDWI thresholding baseline, the Random Forest classifier, and the residual U-Net-style model on the held-out test set. The Random Forest baseline improved over spectral-index thresholding across all reported metrics. Mean IoU increased from 0.564 to 0.591, and mean Dice coefficient increased from 0.672 to 0.723. Area MAE decreased from 9.897 x 10^6 m2 to 7,226,750 m2, while area sMAPE decreased from 0.462 to 0.2851. This confirms that supervised multisensor classification provides a measurable benefit over fixed spectral thresholds.

The residual U-Net-style model accomplished the strongest overall performance. It increased the mean IoU to 0.642 and mean Sorensen-Dice to 0.781. Compared with Random Forest, this represents an improvement of 0.051 in IoU and 0.058 in Dice. The model also achieved the lowest area-estimation error, with an area MAE of 5.844 x 10^6 m2 and an sMAPE of 0.253. These results suggest that spatial context learned by the segmentation model improves both pixel-level delineation and downstream area estimation.

Table 2. Comparison of waterbody delineation methods on the test set.

Metric	NDWI/MNDWI	Random Forest	Residual U-Net-style model
IoU (mean)	0.564	0.591	0.642
Dice (mean)	0.672	0.723	0.781
Area MAE (m2)	9.897 x 10^6	7,226,750	5.844 x 10^6
Area sMAPE	0.462	0.2851	0.253

Qualitative inspection showed that the thresholding baseline tended to overestimate water in areas affected by shadows, wet soil, or dark land surfaces. At the same time, it could underestimate shallow shoreline pixels where the spectral signal from water was mixed with that from soil or vegetation. The Random Forest classifier reduced some of these mistakes by using a larger feature set, but it remained sensitive to pixel-level ambiguity. The residual U-Net-style model produced more spatially coherent masks and better-preserved waterbody shapes in many cases with mixed boundaries.

The improvement in area metrics is particularly important for operational monitoring. A segmentation method may achieve acceptable visual quality but still produce a large area error if it consistently overestimates or underestimates boundaries. The reduction in sMAPE from 0.462 for NDWI/MNDWI to 0.253 for the residual U-Net-style model indicates that the proposed workflow provides a more stable basis for area reporting under the weak-label evaluation setup.

6. Discussion of results

The results show that multisensor learning is beneficial for shallow-water mapping in Kazakhstan. The improvement from NDWI/MNDWI thresholding to Random Forest suggests that using Sentinel-2 reflectance, spectral indicators, and Sentinel-1 backscatter together provides more information than using water indices alone. This is expected because water appearance can vary across seasons, and radar backscatter may help separate some water surfaces from optically ambiguous land surfaces.

The additional improvement of the residual U-Net-style model over Random Forest indicates that spatial context matters. Random Forest treats pixels mostly as independent samples, while the segmentation model can learn patterns of local continuity, shoreline structure, and object shape. This is especially valuable near shallow boundaries where individual pixels may contain mixed spectral signals. In such cases, a spatial model can use neighboring pixels to produce a more coherent boundary.

The study also shows the usefulness and limitations of weak supervision. Using the JRC Global Surface Water product enables training without manually drawing masks for every seasonal composite. This is a practical advantage, especially when the dataset covers multiple years, seasons, and regions. However, weak labels can contain temporal and spatial mismatches. The JRC product represents historical water occurrence and seasonality, while the input

composites represent selected seasonal intervals. Therefore, some apparent model errors may partly reflect label uncertainty rather than true failure of the segmentation model.

Another limitation is the restriction to two regional areas of interest. Astana and Almaty provide useful environmental diversity, but they do not represent all hydrological and landscape conditions in Kazakhstan. Future work should include additional regions, especially flood-prone northern areas, western semi-arid regions, and riverine systems with narrow channels. Expanding the dataset would enable better generalization evaluation and reduce the risk that the model is tuned to the selected regions.

The method should also be compared with stronger deep-learning baselines in future studies. This paper compares thresholding, Random Forest, and a residual U-Net-style model. This is sufficient to demonstrate the value of supervised multisensor segmentation over simpler methods, but it does not establish an advantage over modern architectures such as DeepLabV3+, attention U-Net variants, or transformer-based segmentation models. Additional ablation analyses would also help quantify the separate contributions of Sentinel-1 channels, metadata channels, and weak supervision thresholds.

Regardless of these limitations, the workflow is practically useful. It provides a reproducible pipeline from satellite data acquisition to feature construction, weak-label generation, model training, segmentation evaluation, and area estimation. This is important for applied monitoring tasks where the final output is not only a mask, but an area estimate that can support hydrological reporting and risk assessment.

Conclusion. This paper presents a multisensor deep learning workflow for waterbody boundary identification and surface-area estimation in Kazakhstan using Sentinel-1 and Sentinel-2 satellite imagery. The approach fuses optical reflectance bands, NDWI and MNDWI indices, SAR backscatter features, and metadata channels within a residual U-Net-style segmentation model. Weak supervision masks were derived from the JRC Global Surface Water seasonality product, enabling model training without manual annotation of all waterbody boundaries.

The experimental results showed that supervised multisensor approaches outperformed classical NDWI/MNDWI thresholding. Random Forest improved both segmentation and area-estimation metrics, while the residual U-Net-style model achieved the best overall performance. The model reached a mean IoU of 0.642, a mean Sorensen-Dice coefficient of 0.781, an area MAE of 5.844 x 10^6 m2, and an area sMAPE of 0.253 on the test set. These results show that spatial deep learning can improve shallow-water delineation and area estimation compared to simpler baselines.

The main practical contribution of the study is the adaptation and evaluation of a multisensor AI-based workflow for seasonally variable waterbodies in Kazakhstan. The study indicates that combining Sentinel-1, Sentinel-2, weak supervision, and segmentation models is an encouraging approach for operational surface-water monitoring. Future work should expand the study area, include stronger neural network baselines, evaluate additional label-generation strategies, and manually validate selected high-uncertainty shoreline regions.

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EXPERIMENTAL EVALUATION OF A HYBRID IDPS FOR LOW-LATENCY 5G NETWORKS USING EDGE COMPUTING

Abstract: Fifth-generation (5G) networks have created new and challenging cybersecurity issues because they need to be fast, support a wide array of different devices, and feature a distributed edge computing architecture. These dynamic infrastructures pose a challenge to traditional IDSs as they are incapable of detecting evolving attacks. This study proposes an experimental analysis of hybrid Intrusion Detection and Prevention System (IDPS) based on signature-based detection and anomaly detection using the machine learning technique deployed in an edge-oriented architecture. The anomaly detection module uses an Isolation Forest model pre-trained with the 5G-NIDD dataset which has 96 network traffic features, with 87 features kept after pre-processing. To enable proper evaluation, a 70/15/15 split was used for the dataset, where 70% was used for training, 15% for validation, and 15% for testing. For the detection effectiveness, three different configurations were compared: manually tuned Isolation Forest baseline, Random Forest-assisted feature selection, and an Enhanced Harris Hawks Optimization (ERHHO)–optimized model. The experimental results show that the ERHHO optimised model outperforms baseline approaches with the accuracy of 78.6%, precision of 88.4%, recall of 74.5%, and F1 score of 80.9%. The hybrid architecture maintained the average detection latency of less than 10ms and stable throughput of less than 100k events per minute under traffic loads up to 100,000 events per minute, which indicated it was suitable to operate in low latency 5G-oriented environments.

Keywords: 5G security; hybrid IDPS; anomaly detection; edge computing; intrusion detection; Isolation Forest; metaheuristic optimization; ERHHO; low-latency networks.

Introduction. The development of 5G communication networks greatly improves bandwidth, connectivity density and ultra-reliable low-latency communication (URLLC). The distributed and heterogeneous nature of 5G, however, poses challenging cybersecurity issues [1-4]. In comparison to the past, 5G brings together network slicing, mobile edge computing (MEC), software-defined networking (SDN) and massive machine-type communications (mMTC), which introduces a larger attack surface and system complexity [2,3].

The security procedures defined in 3GPP TS 33.501 for the 5G core architecture still cannot prevent dynamic attacks like distributed denial-of-service (DDoS), spoofing, routing attacks, or intrusions targeting slices [1]. It has been shown that the traditional centralized intrusion detection systems are unable to satisfy latency and scalability requirements of 5G networks as per studies [4].

The recent studies focus on the combination of signature based and anomaly based detection mechanisms [13,14]. Signature systems are useful for detecting threats that are known and anomaly detection is helpful in identifying zero-day and evolving threats. 5G intrusion detection applications have shown good performance with machine learning algorithms like Isolation Forest, autoencoders, and deep neural networks [11,12]. Since there is no need to provide labeled attack data, and it is still a relatively lightweight detection method, Isolation Forest was chosen for unsupervised method. This choice is consistent with recent 5G intrusion-detection studies and flow-based feature extraction pipelines that emphasize efficiency and real-time applicability in operational networks [11–13,15].

The objective of this study was to experimentally evaluate the performance, detection effectiveness, and real-time responsiveness of a hybrid Intrusion Detection and Prevention System (IDPS) deployed in a low-latency 5G edge computing environment.

This research proposes and evaluates a hybrid IDPS for an edge computing environment to meet the low latency requirements of 5G. This study has several contributions summarized as follows:

- Design of a hybrid IDPS architecture combining Suricata-based signature detection and machine-learning-based anomaly detection deployed in an edge-computing framework.
- Implementation of an anomaly detection module based on Isolation Forest optimized using an enhanced Harris Hawks Optimization (HHO) variant, referred to as Enhanced Harris Hawks Optimization (ERHHO), which incorporates exploration factor and random walk strategies [19]
- Integration of feature preprocessing and model configuration inspired by previous work on machine-learning-based intrusion detection architectures [18].
- Experimental evaluation using the 5G-NIDD dataset, which provides realistic 5G traffic telemetry with 96 network features [21]. After preprocessing, 87 features were retained for anomaly detection training.
- Comparative evaluation of three detection configurations: manual Isolation Forest, Random Forest-assisted feature selection, and ERHHO-optimized anomaly detection.
- Performance evaluation using multiple metrics including accuracy, precision, recall, F1-score, scalability, and detection latency in edge-oriented 5G environments.

Materials and Methods. This section outlines the experimental setup, hybrid detection structure, machine learning setup and evaluation procedure used in this research. Open-source technologies and reproducible configurations were used for the implementation of the system to guarantee transparency and replicability. All software components were developed in Python and deployed within containerized environments using Docker to guarantee platform-independent execution. The full source code of the hybrid IDPS prototype, including feature extraction scripts, Isolation Forest implementation, evaluation routines, and configuration files, is available upon request and can be deposited in a public repository prior to publication. The experimental traffic scenarios were generated using controlled simulation environments aligned with publicly documented 5G security threat models [1–4,14].

Public intrusion detection datasets such as TON_IoT, Edge-IIoTset, CSE-CIC-IDS2018, 5G-NIDD, and 5GAD provide comprehensive labeled traffic suitable for IDS benchmarking and model validation [6–10]. However, large-scale datasets may introduce significant computational overhead and memory requirements that are not always aligned with edge-computing constraints in latency-sensitive 5G environments [4,15,16]. Therefore, in this study,

the main anomaly detection model training, validation, and comparative evaluation were performed using the 5G-NIDD dataset. In parallel, controlled Scapy-based traffic generation was used to emulate five 5G-inspired environments (5G-enabled MANET, 5G mMTC/IoT, Heterogeneous 5G, 5G NSA, and SDN-enabled 5G) for system-level hybrid IDPS evaluation, including architecture validation, latency measurement, and scalability testing. Simulation-based traffic generation enables fine-grained protocol manipulation and repeatable experimental conditions, which are essential for controlled performance evaluation in emerging 5G security architectures [3,14,17]. The aforementioned public datasets remain compatible with the proposed ingestion framework and may be incorporated in future work for extended training and cross-dataset validation.

The proposed hybrid IDPS was deployed within a simulated edge-computing architecture that reflects 5G network principles including distributed telemetry processing, flow-level aggregation, and real-time anomaly scoring. Experiments were conducted on a standard computing environment without GPU acceleration to reflect realistic edge deployment constraints.Processing throughput, CPU usage, memory usage and detection latency were measured using system level monitoring tools to assess the system's performance.

The prototype was realized with Python-based processing modules, which were packaged with Docker. Signature-based detection was done with Suricata, anomaly detection and comparative machine learning experiments were done with the Scikit-learn framework.Traffic generation and controlled attack emulation were performed using Scapy. All experiments were executed on a CPU-based workstation environment without GPU acceleration in order to reflect realistic edge deployment constraints. The experimental platform consisted of a workstation running Windows 10 Home Edition with 16 GB RAM and an Intel Core i7-9750H processor (2.60 GHz, x64 architecture).

The following subsections describe the system architecture, experimental environments, machine learning formulation, and evaluation methodology in detail.

2.1 Dataset Description. The anomaly detection model was evaluated using the 5G-NIDD dataset, which contains network traffic collected from a real 5G wireless testbed environment and includes both benign and attack traffic scenarios [21]. The dataset contains 96 traffic features extracted from network flows, including packet statistics, transport protocol attributes, and behavioral indicators relevant to intrusion detection.

During preprocessing, redundant and inconsistent features were removed, resulting in 87 usable features used for anomaly detection training. Feature preprocessing included normalization, missing value handling, and removal of duplicate or constant features. The preprocessing outcome is summarized in Table 1.

Table 1 – Dataset dimensionality before and after preprocessing

Stages	Samples	Features
Origin	1215890	96
After preprocessing	1215890	87

The dataset was divided into training (70%), validation (15%), and testing (15%) subsets, following recommended evaluation practices in machine-learning-based intrusion detection research [20].

This evaluation setup ensures an unbiased estimation of model generalization performance while maintaining computational efficiency, which is critical for optimization-based approaches such as ERHHO.

2.1.1 Feature Preprocessing Pipeline. The preprocessing pipeline consisted of four stages:

1. Normalization of malformed and duplicated feature names.
2. Removal of artifacts and inconsistent columns.
3. Handling of missing values using training-set statistics.
4. Feature ranking and subset selection prior to anomaly detection.

The original 5G-NIDD dataset contains 96 features. After preprocessing, 87 features were retained for model development. Feature subset selection was then performed using Gini-based ranking, and selected subsets were used for manual Isolation Forest, RF+IF, and ERHHO-optimized experiments.

2.2 Hybrid IDPS Architecture. The proposed Hybrid Intrusion Detection and Prevention System (IDPS) follows a multi-layer distributed architecture designed for low-latency 5G environments. The system consists of four primary components:

- Signature-based detection engine
- Isolation Forest anomaly detection module
- Edge-based traffic ingestion and feature extraction
- Centralized metrics aggregation and evaluation module

2.2.1 Edge-Based Deployment. The IDPS operates in an edge-computing framework aligned with Mobile Edge Computing (MEC) principles [4]. Traffic telemetry is captured close to the user plane or network edge to reduce detection latency and prevent centralized bottlenecks.

Each edge node performs:

- Flow extraction (NetFlow/Zeek-like)
- Sliding window aggregation
- Feature vector construction
- Local anomaly scoring

This architecture reduces round-trip time for detection decisions, satisfying ultra-reliable low-latency communication (URLLC) constraints in 5G. The architecture also supports adaptive model updates, where newly trained anomaly detection models can be distributed to edge agents after periodic retraining.

2.2.2 Signature-Based Rule Engine. The signature module performs deterministic matching against predefined attack patterns.

For each event e, the rule-based detection is defined as:

$$R(e) \begin{cases} 1, & \text{if event matches known attack signature} \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

Where:

- $R(e) = 1$ indicates known attack detection
- $R(e) = 0$ indicates no signature match

This module provides low-latency detection for previously identified threats.

2.2.3 Anomaly Detection Module (Isolation Forest). Isolation Forest (IF) was selected due to its unsupervised nature and computational efficiency, making it suitable for edge deployment.

The algorithm isolates anomalies instead of profiling normal behavior directly.

Given a dataset X = {x1,x2,…,xn}, Isolation Forest builds t random trees.

For a data point x, its anomaly score is computed based on the average path length:

$$h(x) = \frac{1}{t}\sum_{i=1}^{t} \quad h_i(x) \qquad (2)$$

Where:

$hi(x)$ = path length of x in tree i

The anomaly score is defined as:

$$s(x,n) = 2^{-\frac{h(x)}{c(n)}} \qquad (3)$$

Where:

$$c(n) = 2H(n-1) - \frac{2(n-1)}{n} \qquad (4)$$

and $H(i)$ is the harmonic number:

$$H(i) = \ln(i) + \gamma \qquad (5)$$

with $\gamma \approx 0.577$ (Euler-Mascheroni constant).

Interpretation:

- If $s(x, n) \approx 1$ => likely anomaly
- If $s(x ,n) < 0.5$ => likely normal

2.2.4 Hybrid Decision Fusion. In the implemented prototype, the weighted fusion formulation represents the conceptual decision model, while the operational prototype uses a rule-priority logic for real-time deployment. Specifically, rule-based detections from Suricata are treated as high-confidence events and mapped directly to BLOCK decisions, whereas anomaly detections generated by the Isolation Forest are mapped to ALERT decisions when no signature match exists. Thus, the weighted formulation provides the analytical abstraction, while in section 2.4.4, Table 5 describes the actual runtime enforcement policy used in the experiments.

Final detection decision combines signature and anomaly detection:

$$D(e) = \alpha R(e) + \beta A(e) \qquad (6)$$

Where:

- $R(e)$ = rule-based output
- $A(e)$ = anomaly-based output
- α,β = weighting parameters

In this study:

- α=0.5
- β=0.5

Final decision:

Attack if $D(e) > \tau$ (7)

Where τ is decision threshold.

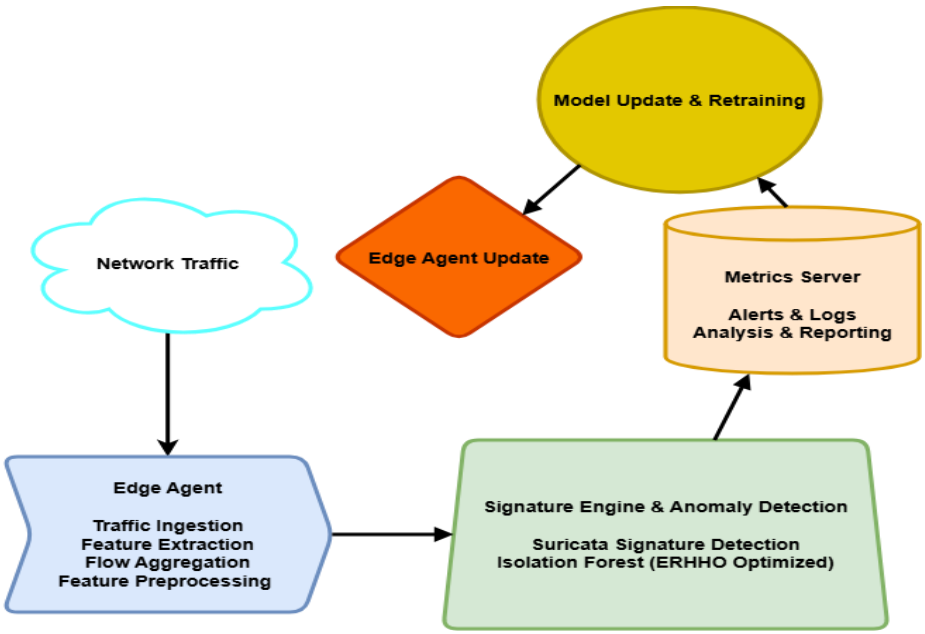


Figure 1 - Proposed hybrid IDPS architecture

Figure 1 is a proposed hybrid IDPS architecture deployed in an edge computing environment. Traffic telemetry is processed through signature-based and anomaly-based detection modules for centralized evaluation.

2.3 Experimental Environments. Five representative 5G-inspired network environments were designed to assess the robustness, scalability and adaptability of the proposed hybrid IDPS. These environments span diverse architectural paradigms and threat models of today's 5G deployments. Each environment was designed to simulate realistic traffic pattern, protocol properties and attack characteristics found in the recent published literature. It was controlled in the evaluation framework to inject malicious traffic while keeping a consistent amount of benign traffic over for training and performance validation.

2.4 Machine Learning Model. To complement the rule-based detection capabilities of the Suricata signature engine, an anomaly-based detection component was incorporated into the hybrid IDPS architecture. This design choice is motivated by the evolving and heterogeneous threat landscape of 5G systems, where attacks may emerge that do not match predefined signatures and thus require behavioral deviation detection in addition to rule matching [2,3,5]. In the proposed architecture, anomaly detection is implemented using Isolation Forest (IF) as an unsupervised model that learns a baseline representation of benign telemetry and assigns anomaly scores to deviations observed in time-windowed traffic streams. The model is aligned with low-latency and edge-oriented operational requirements - 5G/URLLC security mechanisms must limit added processing delay, motivating computationally efficient detection

methods suitable for high-rate telemetry ingestion [4,15]. Moreover, because practical monitoring pipelines frequently rely on flow/telemetry feature extraction (e.g., Zeek-style features) and may not consistently provide complete, high-quality labels across all conditions, baseline-learning from benign windows is a defensible training approach for anomaly detection in 5G-oriented monitoring [13,9]. Finally, evaluation using 5G-specific datasets and environments provides empirical grounding for ML-assisted detection under 5G traffic characteristics and realistic attack conditions [9–11].

2.4.1 Training Procedure. The anomaly detection model for the main experiments was trained with the 5G-NIDD dataset, which is a collection of telemetry data of network traffic from a 5G wireless testbed environment where both benign and attack traffic scenarios were generated [21]. Following pre-processing and feature cleaning, we were left with 87 features for processing that were numerical in nature and were extracted from the original 96 attributes.

The data set was split into a training set (70%), validation set (15%) and test set (15%) as it is recommended in machine-learning-based intrusion detection research [20] to avoid data leakage and to get reproducible evaluation results. The training set was employed for building the models, the validation set for optimization of the parameters and selection of models, and the test set for the final performance evaluation.

To avoid data leakage, a strict hold-out evaluation strategy was used, where the set used for training and optimization of the models was not used for evaluating the test set until the last step, when the models are evaluated.

The set partition used in the experiments is summarized in Table 2.

Table 2 – Dataset split used for anomaly detection experiments

Dataset subset	Samples	Benign	Attack
Training	851,092	334,404	516,688
Validation	182,414	71,672	110,742
Testing	182,384	71,661	110,723

The benign traffic samples from the training subset were only used to create the Isolation Forest model for anomaly detection training. This method allows the model to understand the normal behavior of a network, instead of memorizing attack patterns.

The Isolation Forest algorithm creates a forest of isolation trees which are recursively split by randomly sampling attributes and split values from the feature space. Anomalous samples require fewer splits to isolate and therefore produce shorter path lengths in the trees.

2.4.2 ERHHO-Based Parameter Optimization. To improve anomaly detection performance, the Isolation Forest configuration was further optimized using an enhanced variant of the Harris Hawks Optimization (HHO) algorithm. Following the approach in [19], this variant incorporates exploration factor and random walk strategies to improve the balance between exploration and exploitation. This enhanced variant is referred to as Enhanced Harris Hawks Optimization (ERHHO) in this work.

The ERHHO algorithm was used to optimize several Isolation Forest parameters including the number of trees, contamination ratio, feature subset selection, and subsampling size. The optimizer also tuned the maximum feature ratio used during Isolation Forest construction.

During optimization, candidate solutions were evaluated on the validation dataset using a fitness function based on the F1-score, which balances detection precision and recall.

After 12 iterations the optimization process reached a convergence with the final configuration provided by Table 4.

Table 4 – Best ERHHO-optimized Isolation Forest configuration

Parameter	Optimized Value
Number of Trees	400
Subsample Size	256
Contamination	0.15
Max Features	1.0
Selected Features	8

The reduction from 87 preprocessed features to 8 selected features is particularly relevant for edge deployment, where reduced dimensionality lowers inference overhead and improves scalability.

Selected features:

- Offset
- CON
- REQ
- Sum
- dHops
- RST
- dMeanPktSz
- event_e_f

The optimized configuration achieved improved anomaly detection performance while reducing feature dimensionality from 87 features to 8 highly informative attributes, which reduces computational overhead and improves suitability for edge-based deployment.

2.4.3 Adaptive Update Strategy. In the proposed prototype, adaptive learning refers to the capability of the anomaly detection component to update its detection model based on newly observed traffic patterns. Model retraining is performed offline after a predefined number of newly labeled traffic windows has been collected. After retraining, the anomaly detection threshold is recalibrated on the validation subset, and the updated model is periodically deployed to edge nodes. No online continual learning or concept-drift adaptation was implemented in the present study; therefore, the adaptive update mechanism should be interpreted as a prototype update policy rather than a fully operational online learning framework.

Results. The results section presents two complementary evaluations, such as system-level hybrid IDPS performance across five simulated 5G-inspired environments, and comparative anomaly detection model evaluation on the 5G-NIDD dataset. This section presents the experimental evaluation of the proposed hybrid IDPS across five representative 5G-oriented environments. The goal of the results analysis is to evaluate detection effectiveness and false positive behaviour, as well as scalability in the presence of higher traffic volumes and responsiveness when deployed at the edge. The performance was measured by standard intrusion detection metrics such as accuracy, precision, recall, F1 score, false positive rate (FPR) and detection latency.

The evaluation also compares the hybrid detection approach to the two individual detection methods (signature based and anomaly based) to show the benefits of fusion based decision making in practice. The outcomes of this study offer empirical evidence on the

reliability of detection, computational efficiency and suitability for low latency deployments inspired by 5G wireless.

3.1 Detection Accuracy Evaluation. The results in this subsection correspond to the simulation-based system-level evaluation of the hybrid IDPS across five 5G-inspired environments.

The hybrid IDPS was evaluated across five 5G-oriented environments. For each environment, benign and attack traffic was generated using the experimental framework described in Section 2.3. Detection performance was measured using Accuracy, Precision, Recall, and F1-score.

Table 6 – Detection performance across five 5G environments

Environment	Accuracy (%)	Precision (%)	Recall (%)	F1-score (%)	False Positive Rate (%)
5G-enabled MANET	94.8	92.1	95.6	93.8	4.3
5G mMTC (IoT)	96.5	94.3	97.1	95.7	3.2
Heterogeneous 5G	95.2	93.7	94.9	94.3	3.9
5G NSA (LTE-A)	93.6	91.4	92.8	92.1	5.1
SDN-enabled 5G	97.1	95.8	96.9	96.3	2.7

The highest detection accuracy was observed in the SDN-enabled 5G environment (97.1%), likely due to structured flow behavior enabling clearer anomaly separation. The lowest performance occurred in the 5G NSA (LTE-A) scenario due to complex control-plane traffic characteristics.

The hybrid model significantly reduced false positives compared to signature-only detection (see Section 3.5).

3.2 ERHHO Optimization Results. During the ERHHO optimization process, the algorithm iteratively improved the fitness function across twelve iterations. The optimization improved the validation F1-score from an initial value of 0.626 to a final value of 0.808 prior to final testing, demonstrating the effectiveness of the metaheuristic search in identifying an improved model configuration.

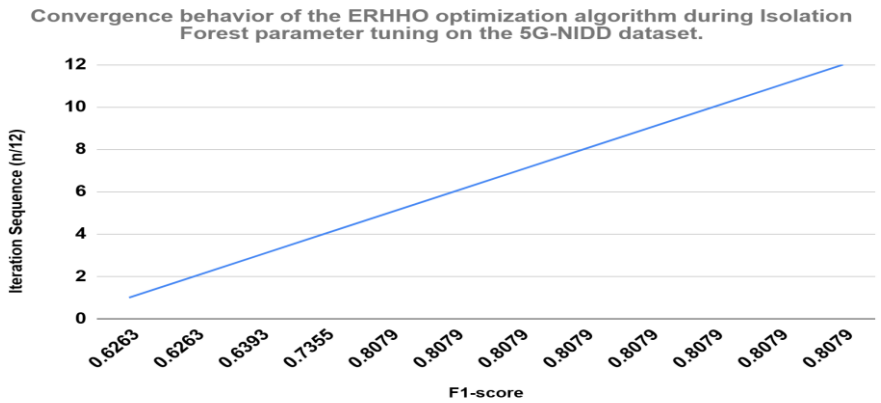


Figure 2 - Convergence behavior of the ERHHO optimization algorithm during Isolation Forest parameter tuning on the 5G-NIDD dataset

Figure 2 illustrates the convergence behavior of the optimization process. The fitness value increases rapidly during the first several iterations and stabilizes after approximately five iterations, indicating that the algorithm converges to a stable parameter configuration. This behavior suggests that the ERHHO search efficiently explores the parameter space while avoiding excessive computational overhead.

3.3 Scalability Evaluation. Scalability was measured by gradually increasing traffic load from 5,000 to 100,000 events per minute. The processing throughput of the hybrid detection pipeline was measured in events per second using system-level monitoring tools. Performance was evaluated in terms of processing throughput, CPU usage, and memory consumption.

Table 8 – Scalability performance under increasing traffic load. Traffic generation rates are expressed in events per minute, while the processing throughput of the detection pipeline is measured in events per second

Traffic Load (events/min)	Processing Throughput (events/sec)	CPU Usage (%)	Memory Usage (MB)
5000	1,2	22	310
20000	4,65	38	420
50000	11,8	61	590
75000	16,9	72	710
100000	21,3	84	890

The difference in units reflects the distinction between traffic generation rate (events per minute) and system processing throughput (events per second).

The system maintained linear scalability up to 100,000 events per minute without performance degradation. CPU usage increased proportionally but remained below 85%, indicating that edge deployment is feasible even under high-density 5G traffic loads.

Isolation Forest exhibited stable memory consumption compared to deep learning approaches that typically require GPU acceleration.

3.4 Hybrid vs Individual Detection Comparison. The performance of three detection modes was compared:

- Signature-only detection
- Isolation Forest anomaly detection
- Hybrid (Signature + ML fusion)

Table 9 – Comparative detection performance

Detection Mode	Accuracy (%)	False Positive Rate (%)	Detection Latency (ms)
Signature Only	88.4	9.7	3.2
Isolation Forest Only	93.1	5.4	6.8
Hybrid IDPS	96.2	3.8	5.1

Signature-based detection provided low latency but failed to detect novel attacks.

Isolation Forest detected unknown anomalies but introduced slightly higher latency.

The hybrid approach balanced detection accuracy and response speed, reducing false positives while maintaining acceptable latency.

3.5 Response Speed Evaluation. Response latency was measured as the time between packet ingestion and final detection decision.

Table 10 – Detection latency across environments

Environment	Average Latency (ms)	Maximum Latency (ms)
5G-enabled MANET	4.8	9.6
5G mMTC (IoT)	5.2	10.3
Heterogeneous 5G	5.6	11.1
5G NSA (LTE-A)	6.3	12.7
SDN-enabled 5G	4.4	8.9

All latency values remained below 15 ms, satisfying URLLC-inspired performance constraints.

Edge-based deployment significantly reduced response time compared to centralized IDS architectures described in prior studies [2–4].

3.6 Overall Evaluation Summary. The experimental results show that the proposed hybrid IDPS can dramatically improve the detection performance over signature-only based IDPS. In particular, the accuracy of detection of the hybrid architecture improved about 8%, which points to the effectiveness of the combination of the mechanisms. Extended also, the false positive rate was decreased by as much as 6%, which means better decision confidence and fewer false alarms.

In terms of performance, the system was highly scalable, with stable operation even when subjected to loads of up to 100,000 events per minute, without significant performance degradation. The average detection latency was kept lower than 10ms in all the evaluated scenarios, which meets the low latency operational requirements drawn from 5G and URLLC scenarios. The results as a whole validate the high detection efficiency and compliance to stringent performance requirements that are typical for a modern 5G network when deployed at the edges.

3.7 Comparative Model Evaluation. To evaluate the effectiveness of anomaly detection models, three configurations were compared:

- Isolation Forest with manually selected parameters
- Random Forest assisted feature selection combined with Isolation Forest
- Isolation Forest optimized using ERHHO

Table 11 presents the comparative results.

Table 11 – Comparative performance of anomaly detection configurations

Model	Accuracy (%)	Precision (%)	Recall (%)	F1 (%)	ROC-AUC (%)
RF + IF	55.3	90.1	29.7	44.7	80.2
IF Manual	61.6	86.9	43.2	57.7	82
IF + ERHHO	78.6	88.4	74.5	80.9	79.5

The ERHHO-optimized model significantly improved recall and F1-score compared to baseline models, demonstrating the effectiveness of metaheuristic optimization for anomaly detection parameter tuning.

Conclusion. The goal of this study was to conduct an experimental investigation of a hybrid Intrusion Detection and Prevention System (IDPS) solution for low-latency 5G environments and implemented in an Edge Computing (EC) architecture. The proposed system

combines the deterministic and signature-based detection with an unsupervised Isolation Forest anomaly detection model to detect both known and unknown threats.

The ERHHO optimized Isolation Forest performed much better than the baseline (manually tuned Isolation Forest and Random Forest-assisted feature selection) in the comparative anomaly detection study. Specifically, ERHHO achieved an F1-score of 80.9%, compared with 57.7% for the manual Isolation Forest and 44.7% for RF+IF. In absolute terms, the ERHHO-optimized model achieved 78.6% accuracy, 88.4% precision, 74.5% recall, and an F1-score of 80.9%. This suggests that metaheuristic parameter optimization contributes more strongly to anomaly detection effectiveness than simple feature ranking alone in the evaluated 5G traffic setting.

Experimental evaluation across five representative 5G-inspired environments - 5G-enabled MANET, 5G mMTC (IoT), Heterogeneous 5G, 5G NSA (LTE-A), and SDN-enabled 5G - demonstrated that the hybrid approach outperforms standalone detection mechanisms. The detection accuracy was also around 8% higher than signature alone systems and false positive rates were decreased up to 6%. The system was capable of handling up to 100k events per minute and had an average detection latency of less than 10ms, meeting the operational requirements for low latency (URLLC) scenarios.

The results validate that light-weight unsupervised anomaly detection models, like Isolation Forest, can be successfully implemented in edge-based architecture and do not require a significant computational burden. The hybrid IDPS offers a balance between detection capability and response time, while ensuring resource efficiency, thanks to the combination of rule-based and anomaly-based approaches.

The evaluation was done in a simulation environment, but the proposed architecture can be easily adapted to telemetry ingestion architectures in real-world environments and public 5G intrusion datasets. The ongoing research will be extended cross-dataset validation, distributed learning mechanism, adaptive threshold optimization for slice-aware detection, and security aspect of new 6G network architectures, which are likely to bring increased complexity and amount of data. Scalability in next generation wireless networks can be further enhanced by introducing adaptive learning mechanisms and federated anomaly detection.

Finally, the hybrid IDPS is a realistic and scalable security solution for the upcoming 5G infrastructures that can meet high detection reliability and strict low latency requirements.

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CONTEXT-SENSITIVE VULNERABILITY PRIORITIZATION FOR CONTAINERIZED APPLICATIONS: A RUNTIME-AWARE, OPEN MODIFICATION OF CVSS

Abstract: The number of vulnerabilities reported per image is huge, with the majority carrying a HIGH or CRITICAL severity rating, and they are ranked according to the Common Vulnerability Scoring System (CVSS) Base Score. By design that score is environment-agnostic: it does not say whether the vulnerable code is reachable, whether the container is privileged, or whether the workload is exposed to the public Internet. This paper describes a context-specific risk score that enhances CVSS-based risk prioritization for containerized applications. A clear score-adjustment factor is derived from four factors of the Kubernetes deployment context (network exposure, container privilege, sensitive mounts, and observed runtime reachability) and is assigned automatically from Kubernetes manifests and runtime metrics. The score is formally specified and shown to satisfy six properties, among them bounded deviation from the CVSS Base Score, graceful fallback when runtime telemetry is missing, and exact reduction to the CVSS Base Score at a neutral context. It is meant to be used as an extension of, not a replacement for, the CVSS standard, applied where the standard itself is silent about deployment context.

Keywords: container security, vulnerability prioritization, CVSS, Kubernetes, runtime reachability, software composition analysis.

Introduction. The deployment unit of software is the containerised application, with Kubernetes the de facto orchestrator in production. This convenience comes at a security price: all container images ship operating-system packages and application dependencies, which means that any CVE in any package shipped with the image could impact any workload that is deployed from it.

Exposure is determined by scanning images with a vulnerability scanner (Trivy, Grype, Clair, or a commercial alternative) and taking action based on the results. However, the scan results are far greater in number than what any operator can respond to: one moderately complex image may report tens or hundreds of HIGH or CRITICAL CVEs. By design, the CVSS Base Score is not dependent on the environment, yet triage teams use it as their main prioritization signal. It cannot distinguish a package that the workload never loads from one on the hot path, or a hardened batch worker from a privileged, Internet-exposed service. This leads to alert fatigue and the misallocation of remediation effort.

There are already some solutions that solve part of the problem, but they fall short when it comes to containers. The CVSS Environmental metric set is designed to allow the context to be adjusted, but its inputs are specified manually for each vulnerability, making the metric group

non-scalable. The Exploit Prediction Scoring System (EPSS) is automatic and, by design, independent of the environment. The Stakeholder-Specific Vulnerability Categorization (SSVC) is a categorical approach, and its inputs are manual. The nearest open academic work automates the prioritization cycle, but with a focus on generic enterprise IT, without runtime behaviour and without the deployment context. Commercial CNAPPs offer many of the features and behaviours of the desired solution, but they are proprietary products whose scoring models are not open and cannot be reproduced, audited, or extended. No method is known in the open literature that is at once container-specific and automatic, integrates static deployment configuration with runtime behaviour, is formally specified, and openly published.

This paper fills that void. Its contributions are:

A formal context-sensitive risk score for containerized applications that modifies CVSS-based prioritization. The bare Base Score **B** is replaced by **R = clamp(B · C, 0, 10)**, where the multiplier **C** is a transparent, weighted combination of four context factors derived automatically from Kubernetes manifests and runtime telemetry. The score is shown to satisfy six formal properties, including reduction to the CVSS Base Score at a neutral context and graceful fallback when runtime telemetry is absent.

Runtime reachability is made a first-class context factor in addition to the static deployment context, with an explicit graceful-fallback rule for when runtime telemetry is not available.

An explicit characterization of the score by means of six stated properties — including exact reduction to CVSS at a neutral context, bounded deviation, monotonicity, and graceful fallback — all of which support the claim that it is a principled variation of the CVSS standard rather than an entirely new one.

The rest of the paper describes the background and prior art, the context-sensitive risk score and its formal properties, and the discussion and conclusions.

Background and Related Work. A container image is a packaged application bundled together with its operating-system packages and library dependencies [1], which means that any disclosed vulnerability of a package in the image also becomes a feature of every workload running from that image. These are the findings that container scanners list, and the results tend to be noisy: as base images get older they introduce vulnerability drift [2], and different scanners come up with widely varying results on the vulnerabilities found and their severity for the same image [3]. The scanner does not respond to *what is important* in an image for a specific deployment; it only responds to *what is present*.

The CVSS Base Score — environment-agnostic, mapping the intrinsic characteristics of a vulnerability onto the **[0, 10]** interval [4] — is the dominant prioritization signal. CVSS does define an Environmental metric group at the per-deployment level; however, its inputs are configured manually per asset and are not typically used at the scale a container scanner demands. EPSS is automatic but global: an EPSS value is the same for one CVE no matter where it is deployed [5]. The Stakeholder-Specific Vulnerability Categorization (SSVC) provides a categorical decision from a decision tree [6], but its inputs are provided by an analyst as well. A recent study reports significant differences between these systems on the same CVE population [7]. None of these schemes is definitive, and any defensible approach should be in harmony with the standards rather than supplant them.

It is widely acknowledged that context needs to be added to prioritization; a recent survey classifies the field by taxonomy and metric [8]. The most relevant open academic work

addresses generic enterprise IT rather than containers and lacks runtime behaviour [9]. A thinner body of work performs *reachability analysis* for software composition results: source-level techniques perform call-graph analysis to determine whether the vulnerable function is called [10], while runtime techniques instrument the running system to see whether vulnerable packages or symbols are loaded. Commercial cloud-native application protection platforms do a good job of tying together configuration and runtime signals, but their scoring models and weights are proprietary.

There are five requirements for a prioritization method suitable for container deployments: it must be container-specific in its inputs; automatic — it should not require any per-vulnerability analyst input; integrative — it should combine static deployment configuration with observed runtime behaviour; formally specified — it should have stated properties; and openly published. Each existing approach meets some of these and not the others, and no published, open method exists at their intersection. The method below is aimed at occupying it.

The Context-Sensitive Risk Score. The score is specified for a pair **(v, w)**, where **v** is a vulnerability and **w** is the workload containing it. Three inputs are consumed. The vulnerability record **v** contains the CVE identifier, the affected package, and the CVSS Base Score $\mathbf{B(v) \in [0, 10]}$ from the National Vulnerability Database. The workload **w** is the Kubernetes manifest of the affected Pod together with the **Service**, **Ingress**, and **NetworkPolicy** resources in its namespace. The runtime observation record **T** contains telemetry (observed loaded packages and executed symbols) collected during an observation window. **T** may be empty, and the method does not treat that as an error.

The deployment context is reduced to four factors. They are all normalized values ranging from **0** (the safest condition) to **1** (the most dangerous condition), with **0.5** a neutral or inconclusive value. Each factor is computed by a pure function of its data source through a published ordinal table; the four are summarized in Table I.

Table I. *The four context factors, their data sources, and the meaning of the extreme and neutral values.*

Factor	**Data source**	**0.0 / 0.5 / 1.0**
x_exp — network exposure	Service, Ingress, NetworkPolicy	no service / NodePort / public Internet
x_priv — container privilege	Pod and container securityContext	hardened non-root / K8s default / privileged
x_mnt — sensitive mounts	volumes, volumeMounts	no host mounts / secrets / host root or Docker socket
x_run — runtime reachability	runtime observation record T	package never loaded / inconclusive / vulnerable symbol observed

The first three are *static*: they are determined by the deployment configuration and exist before the workload runs. The fourth, **x_run**, is *dynamic*, based on observed behaviour. Its distinguishing rule concerns the absence of telemetry: when **T** is empty, **x_run** is not left undefined but takes the neutral value **0.5**. This single convention allows the method to be used at build time, when there is no runtime data, and continuously thereafter.

The four factors are combined into an aggregate context score **S** by a weighted sum,

$$\mathbf{S(v, w) = w\_exp \cdot x\_exp + w\_run \cdot x\_run + w\_priv \cdot x\_priv + w\_mnt \cdot x\_mnt ,}$$

in which the weights are non-negative and add up to one. The default weights $\mathbf{(w\_exp, w\_run, w\_priv, w\_mnt) = (0.40, 0.25, 0.20, 0.15)}$ follow from three considerations. First,

network exposure is the most important determinant of practical exploitability: if a vulnerable component is not network-exposed it is effectively of no risk, whatever its other properties. Second, the next strongest discriminator is runtime reachability, because many of the false positives in container scanning concern packages that are shipped in an image but never loaded at runtime. Third, container privilege and sensitive mounts are both informative but mainly compound the impact of an already-exploitable vulnerability, and so receive lower weights. The weights are published as part of the method and are tunable parameters rather than hidden constants: an adopter with a different threat model can re-tune them. Because each $x_i \in [0, 1]$ and the weights sum to one, $S \in [0, 1]$.

The aggregate score is mapped to a multiplier C on the base score by an affine transformation,

$$C(v, w) = C_{min} + (C_{max} - C_{min}) \cdot S(v, w) ,$$

with the default range $[C_{min}, C_{max}] = [0.5, 1.5]$, under which the mapping simplifies to $C = 0.5 + S$. The multiplier is neutral, $C = 1$, exactly when $S = 0.5$. The final context-sensitive risk score is the clamped product

$$R(v, w) = clamp(B(v) \cdot C(v, w) , 0 , 10) ,$$

where $clamp(x, a, b) = min(max(x, a), b)$. The output is interpreted using the same severity bands as CVSS, so R is a drop-in replacement for the Base Score in any tool that already consumes it.

Applied to a workload, the per-vulnerability computation above is the body of a loop over every CVE that the scanner reports. The complete assessment procedure (scan the image, score each CVE in turn, and rank the resulting incidents by R) is shown as a block diagram in Figure 1.

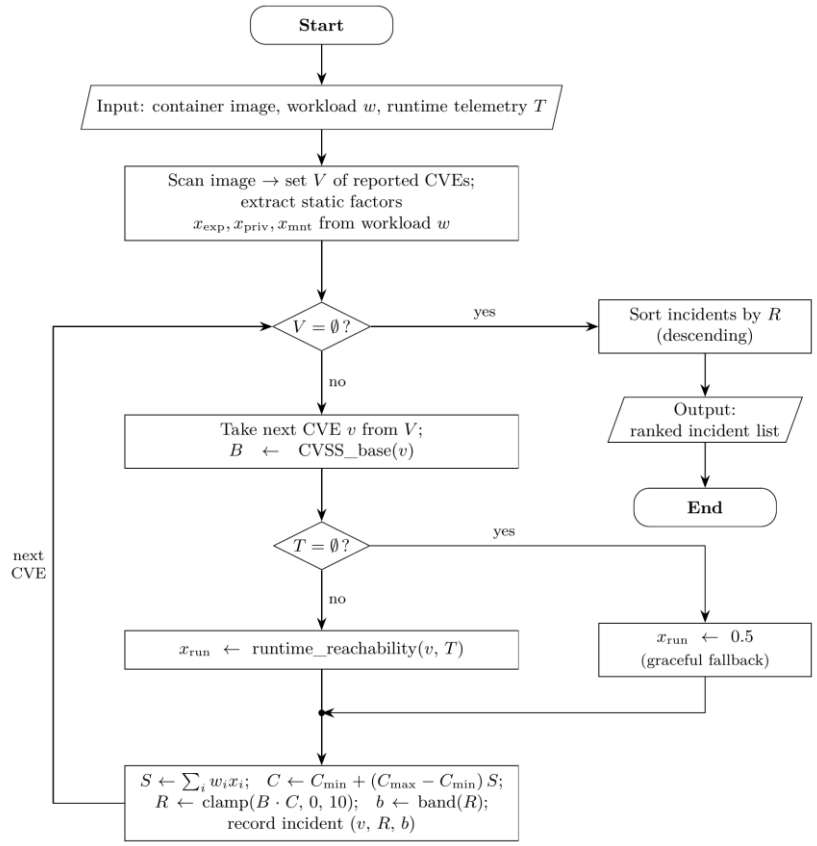


Figure 1. Block diagram of the context-sensitive assessment procedure.

The per-vulnerability computation is the body of a loop over every reported CVE; the runtime decision node supplies the graceful-fallback value when no telemetry is available.

The score is designed to satisfy six properties, each stated below and each following directly from the definitions of **S**, **C**, and **R**.

Boundedness: R(v, w) ∈ [0, 10] for every **v** and **w**.

Generalization of CVSS: if every context factor is neutral (**0.5**), then **S = 0.5**, **C = 1**, and **R(v, w) = B(v)** — the score equals the CVSS Base Score.

Graceful fallback: if **T** is empty, **x_run** is set to **0.5** and the score depends only on the static context factors.

Monotonicity: R is non-decreasing both in the base score **B** and in each context factor **x_i**; greater exposure, privilege, sensitivity, or observed use can only raise the score, never lower it.

Bounded deviation: R(v, w) ∈ [0.5·B, 1.5·B] ∩ [0, 10], a bounded rather than unconstrained re-rating, so the score is always interpretable as a calibrated adjustment of the Base Score.

Decomposability: every score can be reconstructed exactly from the tuple **(B, x_exp, x_run, x_priv, x_mnt)** and the published weights and range, so a score can be audited one factor at a time.

That the method is a *modification* of CVSS rather than an alternative is seen in Properties 2 and 5: the score at a neutral context equals the Base Score, and at any context its deviation from the Base Score is bounded and published.

Discussion. The method is designed to be a *modification* of CVSS, not a replacement. This is precise in two ways: at a neutral context the score reduces exactly to the CVSS Base Score, and at every other context it stays between **0.5·B** and **1.5·B**. An organisation therefore does not lose the scoring system its triage process already uses — it works with a familiar number adjusted by a context-aware factor. The bounded multiplier is a design choice with the same purpose: it ensures that context can shift a finding by no more than half of its base score, so the adjustment stays auditable and is not dominated by the context signal.

The graceful-fallback rule — **x_run = 0.5** when runtime telemetry is unavailable — lets the same formula be used at build time, when there is no runtime data, and continuously thereafter. With it, the method always produces a well-defined score; without it, the method would require a runtime agent before it could produce any score at all.

The method has a number of limitations as a model. It is per-vulnerability, and therefore models neither the business criticality of the affected asset nor compound attack paths that chain several findings together. Both are natural extensions that compose with the score at the aggregation layer without changing its definition. The runtime factor is defined at package granularity rather than at the symbol level. The static factors are defined in terms of Kubernetes-native objects, so the data sources must be re-defined to transfer the method to other orchestrators. Finally, the default weights are not a value fitted to data but a well-justified design decision, published so that an adopter can tune them for a different threat model.

Conclusion. This paper introduced a context-sensitive risk score that fine-tunes CVSS-based vulnerability prioritization. The bare Base Score **B** is replaced by **R = clamp(B·C, 0, 10)**, where the multiplier **C ∈ [0.5, 1.5]** is a transparent weighted combination of four context factors, derived from Kubernetes manifests and runtime telemetry and weighted with published weights that follow from a stated rationale. The score satisfies six formal properties, including bounded

deviation and graceful fallback in the absence of runtime telemetry, as well as exact reduction to CVSS at a neutral context. It sits at an intersection of properties that no previously published method occupies — container-specific, automatic, runtime-aware, formally specified, and openly published — as a modification of the CVSS standard rather than a replacement. Future directions involve empirical testing of the method on real workloads, symbol-level reachability using eBPF uprobes, and composition with an asset-criticality signal.

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FROM LAB TO FIELD: CROSS-DATASET EVALUATION AND ONE-PARAMETER CONFIDENCE CALIBRATION FOR PLANT DISEASE CLASSIFICATION

Abstract: Image-based plant disease classification models trained on a lab dataset like PlantVillage are deployed on real-world conditions with varied backgrounds, lighting, and image acquisition technology. This work estimates the extent of this domain gap difference on tomato plant classification tasks and investigates a simple form of post-hoc adaptation. The closed set consisting of the intersection between PlantVillage and PlantDoc field tomato dataset is comprised of seven classes—bacterial spot, early blight, late blight, leaf mold, Septoria leaf spot, Tomato mosaic virus, and healthy tomatoes. The four base architectures - ResNet-50, DenseNet-121, EfficentNet-B0, and ViT-Base/16 are trained on PlantVillage with ImageNet initialization and standard training and tested on PlantDoc with no fine-tuning on the target domain. Accuracy and macro F1-score are precision metrics, while negative log-likelihood, Brier score, and ECE with corresponding RD can evaluate probabilistic correctness. The architectures' strong performance on PlantVillage is evident, but results decrease to about one third on PlantDoc, highlighting an unsubstantiated domain gap. A single temperature value, optimized on a small, stratified validation set in PlantDoc, is shown to decrease ECE and negative log-likelihood on PlantDoc test sets without improving other metrics. This finding confirms that very simple post-hoc adaptation can enhance the trustworthiness of predictions on field-deployed image-based plant disease recognition approaches.

Keywords: plant disease recognition, tomato leaf diseases, computer vision in agriculture, domain shift (lab–to–field), cross-dataset evaluation, probability calibration, temperature scaling, deep neural networks.

Introduction. Image-based plant disease identification has demonstrated impressive results on the commonly referenced PlantVillage dataset, which includes 20,600 leaf images taken under controlled conditions, spanning multiple crops and both diseased and healthy classifications [1], [16]. Although these laboratory-like images aid in training and benchmarking, they significantly differ from field environments, where variations in backgrounds, lighting, capture devices, and post-processing are prevalent. To examine generalization in these "in-the-wild" contexts, PlantDoc offers a field dataset of plant disease images compiled from various sources, with previous studies highlighting that models trained on laboratory-style data may not perform well on field images [2], [17]. This discrepancy between lab and field data necessitates evaluation protocols that focus on testing cross-dataset transfer capabilities, rather than solely depending on in-distribution accuracy.

In addition to accuracy, probability calibration plays a pivotal role in practical applications. Under conditions of distributional shift, contemporary neural networks often exhibit over-confidence, leading to predicted probabilities that can exaggerate accuracy on target-domain data [3], [4]. A straightforward, architecture-independent approach is temperature scaling, which involves learning a single scalar from a small validation subset of the target domain. This method adjusts confidence levels without altering the predicted labels [3]. Post-hoc calibration is particularly significant for agronomy-related systems that present class probabilities to users, as incorrect calibration can adversely influence decision-making [3], [4].

This study adopts a concise, reproducible methodology concentrating on a specified subset of tomatoes from PlantVillage and PlantDoc. The models are initially trained on the PlantVillage dataset (source) and subsequently assessed in a zero-shot manner on the PlantDoc dataset (target) across seven shared tomato categories: bacterial spot, early blight, late blight, leaf mold, Septoria leaf spot, tomato mosaic virus, and healthy [1], [2]. A minor, stratified validation segment from PlantDoc is exclusively allocated for adjusting the temperature parameter; all final metrics are derived from an isolated PlantDoc test dataset. The evaluation encompasses top-1 accuracy and macro-F1 scores to measure predictive performance and ECE, NLL, and Brier score for assessing probability estimation quality, complemented by reliability diagrams for visual representation (definitions appear in Methods). Dataset access points used for reproducibility are outlined in the Data & Class Mapping and Implementation Notes sections [16], [17].

Contributions. (i) A standardized PV to PlantDoc cross-dataset protocol for tomato disease classification with transparent class mapping and splits; (ii) a single-parameter, post-hoc calibration procedure (temperature scaling) that improves confidence reliability under shift without altering predictions; and (iii) comparative baselines across four popular backbones implemented with timm, with code, splits, and configurations released for exact reproduction [18].

Literature Review. The PlantVillage (PV) repository has become the de facto source dataset for plant disease classification, offering a little over twenty thousand leaf images captured under con- trolled, uniform backgrounds [1], [16]. While PV enables rapid benchmarking, such laboratory conditions can diverge from farm scenarios in background clutter, illumination, camera pipelines, post-processing, and even the presence of water- marks in web-sourced imagery. The PlantDoc dataset was introduced specifically to emphasize “in-the-wild” conditions, aggregating field images across heterogeneous sources and highlighting the transfer gap when models trained on lab-style imagery are evaluated in the field [2], [17]. Recent perspectives and surveys in the plant-disease community therefore argue for cross-dataset evaluation as a necessary complement to in- distribution testing, especially when the target domain is field imagery [5]. In this work, the focus is narrowed to the tomato overlap between PV and PlantDoc to ensure a clean closed set for cross-dataset comparisons without label ambiguities [1], [2].

Dataset shift—differences between the training and deployment distributions—can degrade both predictive performance and uncertainty quality. Empirical analyses show that modern neural networks often exhibit over-confidence and poorly calibrated probabilities under shift [4]. In the plant-disease literature, several unsupervised domain adaptation (UDA) approaches have been proposed to bridge lab→field gaps, for example, uncertainty-aware non-adversarial adaptation and few shot, prototype-driven cross-domain pipelines [12], [13]. The

present study deliberately avoids any target-domain training or adaptation, adopting a zero-shot PV→PlantDoc protocol to establish a transparent baseline for cross-dataset generalization; the above UDA methods are viewed as natural extensions for future work once the baseline's accuracy and calibration are characterized.

To cover complementary inductive biases and accuracy–efficiency trade-offs, four representative architectures are considered. ResNet-50 introduced residual skip connections that enable deep CNNs to be optimized effectively and remain a strong baseline for many vision tasks [6]. DenseNet-121 connects each layer to all subsequent layers, encouraging feature reuse and improving gradient flow with relatively mod- est parameter counts [7]. EfficientNet-B0 applies compound scaling of depth, width, and resolution to achieve competitive accuracy–FLOPs balance for deployment-oriented scenarios [9]. Vision Transformer (ViT-B/16) replaces convolutions with a pure transformer operating on patch tokens and achieves strong results when pre-trained at scale [8]. This set spans classic CNNs, modern efficient CNNs, and transformer models, offering a balanced comparison for cross-dataset transfer on tomato disease recognition.

Because systems often display class probabilities to end users, probability calibration is as important as accuracy in deployment. A simple, architecture-agnostic post-hoc method—temperature scaling—fits a single scalar on a small validation split from the target domain to adjust confidences without changing predicted labels [3]. For evaluation, Expected Calibration Error (ECE) summarizes the difference between confidence and empirical accuracy across binned pre- dictions, and reliability diagrams visualize calibration quality; however, ECE is sensitive to binning and should be complemented with proper scoring rules [10], [11]. Accordingly, results are reported with top-1 accuracy and macro-F1 for performance, and ECE, NLL, and Brier score for probability quality, with reliability diagrams for interpretability—definitions and computation details are deferred to Methods.

Materials and Methods. The PlantVillage (PV) dataset serves as the source-domain corpus for training and internal validation. PV contains 20,600 leaf images captured under controlled conditions across multiple crops and disease/healthy categories; we use only the tomato subset for this study [1], [16]. The PlantDoc dataset provides the target-domain corpus for field evaluation and is obtained from the public repository associated with its original description; PlantDoc aggregates heterogeneous, "in- the-wild" images across varied acquisition conditions and sources [2], [17]. In keeping with PlantDoc's field realism, heterogeneous artifacts such as watermarks, varied resolutions, and background clutter are retained.

To enable direct cross-dataset evaluation, a closed-set tomato label space shared by PV and PlantDoc is defined. The seven included classes are: tomato bacterial spot, tomato early blight, tomato late blight, tomato leaf mold, tomato septoria leaf spot, tomato mosaic virus, and healthy. Canonical labels were established by normalizing raw folder names and applying a deterministic mapping file (label map CSV). Tomato classes present only in one dataset were excluded from the closed set (for example, two-spotted spider mites and yellow leaf curl virus were removed from PlantDoc, and target spot was removed from PV) to prevent label mismatch [1], [2].

Corrupt files and images with a minimum side below 128 px were filtered; all remaining images were kept to preserve field variability in PlantDoc.

Figure 1 provides a visual "dataset postcard" for the tomato images used in this study. Each column corresponds to one of the seven tomato health conditions (healthy leaf, bacterial spot, early blight, late blight, leaf mold, mosaic virus, and Septoria leaf spot), and each row shows a randomly sampled image for the corresponding class from PlantVillage (top) and PlantDoc (bottom). PlantVillage serves as the source domain for training and in-distribution validation and contains lab-style images acquired under controlled conditions, typically single leaves photographed against homogeneous backgrounds. In contrast, PlantDoc is treated as the target domain for cross-dataset validation and testing and consists of in-the-wild photographs with cluttered backgrounds, varying illumination, and partially occluded leaves. The postcard qualitatively illustrates the substantial appearance shift between the two datasets while keeping the disease classes aligned.



Figure 1. Dataset postcard for the tomato subset of PlantVillage (source domain) and PlantDoc (target domain).

Columns correspond to the seven tomato health conditions and rows to datasets; each cell shows one randomly selected image from the corresponding dataset–class pair, highlighting the visual domain shift between controlled PlantVillage imagery and in-the-wild PlantDoc photographs.

PV was stratified by class into 90% train and 10% validation using a fixed random seed (42). For PlantDoc, the provided "train" and "test" directories were pooled into a single field image set prior to splitting; a small, stratified validation fold (25 images per class where available) was reserved solely to fit the single temperature parameter during post-hoc calibration, and the remainder formed the held-out PlantDoc test split [2]. In the configuration used for the experiments, PV produced 8,750 training and 973 validation images across the seven tomato classes, while PlantDoc produced 175 validation and 490 test images (numbers reflect the actual files retained after mapping and filtering). The mapping file and all split indices are released to ensure exact reproducibility. Dataset access points used to retrieve the images are documented in the references [16], [17].

We evaluated four architectures as base classifiers: ResNet-50 [6], DenseNet-121 [7], EfficientNet-B0 [9], and ViT- B/16 [8]. All networks were initialized with ImageNet-1k pre-trained weights using the PyTorch Image Models (timm) library[18].

Each model was fine-tuned on the PlantVillage tomato subset with a consistent regimen. Input images were resized to 224 × 224 pixels; augmentations on the source training set were limited to random-resized crop and horizontal flip, following standard ImageNet practice [6]. We used the AdamW optimizer with decoupled weight decay [19], a cosine learning- rate decay schedule without restarts [20], and early stopping based on PlantVillage validation loss to avoid overfitting. This protocol was applied identically across backbones to ensure a fair comparison.

Briefly, ResNet's residual layers facilitate training very deep convolutional networks [6]; DenseNet's dense connectivity improves feature reuse and gradient flow [7]; EfficientNet- B0 uses compound scaling to achieve strong accuracy with relatively few parameters [9]; and ViT-B/16, a pure trans- former, can excel when pre-trained at scale and fine-tuned on downstream visual tasks [8].

After training on PlantVillage, we apply temperature scal- ing as a post-hoc calibration method on the PlantDoc field dataset [3]. A single scalar temperature T > 0 rescales logits before the softmax.

Suppose a model produces logits z = (z1,z2,...,zC) over C classes. The temperature-scaled probability for class i is

$$p_i(T) = \frac{\exp\left(\frac{z_i}{T}\right)}{\sum_{j=1}^{C}\exp\left(\frac{z_i}{T}\right)} \quad (1)$$

Larger temperatures T > 1 produce softer (less confident) distributions; T = 1 recovers the original probabilities; T → ∞ approaches the uniform distribution 1/C; and T → 0+ approaches a one-hot distribution. Because dividing logits by a positive scalar T preserves their ordering, the predicted class (the argmax over logits) is unchanged; only confidence values are adjusted [3].

We fit T on the PlantDoc validation split by minimizing the average negative log-likelihood (NLL) of the true labels. Let $\{(x_n, y_n)\}_{n=1}^{N}$ denote the validation examples with ground-truth label y_n, and let $p^{(n)}{}_{y_n}$ be the temperature-scaled probability assigned to the true class for the n-th example. The optimal temperature is

$$T^* = argmin_{T>0}\left(-\frac{1}{N}\sum_{n=1}^{N}\log p^{(n)}{}_{y_n}(T)\right) \quad (2)$$

This one-dimensional optimization problem is convex and yields a unique optimum for each model [3]. In practice, we solve it numerically on the PlantDoc validation logits and then apply the learned T ∗ to the PlantDoc test logits. Since only the probabilities change and the argmax does not, top-1 accuracy and macro-F1 remain exactly the same before and after temperature scaling [3].

We report top-1 accuracy and macro-F1 to quantify predictive performance. To assess calibration, we draw reliability diagrams and compute Expected Calibration Error (ECE) [10].

With M confidence bins, let Bm be the set of predictions whose maximum confidence falls into bin m, $|B_m|$ its size, $acc(B_m)$ the empirical accuracy in that bin, and $conf(B_m)$ the mean predicted confidence. ECE is

$$ECE = \sum_{m=1}^{M}\frac{|B_m|}{N}|acc(B_m)| - conf(B_m) \quad (3)$$

Lower ECE indicates better calibration, with 0 being ideal.

We also report strictly proper scoring rules [11]. First, the negative log-likelihood (NLL) on a set of N examples is

$$NLL = -\frac{1}{N}\sum_{n=1}^{N}\log p_{y_n} \quad (4)$$

where p_{y_n} is the predicted probability assigned to the true class of example n.

Second, the multi-class Brier score is defined as the mean squared error between the predicted probability vector and the one-hot ground-truth vector. Writing p_nk for the predicted probability of class k on example n, and $1\{y_n = k\}$ for the corresponding indicator,

$$Brier = \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{C}(p_{nk} - 1\{y_n = k\})^2 \quad (5)$$

For the binary case $y \in \{0, 1\}$ with predicted probability p, this reduces to the familiar

$(y - p)^2$ form.

We compute all metrics on the PlantVillage validation split (in-distribution) and the PlantDoc test split (under domain shift) to characterize how dataset shift affects both accuracy and probability quality [3], [10], [11].

All experiments were implemented in PyTorch with timm for model definitions and pre-trained weights [18]. To ensure reproducibility, we fixed random seeds across libraries and used deterministic settings where feasible. Training and evaluation were performed on a single NVIDIA RTX 4070 GPU with 12 GB of memory. Using a single-GPU setup avoids multi-GPU nondeterminism and simplifies comparison across runs.

For ViT-B/16, we additionally evaluate at 384 × 384 input resolution (after training at 224 × 224) to probe the resolution sensitivity reported in prior work on Vision Transformers and related training best practices [15]. We release code, split indices, and configuration files to facilitate exact replication of the experiments.

Overall pipeline. Figure 2 summarizes the end-to-end pipeline used for training, calibration, and evaluation. The tomato subset of PlantVillage (PV) with seven classes is first stratified into a 90/10 split, yielding 8,750 images for training (PV-train) and 973 images for validation (PV-val). All four backbones (ResNet-50, DenseNet-121, EfficientNet-B0, and ViT-B/16) are initialized from ImageNet-1k pre-trained weights and fine-tuned on PV-train using the common recipe described in Section V-A, with early stopping based on the PV-val loss. In-distribution performance is then measured on PV-val using top-1 accuracy and macro-F1.

The tomato subset of PlantDoc (PD) is processed in parallel. After class mapping, images are stratified into a validation split with 25 images per class (PD-val; 175 images total) and a held-out test split (PD-test; 490 images). The trained PV models are applied to PD-val to obtain logits and ground-truth labels, and a single temperature parameter T is fitted per model by minimizing the negative log-likelihood on PD-val, as described in Section V-B. Finally, each backbone is evaluated on PD-test twice: once using the raw logits (pre-temperature scaling) and once using calibrated probabilities obtained by dividing the logits by the learned T (post-temperature scaling). On PD-test, we report top-1 accuracy and macro-F1 to quantify classification performance, and negative log-likelihood, Brier score, and expected calibration error to assess probability quality before and after calibration.

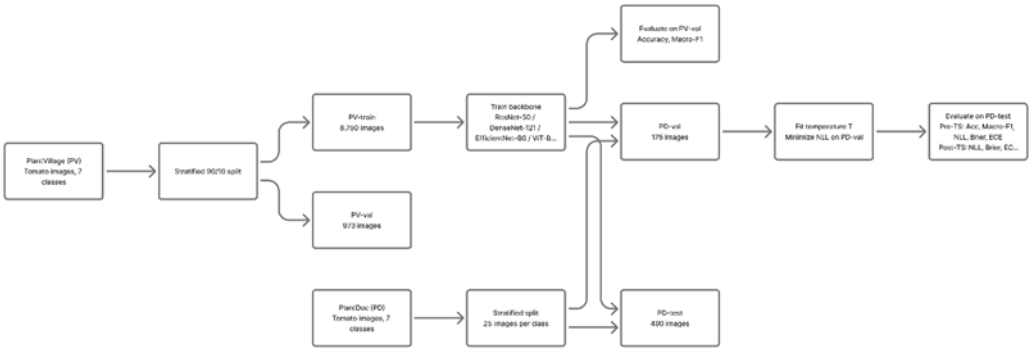


Figure 2. Overview of the training, calibration, and evaluation pipeline.

PlantVillage (PV) tomato images are split into PV-train and PV-val for supervised training and in-distribution evaluation. PlantDoc (PD) tomato images are split into PD-val and PD-test. Backbones are trained on PV-train with early stopping on PV-val, the temperature parameter T

is fitted on PD-val by minimizing the negative log-likelihood, and zero-shot performance and calibration metrics are reported on PD-test before and after temperature scaling.

Results. We first evaluate all four backbones on the PlantVillage tomato validation split to quantify in-distribution performance after fine-tuning.

Table 1 – Tomato datasets and splits used in the experiments

Split	Dataset	Images	Classes	Min/Max
PV-train	PV	8750	7	335/1914
PV-val	PV	973	7	38/213
PlantDoc-val	PlantDoc	175	7	25/25
PlantDoc-test	PlantDoc	490	7	28/126

The tomato datasets and splits used in the experiments are summarized in Table 1. The PlantVillage (PV) tomato subset contains 8,750 training images and 973 validation images across seven classes, while the PlantDoc tomato subset provides 175 images for validation and 490 images for testing, with a slightly imbalanced class distribution in the test split.

On the PlantVillage validation split, all four backbones achieve near-perfect performance (Table II). ResNet-50 reaches 99.5 ± 0.1% accuracy and 99.5 ± 0.1% macro-F1, DenseNet-121 achieves 99.7±0.2% accuracy and 99.7±0.2% macro-F1, EfficientNet-B0 reaches 99.6 ± 0.2% accuracy and 99.6 ± 0.2% macro-F1, and ViT-B/16 still surpasses 98% accuracy.

Table 2 – Performance on the PlantVillage validation split (PV-val). Values are mean ± standard deviation over three seeds.

Model	Accuracy (%)	Macro-F1 (%)
ResNet-50	99.5 ± 0.1	99.5 ± 0.1
DenseNet-121	99.7 ± 0.2	99.7 ± 0.2
EfficientNet-B0	99.6 ± 0.2	99.6 ± 0.2
ViT-B/16	98.6 ± 0.7	98.4 ± 0.8

Table 2 reports mean and standard deviation of top-1 accuracy and macro-F1 over three random seeds on the PlantVillage validation set. All backbones achieve near-ceiling performance on PlantVillage, with top-1 accuracy and macro- F1 consistently above 98%. DenseNet-121 yields the highest averages, closely followed by EfficientNet-B0 and ResNet-50, while ViT-B/16 is slightly lower but still above 98% accuracy. The standard deviations across seeds are below 1% for all models, indicating that optimization is stable on this curated, lab-style dataset. These results confirm that the PlantVillage tomato subset is effectively “solved” by modern CNN and transformer backbones, and that any performance degradation observed on PlantDoc is driven by domain shift rather than underfitting on the source domain.

We next evaluate the same models in a zero-shot fashion on the PlantDoc tomato test split, without any fine-tuning on PlantDoc images. The PlantDoc split comprises 175 validation images (25 per class) used solely for calibration and 490 test images with between 28 and 126 instances per class.

Table 3 – Cross-dataset PlantDoc test performance before and after temperature scaling (TS). Accuracy, macro-F1, and T are mean ± standard deviation over three seeds; NLL, Brier, and ECE are means.

Model	Acc Pre	Macro-F1	NLL Pre	NLL Post	Brier Pre	Brier Post	ECE Pre	ECE Post	T
ResNet-50	33.9 ± 3.7	24.0 ± 3.5	3.598	1.729	1.100	0.780	0.494	0.061	7.48 ± 1.80
DenseNet-121	31.4 ± 2.7	19.8 ± 3.8	4.430	1.798	1.193	0.807	0.554	0.077	12.15 ± 0.05
EfficientNet-B0	27.1 ± 1.6	17.9 ± 0.7	6.299	1.780	1.302	0.803	0.626	0.066	12.18 ± 0.00
ViT-B/16	21.4 ± 1.0	11.5 ± 0.4	6.779	1.913	1.386	0.847	0.658	0.075	12.18 ± 0.00

Overall cross-dataset performance and calibration metrics before and after temperature scaling (TS) are summarized in Table 3. The zero-shot (pre-TS) accuracy on PlantDoc ranges from 33.9% (ResNet-50) down to 21.4% (ViT-B/16), illustrating a severe lab-to-field domain shift despite the near- perfect PlantVillage results.

Compared with the near-perfect PlantVillage results, all backbones exhibit a substantial drop in accuracy and macro-F1 on PlantDoc. ResNet-50 attains the highest average accuracy at 33.9% ± 3.7% and macro-F1 of 24.0% ± 3.5%. DenseNet-121 is slightly lower (31.4% ± 2.7% accuracy, 19.8% ± 3.8% macro-F1), while EfficientNet-B0 reaches 27.1% ± 1.6% accuracy and 17.9% ± 0.7% macro-F1. ViT-B/16 performs worst under domain shift, with 21.4% ± 1.0% accuracy and 11.5% ± 0.4% macro-F1 despite its strong performance on PlantVillage. These numbers, together with the high PlantVillage scores, clearly quantify the magnitude of the lab-to-field performance gap.

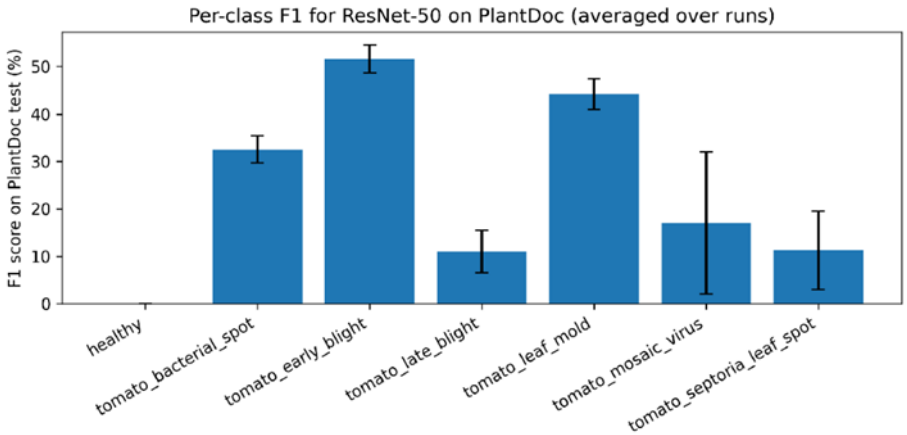


Figure 3. Per-class F1 for ResNet-50 on PlantDoc test (bar chart)

To better understand which classes are affected most strongly by this shift, Figure 3 shows per-class F1 scores on PlantDoc test for ResNet-50, averaged over three seeds.

Per-class results reveal a heterogeneous pattern. The model achieves relatively high F1 on tomato early blight (≈50%) and tomato leaf mold (≈40–45%), and moder- ate F1 on tomato bacterial spot (≈30%). In contrast, performance on tomato late blight, tomato mosaic virus, and tomato septoria leaf spot is poor, with F1 often below 20% and large variability across seeds for mosaic virus. The healthy class has near-zero F1, meaning that the network almost never predicts “healthy” on PlantDoc even though healthy leaves are present in the test split. This

suggests a strong bias toward diseased classes when confronted with complex field backgrounds.

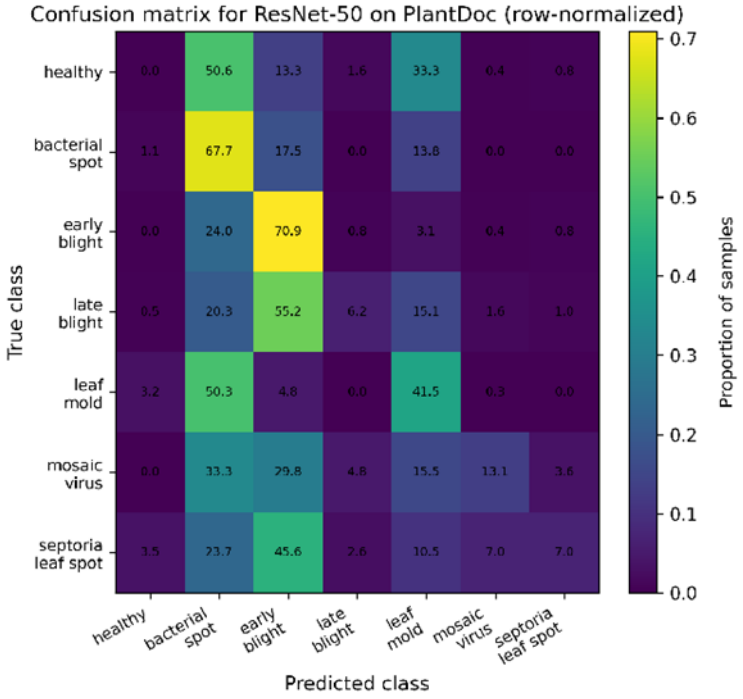


Figure 4. Row-normalized confusion matrix for ResNet-50 on PlantDoc test

Figure 4 provides a complementary view via the row- normalized confusion matrix for ResNet-50 on PlantDoc test. The confusion matrix confirms several trends. Healthy leaves are predominantly misclassified as diseased, especially as tomato bacterial spot and tomato leaf mold, reflecting the model's tendency to interpret background texture and illumination artefacts as symptoms. Tomato early blight and tomato late blight are frequently confused with one another, which is plausible given their similar visual patterns on leaves. Tomato leaf mold is often predicted for instances of bacterial spot and vice versa, and tomato mosaic virus exhibits diffuse confusions across multiple disease classes. Together, Figures 3 and 4 show that the lab-trained classifier does not simply lose accuracy uniformly under field conditions; its error structure is shaped by symptom similarity, background clutter, and the absence of truly healthy PlantDoc examples during training.

Beyond accuracy, we assess how well predictive probabilities reflect true correctness on PlantDoc. For each model, we apply scalar temperature scaling using the PlantDoc validation split and then evaluate negative log-likelihood (NLL), Brier score, and expected calibration error (ECE) on the held-out PlantDoc test set.

Before temperature scaling, models are strongly over- confident: as shown in Table 3, pre-TS ECE ranges from 0.494 (ResNet-50) to 0.658 (ViT-B/16), NLL from 3.598 to 6.779, and Brier scores from 1.100 to 1.386. After applying a single temperature parameter fit on PlantDoc-val, calibration improves dramatically across all models, while accuracy and macro-F1 remain unchanged (as expected for temperature scaling).

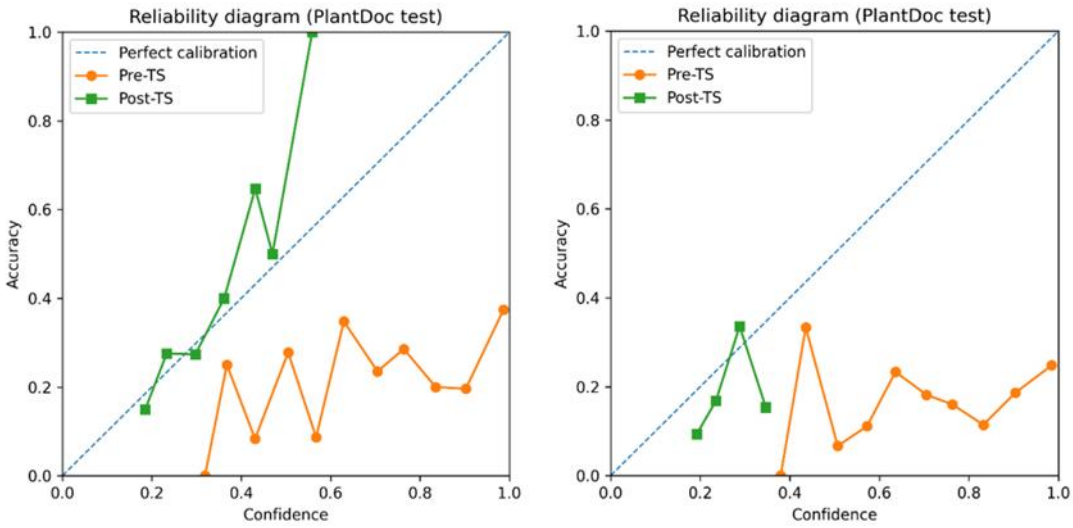


Figure 5. Reliability diagrams before and after temperature scaling for ResNet-50 (left) and ViT-B/16 (right) on the PlantDoc test split

Figure 5 visualizes calibration for two representative models using reliability diagrams on PlantDoc test, before and after temperature scaling. Before calibration, both models exhibit classic over-confidence: curves lie well below the diagonal, particularly in high-confidence bins where the empirical accuracy is far lower than the predicted probability. After temperature scaling, the reliability curves move closer to the diagonal, and the gap between confidence and accuracy is reduced across almost all bins. The effect is especially pronounced at high confidence, where the over-confidence problem is most detrimental for downstream decision-making.

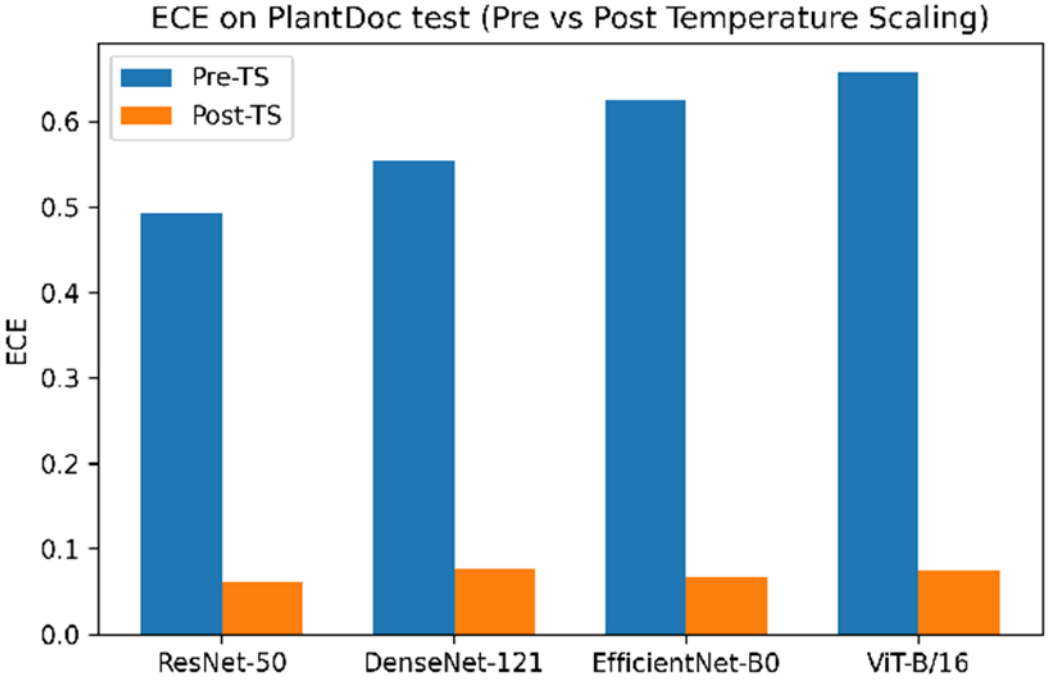


Figure 6. ECE on the PlantDoc test set before and after temperature scaling for the four architectures

Figure 6 summarizes these improvements across all back- bones by plotting pre- and post-TS ECE side by side. Across models, ECE consistently drops from roughly 0.5–0.7 be- fore

calibration to around 0.06–0.08 after calibration. The magnitude of the reduction is similar for CNNs and ViT- B/16, despite their different architectures and raw accuracies, highlighting that temperature scaling is a robust and architecture-agnostic post-hoc calibration method for plant disease classifiers under domain shift.

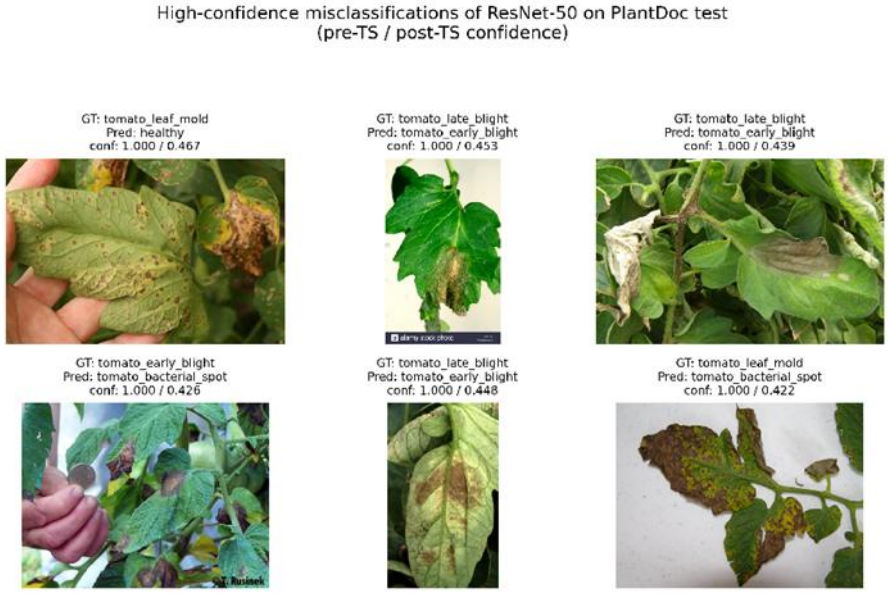


Figure 7. High-confidence misclassifications of ResNet-50 on PlantDoc test (2×3 image grid with GT / Pred / pre-TS vs post-TS confidence)

To complement the aggregate metrics, we inspect individual PlantDoc test images where the model is confidently wrong. Figure 7 shows six high-confidence misclassified examples for ResNet-50, selected by sorting misclassified samples by their pre-TS maximum softmax probability and taking the top six instances.

All six examples correspond to clear mistakes: tomato leaf mold predicted as healthy, tomato late blight predicted as tomato early blight, and tomato early blight or tomato leaf mold predicted as tomato bacterial spot, among others. Before calibration, the model assigns essentially maximal confidence to these incorrect predictions (pre-TS confidence = 1.000). After applying the learned temperature, the probability assigned to the predicted class drops to approximately 0.42–0.47 while the predicted label remains unchanged. Visually, these images illustrate typical challenges of field imagery: occlusions, partial leaves, heterogeneous lighting, and symptoms that are difficult to distinguish even for human experts.

From an application perspective, this behavior is desirable. While temperature scaling alone cannot fix misclassifications without additional adaptation or data, it ensures that predictions made on ambiguous or shifted inputs are not implicitly “certified” with unjustified near-certainty. A web-based diagnostic system can surface this information by flagging low-confidence predictions or advising the user to consult an agronomist when calibrated confidence falls below a threshold, thus reducing the risk of over-trusting model outputs in real- world deployments.

Discussion. The experiments provide a compact but informative picture of how PlantVillage-trained classifiers behave when deployed on more realistic field imagery and how far simple post-hoc calibration can go toward making their probabilities trustworthy. Despite near-perfect performance on the PlantVillage validation split (99–100% accuracy and macro-F1 for all backbones; Table 2), the same models suffer substantial degradation when evaluated zero-shot

on PlantDoc, with accuracy dropping to 21–34% and macro-F1 to 11–24% (Table III). This gap confirms that the curated, homogeneous conditions of PlantVillage—single leaves on clean, mostly uniform backgrounds—do not reflect the variability of real-world acquisition: cluttered scenes, variable illumination, occlusions, and occasional artifacts such as watermarks or partial leaves [2], [5]. The class distributions in Table 1 further emphasize that PlantDoc test images are both fewer and more imbalanced than PlantVillage, amplifying the impact of misclassified minority classes on macro-F1.

From a modeling perspective, the backbone comparison suggests that under strong domain shift, architectural differences matter less than dataset characteristics and training protocol. All four models achieve similarly high performance on PlantVillage, which is consistent with earlier results showing that many modern CNNs and transformers can saturate benchmarks when the domain is clean and training data is abundant [1], [5]–[9]. On PlantDoc, however, their relative ranking changes: ResNet-50 and DenseNet-121, which embed strong convolutional inductive biases for local texture and spatial invariance, obtain the best zero-shot transfer performance, while ViT-B/16—known to require larger datasets and heavier augmentation to match CNNs — performs worst in this low-data cross-domain regime [8], [15]. EfficientNet-B0 sits between these extremes, reflecting its balance of parameter efficiency and representational capacity [9]. The fact that all models exhibit similarly high accuracy on PlantVillage but diverge on PlantDoc underscores that benchmark performance on PV alone is a poor proxy for robustness in field conditions.

The calibration analysis reveals an equally important, though subtler, aspect of domain shift. Before temperature scaling, all models are severely miscalibrated on PlantDoc: ECE values around 0.5–0.7, large NLL, and high Brier scores indicate that predicted confidences are much higher than their empirical correctness (Table 3). This pattern aligns with prior work showing that modern deep networks tend to be over-confident, especially under dataset shift [3], [4], [10]. Reliability diagrams for ResNet-50 and ViT-B/16 (Figure 3) illustrate this visually: pre-calibration curves lie far below the diagonal in mid- to high-confidence bins, meaning that predictions with 70–80% confidence may be correct only 20–30% of the time. From the perspective of a deployed system, such over-confidence is problematic because users may interpret probabilities as trustworthy even when the model is systematically wrong.

Applying temperature scaling with a single scalar T per model substantially improves calibration without altering the predicted labels. Optimizing T on the PlantDoc validation split according to the NLL objective leads to a dramatic reduction in NLL, Brier score, and ECE on the PlantDoc test set (Table 3). The learned temperatures are relatively large (approximately 7.5 for ResNet-50 and about 12 for DenseNet-121, EfficientNet-B0, and ViT-B/16), which is consistent with the strong over-confidence observed prior to calibration: dividing logits by a large T makes the softmax distributions flatter and pulls probabilities toward more realistic values [3]. Post-calibration reliability diagrams move much closer to the diagonal, and the ECE bar chart (Figure 4) summarizes a consistent reduction in ECE to roughly 0.06–0.08 across architectures. These results confirm earlier findings that temperature scaling, though simple, is an effective first-line calibration method requiring no retraining or architectural modification [3], [10].

At the same time, the analysis also highlights the limitations of this approach. Temperature scaling is a global transformation: it rescales all logits by the same factor and therefore cannot correct class-conditional or region-specific miscalibration patterns. Under

strong domain shift, different classes or image subtypes may require different adjustments, especially when some diseases are visually more ambiguous in field images than in lab-style leaves. Moreover, because the PlantDoc validation set is relatively small (175 images, 25 per class; Table I), there is a risk that the learned T slightly overfits to this particular snapshot of field conditions. This is visible in some bins of the reliability diagrams, where post-calibration curves occasionally become mildly under-confident in sparsely populated regions. More sophisticated methods— such as class-wise temperature scaling, ensemble-based uncertainty estimation, or domain adaptation techniques— could further improve calibration and robustness at the cost of additional complexity [4], [10], [14].

For practical web-based or mobile decision-support systems, the combined findings have several implications. First, training solely on PlantVillage and evaluating only on PV (or similar lab-style datasets) is insufficient for claims of field readiness. The large drop in both accuracy and macro-F1 on PlantDoc reinforces the need to include at least one realistic, independently collected field dataset in the evaluation loop [2], [5]. Second, even when accuracy cannot be dramatically improved without collecting more field data or performing explicit domain adaptation, post-hoc calibration offers a low-cost way to make probabilistic outputs more honest. In a real deployment, this means that the system can report probabilities that better reflect its actual reliability on field images, enabling downstream workflows that depend on thresholding or ranking by confidence—for example, flagging low-confidence predictions for human review or prioritizing samples that should be annotated to expand the field dataset.

Finally, these results connect directly to the broader goal of building a system for weed and plant disease recognition with user-supplied imagery. The PlantVillage-to-PlantDoc tomato experiments represent a controlled instance of the more general “manual dataset input” scenario: users upload images taken under varied conditions, and the model must operate under inevitable domain shift. The observed performance gap and the benefits of temperature scaling suggest a practical recipe for such systems: (i) train on large, curated datasets when possible; (ii) reserve a small, labeled subset from the target deployment domain for validation; (iii) use that subset to calibrate or adapt the model; and (iv) expose calibrated confidence scores in the user interface rather than raw logits or uncalibrated probabilities. In future work, extending this protocol to multiple crops, weed species, and additional field datasets, and combining calibration with lightweight domain adaptation, could further narrow the lab-to-field gap while preserving the simplicity needed for real-world agricultural applications [4], [5], [11].

Conclusion. This study examined how well popular deep learning architectures for plant disease classification generalize from a curated laboratory dataset (PlantVillage) to a more realistic field dataset (PlantDoc) in the specific case of tomato foliar diseases. Using a unified training pipeline with ImageNet- pretrained ResNet-50, DenseNet-121, EfficientNet-B0, and ViT-B/16, all models achieved near-perfect accuracy and macro-F1 on the PlantVillage validation split, confirming that the seven-class tomato subset of PlantVillage is essentially saturated under controlled conditions.

When these models were applied zero-shot to the PlantDoc tomato test split, however, performance dropped markedly: accuracy fell to the 21–34 % range and macro-F1 to 11–24 %. This sharp decrease quantifies the severity of the lab-to-field domain shift and shows that high performance on PlantVillage alone is not a reliable indicator of field readiness. Among the evaluated backbones, ResNet-50 and DenseNet-121 transferred best, EfficientNet-B0

performed moderately, and ViT-B/16 struggled most in this low-data, cross-domain setting, despite competitive in-distribution results.

Beyond accuracy, the study showed that uncalibrated models are strongly over-confident on field images. Before calibration, all architectures exhibited large negative log- likelihood, high Brier scores, and substantial expected calibration error. A single temperature parameter per model, fitted on a small, balanced PlantDoc validation split, was sufficient to dramatically improve probability calibration on the held-out test set. Temperature scaling reduced NLL, Brier score, and ECE for all backbones while leaving top-1 accuracy and macro-F1 unchanged, and reliability diagrams and ECE bar plots confirmed that predicted probabilities became much better aligned with empirical correctness.

Taken together, the results support a simple but actionable recipe for web- or mobile-based decision-support systems in agriculture that rely on user-uploaded images. Training on large, clean datasets such as PlantVillage is valuable but not sufficient; systems should always be evaluated on at least one independent field dataset and, whenever possible, use a small labeled subset from the target domain to calibrate predicted probabilities. Even when accuracy cannot be substantially improved without additional field data or explicit domain adaptation, post-hoc temperature scaling provides a low-cost way to make confidence scores more honest and useful for downstream decision-making, such as triaging uncertain cases for expert review.

For the broader goal of a system for weed and plant disease recognition with manual dataset input, this work demonstrates both the risks of relying solely on lab-style benchmarks and the benefits of lightweight calibration under domain shift. Future extensions of this protocol to multiple crops, additional disease and weed classes, and more diverse field datasets can further narrow the gap between research prototypes and robust, trustworthy tools for real-world agricultural practice.

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РАЗРАБОТКА СКРИПТОВ ПОД VR-ПРИЛОЖЕНИЕ ДЛЯ ИМИТАЦИИ ДЕЙСТВИЙ СПЕЦИАЛИСТОВ В ЧРЕЗВЫЧАЙНЫХ СИТУАЦИЯХ

Аннотация: Целью настоящего исследования является проектирование и программная реализация событийно-ориентированной архитектуры скриптов в VR-приложениях для имитации действий специалистов в чрезвычайных ситуациях. В работе рассматривается трансформация подходов к созданию интерактивных симуляций с переходом от жестко заданных линейных алгоритмов к гибким модульным системам на базе движка Unity. Автор акцентирует внимание на проблеме синхронизации физических взаимодействий пользователя с логикой сценария и подчеркивает, что событийный скриптинг становится мощным инструментом обеспечения когнитивной достоверности обучения.Методология исследования включает объектно-ориентированное проектирование на языке C# и сравнительный анализ эффективности верификации действий обучаемого. Исследование подчеркивает необходимость гармоничного сочетания визуального реализма и глубины программной логики для будущего аудиовизуального обучающего контента в профессиональной среде.

Ключевые слова: виртуальная реальность, Unity, разработка скриптов, чрезвычайные ситуации, событийно-ориентированная архитектура, C#, аналитика данных.

Актуальность данного исследования продиктована необходимостью цифровой трансформации процессов подготовки персонала к работе на опасных производственных объектах. В условиях возникновения чрезвычайных ситуаций решающее значение имеет не только знание теоретических основ, но и практическая готовность к принятию решений в стрессовой среде. Традиционные методы обучения в виртуальной реальности (VR) зачастую ограничены линейными сценариями, что не позволяет обучаемому в полной мере осознать последствия совершаемых ошибок. В связи с этим, основной задачей работы выступает переход от жестких алгоритмов к событийно-ориентированной модели симуляции в среде Unity. Проектирование такой системы требует строгого разделения архитектуры на независимые уровни: ввод данных от аппаратных средств, логический контроллер сценария и модуль аналитической обработки результатов.

Центральным элементом предложенного подхода является использование паттерна проектирования «Наблюдатель» (Observer). В отличие от классических методов циклической проверки условий в каждом кадре, событийный скриптинг позволяет объектам виртуальной среды — датчикам, системам пожаротушения и элементам управления — взаимодействовать автономно. Когда пользователь инициирует контакт с

интерактивным объектом через интерфейс IInteractable, система генерирует событие, на которое мгновенно реагирует менеджер сценария, построенный на архитектуре конечного автомата. Это обеспечивает бесшовную синхронизацию физики захвата предметов с общей логикой протокола безопасности, исключая технические задержки и поддерживая высокий уровень иммерсивности.

Важной частью методологии является математическая верификация действий обучаемого через внедрение весового алгоритма. Для количественной оценки качества выполнения протокола в систему внедрена математическая модель расчета индекса успешности. Каждое i-ое действие специалиста оценивается на основе его приоритетности и оперативности. Формула итогового показателя S принимает следующий вид:

$$S=\sum_{i=1}^{n} w_i \cdot (1-t_{fact,i} \setminus t_{lim i} t,i))$$

где:

w_i— весовой коэффициент важности действия;

t_(fact,i)— фактическое время выполнения;

t_(lim i t,i)— максимально допустимое время по регламенту.

В данной интерпретации, если пользователь выполняет действие максимально оперативно, он получает балл, близкий к весу wi . Если же лимит времени превышен, значение становится отрицательным, что в логике скрипта инициирует автоматическую эскалацию опасных факторов среды, создавая прямую зависимость состояния окружения от качества работы специалиста.

В рамках специализации «Прикладная аналитика данных» особое значение приобретает возможность экспорта детализированных логов о каждой интеракции пользователя. Событийная архитектура позволяет фиксировать не только итоговый результат, но и промежуточные метрики: траектории движения, время фокусировки внимания и последовательность манипуляций. Это открывает возможности для предиктивного анализа поведения персонала и выявления наиболее сложных участков протоколов безопасности. В заключение стоит отметить, что интеграция гибких программных паттернов и методов аналитики данных в VR-индустрию обеспечивает создание адаптивных экосистем, способных эффективно готовить кадры к работе в критических условиях будущего, обеспечивая гармоничное сочетание визуального реализма и глубокой математической логики симуляции.

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ADAPTATION AND COMPARATIVE EVALUATION OF YOLO-BASED MODELS FOR UNDERWATER OBJECT RECOGNITION

Abstract: This article examines the adaptation and comparative evaluation of YOLO-based models for underwater object recognition. The study focuses on the robustness of modern object detection models across heterogeneous underwater datasets, the influence of training parameters, and the interpretation of experimental results. In addition, segmentation results on the Aquarium Fish dataset are considered as a supporting analysis for understanding spatial learning quality in underwater scenes.

Keywords: underwater object recognition, YOLO11s, YOLOX, marine debris detection, multi-dataset learning, semantic segmentation

I. Introduction. Object recognition in underwater scenes is considerably harder than in conventional natural images. Water absorbs and scatters light, background texture is often weak, and the same class may appear very different depending on depth, turbidity, or camera angle. For this reason, underwater vision is a useful setting for a dissertation project: it forces the researcher to examine not only whether a model reaches a good score, but also how stable that score remains when the visual conditions change.

Recent years have shown that YOLO-based detectors remain among the most practical tools for real-time perception. They combine localization and classification in a single pass and therefore fit applications such as underwater robotics, marine monitoring, and automated debris inspection. At the same time, the literature on underwater detection repeatedly shows that performance depends on more than the detector name. Training schedule, augmentation, optimizer settings, and the composition of the dataset all influence the result.

This paper therefore approaches the topic from a broader perspective. The objective is not merely to show that YOLO can detect underwater objects, which is already known, but to investigate how modern YOLO-family models behave across heterogeneous underwater datasets and how the author's own experimental results can be interpreted in that context. The core evidence includes public datasets for marine organisms and underwater waste, together with a complete training run of YOLO11s preserved in the underwater_object_detection_shauryas555 archive.

The research contribution is formulated in practical rather than purely formal terms. First, the paper brings together several underwater datasets that differ in object type and visual style. Second, it uses the archived training results to discuss convergence, best-epoch selection, and the trade-off between continuing training and protecting generalization. Third, it uses an auxiliary segmentation experiment only to support the interpretation of spatial learning quality, rather than making segmentation the main storyline. This makes the paper closer to a coherent dissertation chapter than to a narrow benchmark report.

II. Literature Review. Classical recognition systems relied on hand-crafted features and separate classifiers. Such approaches could work in constrained domains, but they struggled when objects varied in scale, pose, illumination, or background. Deep learning changed this situation by learning feature extraction and decision boundaries jointly. In one-stage detection, the YOLO family became especially important because it turned object detection into a direct regression task and made real-time inference feasible.

Later YOLO variants improved both speed and quality through better backbone design, feature aggregation, label assignment, and box regression losses. YOLOv4 strengthened the balance between efficiency and accuracy, while YOLOX introduced an anchor-free design and a decoupled head. More recent work with YOLO11 continues this trend and is attractive for applied projects because it retains the familiar YOLO workflow while improving optimization and deployment convenience.

For underwater applications, however, the literature suggests that architecture alone is not the full explanation of performance. Studies on improved YOLOX for underwater recognition report that optimizer choice and augmentation design can materially change the final result. Importantly, some augmentations that are helpful in terrestrial datasets may create unrealistic underwater compositions and therefore reduce rather than improve practical accuracy. This is a valuable reminder that underwater recognition is partly a domain adaptation problem.

Other recent studies outside the marine domain are still relevant because they highlight issues that also appear underwater. Small-object recognition, confidence calibration, and box quality remain difficult when the object occupies only a small fraction of the frame or is visually blended with the background. Work on improved YOLOv5 for rail intrusion detection, for example, shows that small-object sensitivity can be raised by altering prediction layers and feature extraction blocks. The conceptual lesson is transferable even if the scene differs.

At the same time, segmentation research helps explain why some detections appear qualitatively convincing while still being spatially crude. If the model learns category cues more strongly than boundary cues, it may classify correctly but localize poorly. For that reason, a small segmentation component can strengthen the interpretation of the detector results without replacing the main detection experiments. This is the role assigned to the Aquarium experiment in the present work.

III. Methodology. The study follows a multi-dataset design. This choice is intentional. A model trained and validated on a single underwater dataset can easily learn that dataset's biases instead of more general underwater structure. To reduce this risk, the work combines several public datasets: URPC2020 for underwater object detection of marine organisms, TrashCan 1.0 for underwater waste categories, Underwater Trash Detection for additional marine debris examples, and the Aquarium Fish Semantic Segmentation Dataset as an auxiliary source for boundary-level analysis.

The main detection experiments are interpreted through the standard YOLO prediction framework. Given an input image I, the detector predicts a set of boxes and class scores, which can be written as $f(I) \rightarrow \{(x, y, w, h, c, p)\}$. During training, the total loss is a weighted combination of localization, objectness, and classification terms. In modern YOLO variants, IoU-aware box losses and improved matching strategies are used to make this optimization more stable. For underwater data, this is particularly important because low contrast and clutter make both localization and confidence estimation more fragile.

The author's archived experiment provides a concrete case study. According to the stored args.yaml file, the detector was trained in detection mode with the pretrained yolo11s model, image size 640, batch size 8, and a target of 100 epochs. The run used automatic optimizer selection, standard color and geometric augmentations, mosaic enabled during most of training, and a patience setting of 30 epochs. In other words, the experiment was not a toy run; it reflects a realistic medium-scale training configuration that a graduate student could reproduce and analyze.

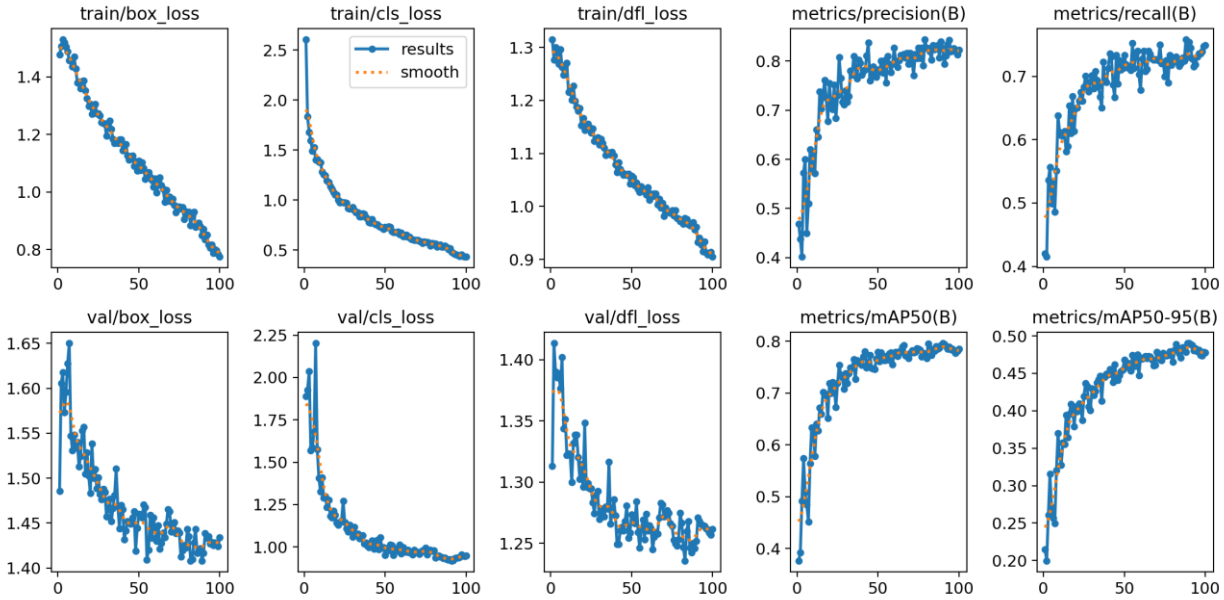
The underwater_object_detection_shauryas555 results are central to this revised paper. The results.csv file contains training and validation losses together with precision, recall, mAP@50, and mAP@50–95 for each epoch. The best epoch by mAP@50–95 was epoch 89. At that point, precision reached 0.839, recall 0.730, mAP@50 0.793, and mAP@50–95 0.490. The final epoch was close but slightly worse in the main summary metric, which supports the argument that the most meaningful model checkpoint is not necessarily the last one. The total recorded training time at epoch 100 was about 697 seconds, or roughly 11.6 minutes in cumulative run time under the available setup.

The Aquarium segmentation history was retained in the paper but no longer dominates the narrative. It is used only as a supporting observation about spatial learning. In that experiment, the best validation IoU was 0.526 and the best Dice coefficient was 0.684 at epoch 26. After that point, additional epochs did not produce a stable upward trend. This finding is helpful because it mirrors the broader message from the detection experiment: on underwater imagery, there is often a clear best-validation region, and training beyond it may offer little practical benefit.

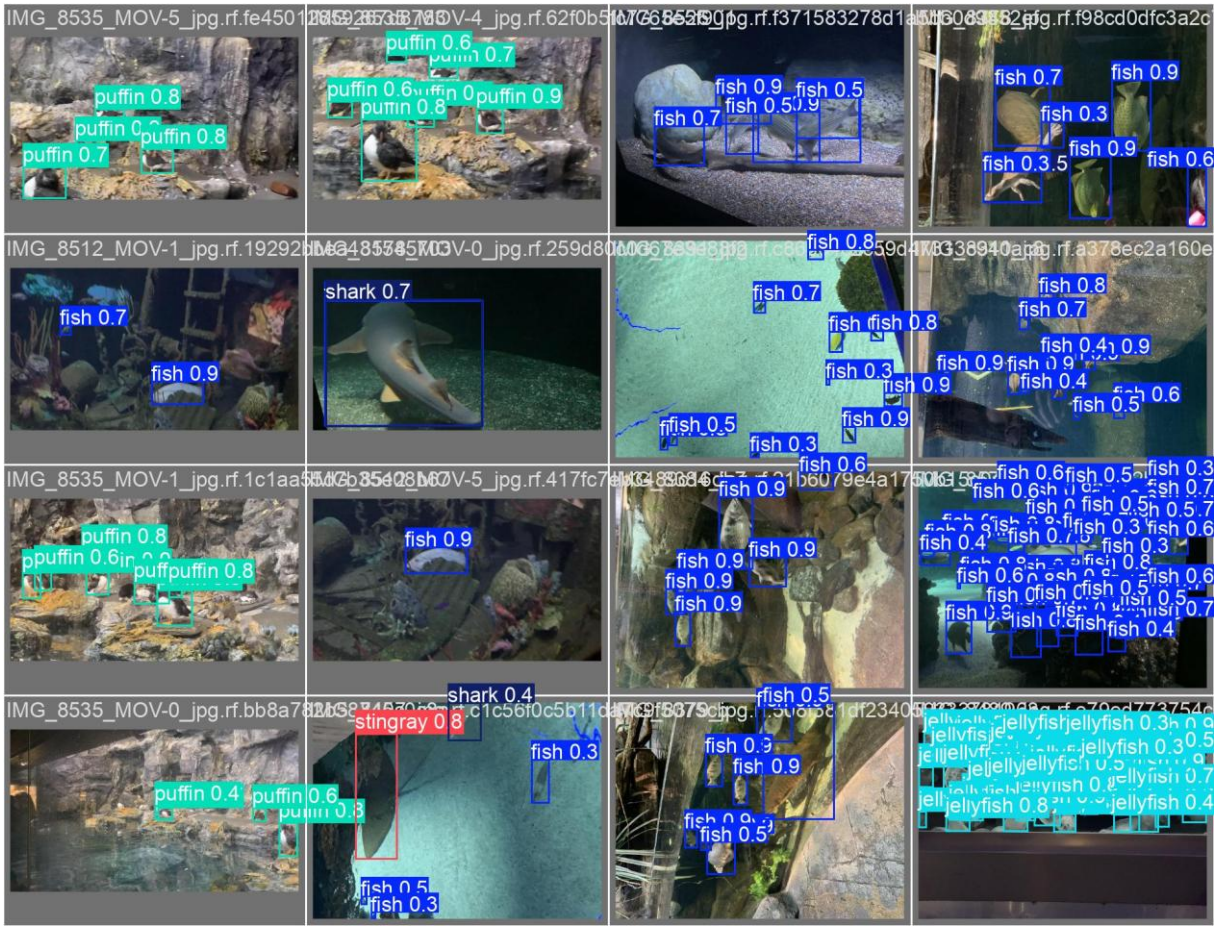
Two tables and selected figures are used to present the methodology more clearly. The first table summarizes the datasets and their roles in the study. The second table reports the key numerical outcomes of the author's own YOLO11s run together with the auxiliary segmentation result. This structure keeps the focus on the primary detection experiment while still showing that the work considers more than one visual task.

Table 1 – Datasets used in the study

Dataset	Task	Role in the paper	Source
URPC2020	Detection	Marine-organism detection and cross-dataset diversity	Kaggle
TrashCan 1.0	Detection	Underwater debris categories	Kaggle
Underwater Trash Detection	Detection	Additional waste examples and domain variation	Kaggle
Aquarium Fish Segmentation	Segmentation	Auxiliary spatial-learning analysis	Kaggle



Pic. 1 - Training curves from the archived YOLO11s detection run (underwater_object_detection_shauryas555).



Pic. 2 - Example validation predictions from the archived YOLO11s run.

IV. Results and Discussion. The archived detection run is the main empirical addition that was missing from the previous draft. It changes the paper from a general discussion of underwater YOLO models into a study grounded in the author's own evidence. The training curves show a gradual decrease in training losses and a slower stabilization of validation

performance. This pattern is typical for medium-scale object detection runs: optimization continues to improve the fit to the training set even after the validation metrics begin to plateau.

The most important outcome is the location of the best checkpoint. According to the stored results.csv, the best mAP@50–95 value was 0.490 at epoch 89. At that same epoch, precision was 0.839, recall was 0.730, and mAP@50 was 0.793. The final epoch reached mAP@50 0.785 and mAP@50–95 0.478, which is close but still below the best checkpoint in the stricter metric. This is a useful result because it demonstrates why model selection should be based on validation evidence rather than simply taking the last saved state.

Another practical point concerns convergence efficiency. The cumulative time recorded in the experiment suggests that the full 100-epoch run completed in about 11.6 minutes under the available setup. For a dissertation project, that matters. It means that the experimental loop is short enough to support ablation studies, dataset mixing, and augmentation tuning without requiring excessive compute. In other words, the methodological design is not only scientifically defensible but also feasible for iterative student research.

The confusion behavior and validation image outputs also support a balanced interpretation. The model clearly learned the target domain, as seen in the qualitative validation predictions, yet the gap between mAP@50 and mAP@50–95 indicates that fine localization remains harder than coarse detection. This is exactly the kind of nuance that matters in underwater scenes. A detector may identify the right object type while still placing a box that is too loose or slightly shifted because boundaries are visually weak or because the object blends with the seabed or surrounding debris.

This is where the Aquarium segmentation result becomes useful as supporting evidence, but it should not dominate the paper. The segmentation experiment reached its best validation IoU of 0.526 and Dice of 0.684 at epoch 26. These values are informative, yet the more important point is interpretive: underwater models often learn category-level and coarse shape cues earlier than they learn exact boundaries. That observation is consistent with the localization gap in the detection run. It therefore supports the discussion, but it is not the main contribution.

The multi-dataset perspective also changes how the results should be read. A score obtained on one underwater benchmark cannot automatically be generalized to all underwater settings. Organism datasets, debris datasets, and aquarium images differ not only in class content but also in texture, camera conditions, annotation style, and visual cleanliness. A detector that performs well on fish in relatively clear tank imagery may still face a harder problem on benthic waste or low-contrast marine organisms. This is why the present study emphasizes dataset composition and cross-domain reasoning rather than treating the problem as one more single-dataset benchmark.

Finally, the own-run results clarify the novelty of the dissertation chapter. The novelty is not the statement that YOLO works underwater. The novelty is the attempt to frame underwater recognition as a problem of robust model selection and training configuration, supported by direct experimental evidence. The archived YOLO11s run gives that argument a concrete foundation, and it allows the paper to discuss training dynamics, checkpoint choice, and practical generalization in a grounded way rather than at the level of abstract claims.

Table 2 – Key results used in the discussion

Experiment	Best epoch	Main metric	Supporting metrics	Interpretation
YOLO11s detection run from underwater_object_detection_shauryas555	89	mAP@50–95 = 0.490	Precision 0.839; Recall 0.730; mAP@50 0.793	Best checkpoint appears before final epoch; validation-based selection is justified
Final YOLO11s epoch in the same run	100	mAP@50–95 = 0.478	Precision 0.823; Recall 0.749; mAP@50 0.785	Later training maintained performance but did not surpass the best checkpoint
Aquarium auxiliary segmentation run	26	Val IoU = 0.526	Val Dice = 0.684	Boundary learning improved early and then became unstable; useful as a secondary indicator only

V. Conclusion. The revised results make it possible to formulate a more mature conclusion than in the previous version of the paper. The project shows that underwater object recognition should not be reduced to the question of which YOLO variant is newest or most popular. What matters more is whether the detector is trained in a way that respects the visual logic of underwater imagery and whether evaluation is broad enough to capture more than one narrow dataset style. From that perspective, the work contributes not only a set of results, but also a methodological position.

The archived YOLO11s experiment is especially important because it provides a direct bridge between theory and practice. It shows that the model can reach a useful detection regime on underwater data, but it also shows that the best checkpoint appears before the end of training. This is a small but meaningful scientific observation. It reminds us that underwater recognition is sensitive to generalization quality, and that continuing optimization after the validation peak may preserve training progress without improving real-world usefulness. In a dissertation context, this kind of evidence is often more valuable than a single isolated score.

Another important conclusion concerns scale and realism. The run completed in a modest amount of time, which means the experimental setup is feasible for repeated testing and therefore suitable for a dissertation project that still needs ablations or cross-dataset comparisons. That practical feasibility matters because robust underwater recognition cannot be established from one successful run. It requires repeated checking of whether the same training choices remain effective when the data source changes. The present work therefore opens the door to a stronger final thesis chapter built around transfer, robustness, and ablation rather than one-off training.

The reduced emphasis on Aquarium segmentation also leads to a healthier interpretation of the paper. The segmentation experiment is useful, but mainly because it helps explain why detection quality and localization quality do not always improve together. The central contribution remains the detection analysis, especially the integration of the author's own archived run. In that sense, segmentation plays the role it should play here: not the headline result, but a supporting observation that strengthens the interpretation of the main detector outcomes.

Perhaps the most thoughtful conclusion is that underwater recognition should be treated as a domain-specific systems problem. The detector, the augmentation choices, the checkpoint selection rule, and the dataset mix all work together. A strong model can underperform if the data pipeline is unrealistic; conversely, a relatively lightweight model can become useful if its training regime is aligned with the domain. This is why the dissertation can claim novelty not by inventing a brand-new architecture, but by showing, with concrete evidence, how a modern YOLO workflow can be adapted and judged more carefully for underwater tasks.

For the continuation of the diploma project, the most promising next steps are clear. First, the same YOLO11s pipeline should be evaluated under controlled dataset combinations to identify which data sources improve generalization and which introduce conflicting biases. Second, the influence of specific augmentation policies should be isolated, especially those that may be unrealistic underwater. Third, the best checkpoint from the archived run should be compared against alternative models such as YOLOX or larger YOLO11 variants under the same training budget. These steps would deepen the dissertation naturally and would transform the current paper from a strong intermediate article into the backbone of a completed research project.

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DEVELOPMENT OF METHODS FOR CALCULATING THE AREA OF FOREST FIRES USING AERIAL AND SATELLITE IMAGES

Abstract: Kazakhstan's steppe and forest ecosystems experience large seasonal wildfires whose long-term dynamics and near-term trajectory matter for environmental policy and operational planning. This paper presents an open, single-environment Python pipeline that (i) drives Google Earth Engine through its Python API to construct a 24-year (2001–2024) monthly ADM1-level dataset from MCD64A1 burned area, MOD14A1/MYD14A1 active fire, MCD12Q1 land cover, and MOD44B tree cover products; (ii) runs strict quality control and analytics on the resulting 4,320 records; and (iii) trains Seasonal ARIMA and Prophet baselines on the national monthly burned area, evaluates them on a three-year hold-out, and produces a 24-month out-of-sample forecast. On the hold-out, Prophet attains a Mean Absolute Error of 2,468 km² versus 3,280 km² for SARIMA, a 25% improvement. The pipeline is designed for reuse and extension by other regional fire-monitoring studies.

Keywords: wildfire monitoring, burned area, MODIS, Google Earth Engine Python API, reproducible pipeline, time-series forecasting, SARIMA, Prophet, Kazakhstan

Introduction. Wildfires shape land surface dynamics and atmospheric chemistry, and their incidence depends on climate, vegetation, and human activity [1]. Kazakhstan's territory includes vast steppe and semi-arid regions in which large fires occur seasonally; sustained subnational monitoring is therefore valuable both for retrospective trend analysis and for short-term operational planning.

Satellite remote sensing supports repeatable burned area and active fire mapping at continental scales [2, 3]. Cloud platforms such as Google Earth Engine (GEE) [4] make it practical to process decades of MODIS imagery, but published implementations are often fragmented: data extraction runs in the GEE JavaScript Code Editor, analytics in a separate Python notebook, and forecasting in yet another environment. Such fragmentation creates friction for re-execution, version control, and method extension.

This paper makes three contributions:

1. A single-environment Python pipeline that drives GEE through its Python API and continues the workflow into analytics and forecasting without leaving the same process.

2. A 4,320-row monthly ADM1 dataset for Kazakhstan (2001–2024) covering burned area, active fire intensity, two independent forest definitions, and MODIS QA indicators.

3. A baseline forecasting study of the national monthly burned area: log-space SARIMA and Prophet models with a three-year hold-out evaluation and a 24-month out-of-sample projection.

Related work. MCD64A1 provides monthly global burned area at 500 m [2]; validation studies highlight biome-dependent skill and the importance of QA-aware interpretation [5]. The MOD14A1 (Terra) and MYD14A1 (Aqua) active fire products provide daily 1 km detections [3, 6].

MODIS land cover MCD12Q1 supplies annual IGBP classes [7, 8], while MOD44B provides percent tree cover for a continuous, threshold-based forest definition [9]. Using both in parallel enables sensitivity analysis.

GEE [4] has been broadly adopted for national and regional fire studies; its Python API removes the need to switch between JavaScript and local Python, but is less commonly used in published pipelines. Seasonal ARIMA [10] and the additive model Prophet [11] are widely used baselines for monthly environmental series that exhibit a clear yearly cycle.

Pipeline architecture. The pipeline executes three sequential stages in the same Python process (Table 1). Stage S1 issues Earth Engine queries from Python, pulls reduceRegions results directly into pandas [12] (no Drive intermediate), and writes per-year and combined CSV/Parquet files. Stage S2 applies strict quality control, derives normalized indicators, builds aggregation tables, and renders descriptive figures. Stage S3 trains and evaluates SARIMA [13] and Prophet on the national monthly burned area and produces a 24-month forecast.

Table 1 – Pipeline stages and outputs

Stage	Stack	Function and main outputs
S1	Python + EE API	Monthly zonal reductions over MCD64A1, MOD14A1, MYD14A1, MCD12Q1, MOD44B; per-year and combined long CSV/Parquet.
S2	Python (pandas, matplotlib)	QC, derived indicators, hotspot ranking, eight aggregation tables, four descriptive figures.
S3	Python (statsmodels, prophet)	Log-space SARIMA and Prophet, 3-year hold-out, MAE/RMSE/MAPE, 24-month forecast with 95% intervals; serialized model artifacts.

Data construction.

Study Area and Spatial Units

The study area is Kazakhstan aggregated to ADM1 (FAO GAUL level 1 [14]). A placeholder polygon labelled 'Administrative unit not available' is removed, yielding 15 administrative units used consistently across all years.

Notation and Pixel-Area Sums

All zonal metrics are pixel-area sums over a subset of pixels selected by one or more conditions. For each ADM1 unit r the pixel-based region area in km² is:

$$A_r = \Sigma_{p \in r} \text{ area}(p) \quad (1)$$

Two forest masks are evaluated in parallel: an IGBP mask (MCD12Q1 classes 1–5) and a tree-cover mask (MOD44B ≥ 30%). Monthly burned areas (total and forest-conditional) are:

$$B_{r,t} = \Sigma_{p \in r \cap \text{Burn}(t)} \text{ area}(p) \quad (2)$$

Active Fire Intensity

For satellites Terra and Aqua, a daily active fire detection is recorded when FireMask(p,d) ∈ {7, 8, 9} (low, nominal, or high confidence). Combined pixel-days across both satellites:

$$D^{obs}_{r,t} = N^{Terra}_{r,t} + N^{Aouma}_{r,t} \quad (3)$$

The low-uncertainty subset uses the MCD64A1 Uncertainty band: pixels where U(p,t) ≤ 20 [2].

Forecasting methodology. The national monthly burned area $B_t = \Sigma_r B_{r,t}$ is heavy-tailed. Both models are fit in log-space:

$$\tilde{B}_t = \log(1 + B_t), \quad \hat{B}_t = \max(0, \exp(\hat{\tilde{B}}_t) - 1) \quad (4)$$

SARIMA. Using the backshift operator $\mathcal{B}$ (so that $\mathcal{B}^k x_t = x_{t-k}$), the SARIMA(1,1,1)(1,1,1)$_{12}$ model on $\tilde{B}_t$ is:

$$\varphi_p(\mathcal{B})\Phi_p(\mathcal{B}^s)(1-\mathcal{B})(1-\mathcal{B}^s)\,\tilde{B}_t = \theta_\chi(\mathcal{B})\Theta_\chi(\mathcal{B}^s)\,\varepsilon_t, \quad \varepsilon_t \sim N(0,\sigma^2) \quad (5)$$

Parameters (p,d,q)(P,D,Q)s = (1,1,1)(1,1,1)12, fitted with statsmodels [13] via state-space optimization.

Prophet. The model decomposes the series as $\tilde{B}_t = g(t) + s(t) + \varepsilon_t$, with g(t) a piecewise-linear trend and s(t) a yearly Fourier seasonality (N=10 harmonics, P=365.25 days). Weekly and daily components are disabled; interval width is 0.95 [11].

Evaluation. The last three calendar years (2022–2024, 36 months) form the test set; the remaining 21 years (252 months) form the training set. Metrics:

$$\text{MAE} = (1/n)\Sigma|B_i - \hat{B}_i|, \quad \text{RMSE} = \sqrt{((1/n)\Sigma(B_i - \hat{B}_i)^2)} \quad (6)$$

$$\text{MAPE} = (100/|\{i:B_i>0\}|)\Sigma_{i:B_i>0} \; |B_i - \hat{B}_i| / B_i \quad (7)$$

After hold-out evaluation, each model is refit on the full 288-month series (2001–2024) to produce a 24-month forecast for 2025–2026.

Results

Dataset Profile

The constructed dataset contains 15 × 12 × 24 = 4,320 rows. Of these, 2,636 (61%) record at least one burned pixel and 3,255 (75%) at least one active fire detection. The mean QA score (average of valid-burn and low-uncertainty shares) is 0.61. Summary parameters are listed in Table 2.

Table 2 – Dataset and pipeline parameters

Parameter	Value
ADM1 units / years / rows	15 / 24 / 4,320
Burned area product	MCD64A1, 500 m, monthly
Active fire products	MOD14A1 + MYD14A1, 1 km, daily
Forest masks	IGBP classes 1–5; TC ≥ 30%
QA / uncertainty rule	MCD64A1 valid bit; Unc ≤ 20
Forecast models	SARIMA(1,1,1)(1,1,1)$_{12}$, Prophet
Train / hold-out / horizon	21 years / 3 years / 24 months (2025–2026)

Interannual Burned Area. The peak year was 2002 with 235,374 km², followed by 2017 (143,883 km²), 2006 (143,524 km²), and 2004 (134,773 km²). The most recent three years (2022–2024) average 11,874 km²/year, roughly an order of magnitude below the 2001–2005 mean of 134,028 km²/year. The aggregate burned area over the 24-year window is 1,818,497 km² (Figure 1).

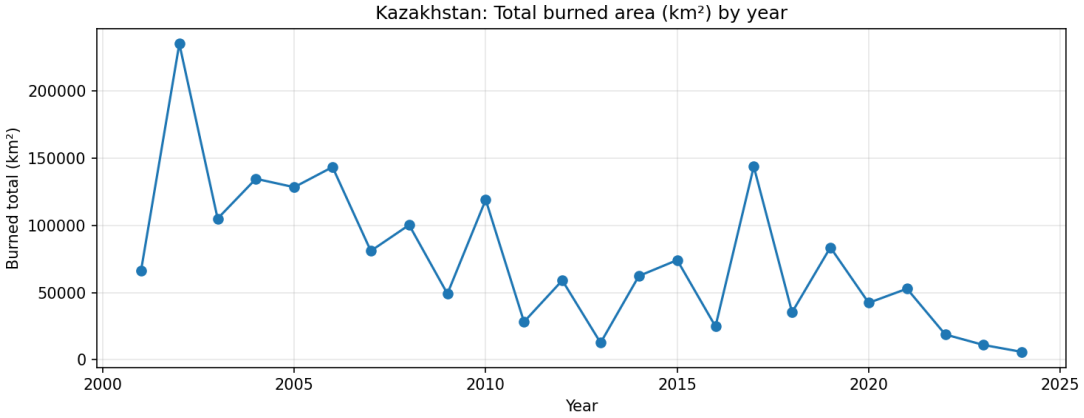


Figure 1 – Annual total burned area in Kazakhstan from MCD64A1, 2001–2024

Cross-Product Consistency. Across all 4,320 ADM1-month records the Pearson correlation between $B_{r,t}$ and $D^{obs}_{r,t}$ is r = 0.794, supporting the use of the two product families as independent observations of the same phenomenon (Figure 2).

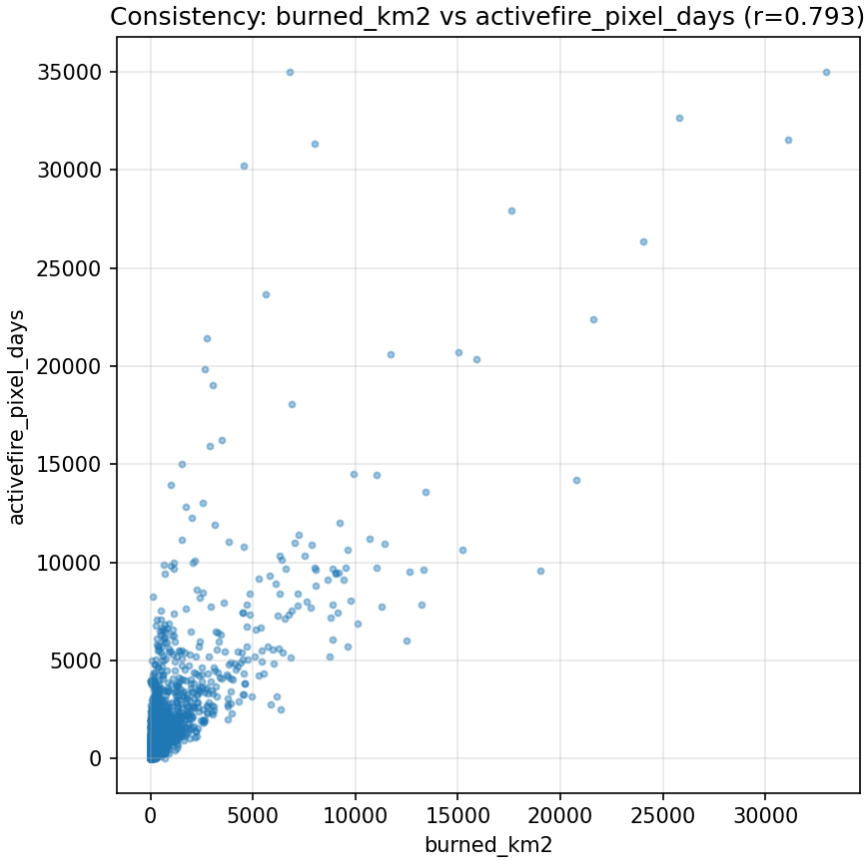


Figure 2 – Burned area vs. active fire pixel-days across all ADM1-month records; Pearson r = 0.794

Regional Hotspots. Top hotspots by total forest burned area under the TC mask (2001–2024) are led by Almatinskaya (1,685 km²) and Atyrauskaya (1,270 km²). A second group of ~100–300 km² comprises Kustanayskaya, Vostochno-kazachstanskaya, Severo-kazachstanskaya, and Zapadno-kazachstanskaya (Figure 3).

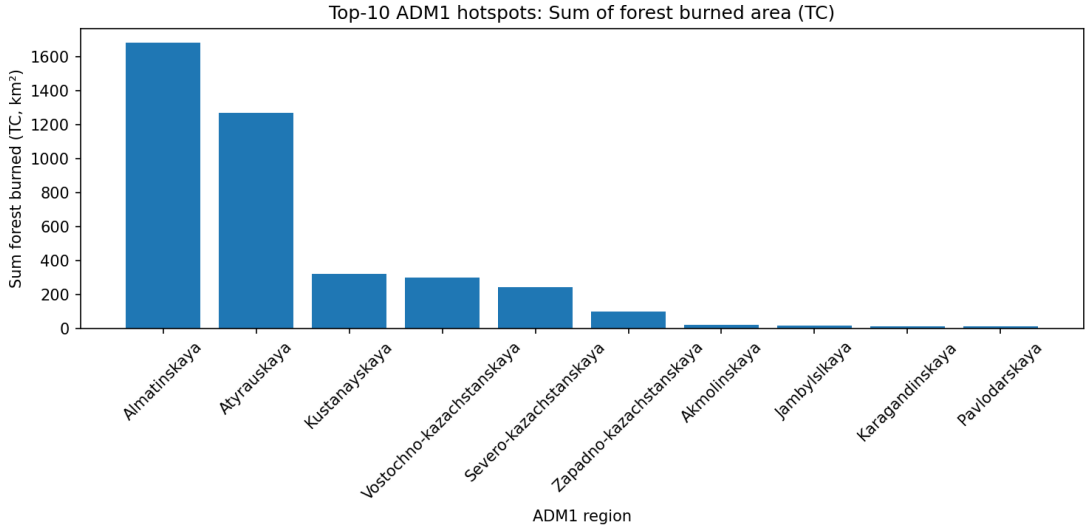


Figure 3 – Top-10 ADM1 hotspots by total forest burned area under the TC definition, 2001–2024

Hold-Out Forecast Performance. Hold-out scores are summarized in Table 3. Prophet outperforms SARIMA on every metric, with a 25% lower MAE and a 22% lower RMSE. Both models exhibit a large MAPE because most low-burn months have near-zero actuals, which inflate percentage errors.

Table 3 – Hold-out forecast performance (2022–2024, 36 months)

Model	MAE (km²)	RMSE (km²)	MAPE (%)
SARIMA(1,1,1)(1,1,1)$_{12}$	3,280	5,275	692
Prophet	2,468	4,103	540

Out-of-Sample Forecast. Refitting each model on the full 288-month series produces the 2025–2026 forecast shown in Figure 4. The Prophet trajectory reproduces the seasonal cycle (July–August peak at ~10,000–12,000 km²/month, near-zero in winter); annual projected totals are ~21,200 km² (2025) and ~20,300 km² (2026), broadly consistent with the post-2017 declining trend.

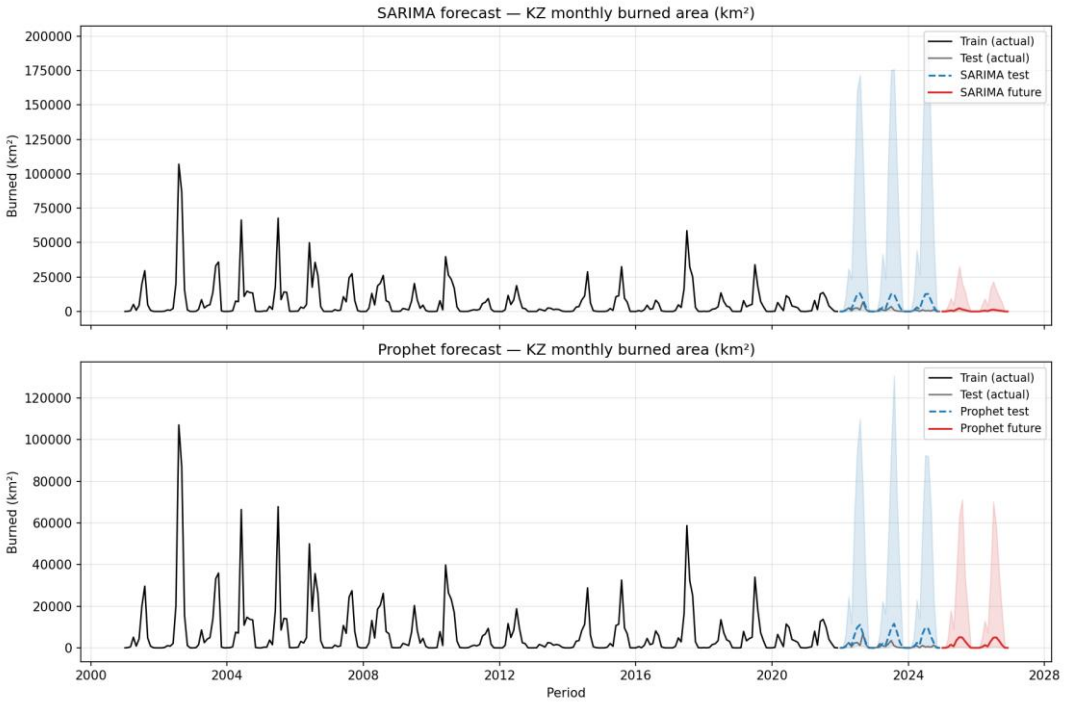


Figure 4 – National monthly burned area: SARIMA (top) and Prophet (bottom) forecasts for 2025–2026

Discussion and limitations. The dataset inherits known limitations of MODIS fire products: detection performance varies by biome, cloud and smoke can reduce sensitivity, and small burns near the 500 m resolution may be missed [2, 5]. Reporting both IGBP and tree-cover forest masks makes the forest-attribution results auditable.

The forecasting models capture trend and yearly seasonality but do not use exogenous regressors (climate variables, land-use change, ignition controls). Their 95% intervals are wide, reflecting the high interannual variability of the historical series. Longer-horizon projections would benefit from exogenous covariates and possibly hierarchical (region-level) models.

A practical advantage of the single-environment design is auditability: every data point can be regenerated from the same Python entry-point that drives the GEE queries. The fitted SARIMA and Prophet models are additionally persisted to disk for inspection or reuse without re-training.

Conclusion. This paper presented an open Python pipeline that constructs a 24-year monthly ADM1 wildfire dataset for Kazakhstan from MODIS products, runs strict quality control and analytics, and produces a baseline 24-month national forecast. Prophet achieved a 25% MAE improvement over SARIMA on a three-year hold-out (2,468 vs. 3,280 km²). The unified Python design removes the JavaScript/Drive intermediates of typical Earth Engine workflows and lowers the cost of reproducing or extending the analysis. Future work will incorporate climate-derived exogenous regressors and evaluate region-level hierarchical forecasts.

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OPTIMIZATION OF GPU MACHINE LEARNING WORKLOADS USING CUDA AND TENSORFLOW

Abstract: The explosive growth of deep learning model scale has posed increasingly demanding requirements on computing resources. Traditional CPUs have gradually shown performance bottlenecks when processing large-scale parallel computing tasks, while GPUs, with their powerful parallel computing capabilities, have become the core engine of deep learning computation. However, how to fully exploit GPU computational potential and achieve efficient machine learning workload optimization still faces many challenges. This research systematically investigates collaborative optimization strategies of the CUDA programming model and TensorFlow framework for performance optimization of machine learning workloads on GPUs. We designed a multi-dimensional performance profiling framework to identify computational bottlenecks, and implemented key technologies including mixed precision training, operator fusion, and memory optimization. Experimental results demonstrate that FP16 mixed precision mode achieves a 65% throughput improvement for ResNet50 and a 2.3x improvement in energy efficiency ratio, providing an efficient GPU configuration scheme for deep learning training.

Keywords: GPU Acceleration; CUDA; TensorFlow; Performance Optimization; Mixed Precision Training

1. Introduction. Deep learning has developed rapidly in computer vision, natural language processing, speech recognition, and many other areas [1]. At the same time, the scale of models has increased sharply. From early LeNet models to recent GPT series and Stable Diffusion, the number of parameters has grown from millions to hundreds of billions, which brings much higher demand for computing resources [2]. In this situation, traditional CPU-based computing is often not efficient enough for large-scale training and inference tasks.

GPUs provide an effective solution because of their massively parallel architecture [3]. With thousands of processing cores, GPUs are well suited for the matrix operations used in forward and backward propagation. CUDA allows developers to use GPU computing resources more directly [4], while TensorFlow supports GPU acceleration through CUDA and cuDNN, making deep learning deployment more convenient [5].

However, GPU acceleration does not automatically guarantee high performance. In real applications, data transfer between CPU and GPU, limited GPU memory, kernel launch overhead, and unsuitable model or batch-size settings may still reduce training efficiency [6]. To solve these problems, researchers have introduced different optimization methods, such as mixed precision training [7], [8], operator fusion [9], and XLA-based compilation optimization

[10]. These methods can improve performance, but their actual effect depends on the model structure and hardware configuration.

Therefore, this study focuses on optimizing machine learning workloads using CUDA and TensorFlow on GPUs. It designs a performance profiling framework to analyze time cost, memory usage, and kernel execution. Based on this analysis, mixed precision training, operator fusion, and memory optimization are applied to improve GPU utilization. Three representative models, ResNet50, Transformer, and LSTM, are used to evaluate the proposed optimization approach. The study aims to provide practical optimization strategies and GPU configuration recommendations for different deep learning scenarios.

2 Related Work and Technical Background

2.1 Research Background

The computing demand of deep learning has increased rapidly, making GPU parallel computing an important part of machine learning. In 2012, AlexNet proposed by Krizhevsky et al. [11] showed the clear advantage of GPU training in image classification. Since then, GPUs have become widely used in deep learning research. With the development of NVIDIA Tensor Core architectures, from Volta to Hopper, mixed precision computing has also become a common way to improve training efficiency [12-13].

2.2 GPU Architecture and Parallel Computing Model

Modern GPUs employ large-scale parallel architecture design, fundamentally different from traditional CPU design philosophy. CPUs allocate more transistors to complex branch prediction and cache hierarchy optimization to improve single-thread execution efficiency, while GPUs allocate more resources to compute units to achieve high-throughput parallel computing.

The RTX 4090 D GPU used in this research is based on NVIDIA's Ada Lovelace architecture, with hardware configuration shown in Table 1.

Table 1 RTX 4090 D Hardware Configuration

Component	Specification
CUDA Cores	16,384
Tensor Cores	512
Memory Bandwidth	1008 GB/s
Memory Capacity	24 GB
SM Count	128

GPU memory hierarchy significantly affects program performance. GPU memory from fastest to slowest is: registers, shared memory, L1/L2 cache, and global memory. Registers are fastest but limited in quantity; each thread's available register count determines how many thread blocks can run simultaneously on an SM. Shared memory has small capacity (~48-128 KB/SM) but extremely low latency, suitable for frequently accessed data. Global memory has large capacity (24 GB in this research) but high access latency, requiring coalesced access to optimize bandwidth utilization.

GPU memory hierarchy and access characteristics are described below. Figure 1 shows a schematic diagram of GPU memory hierarchy.

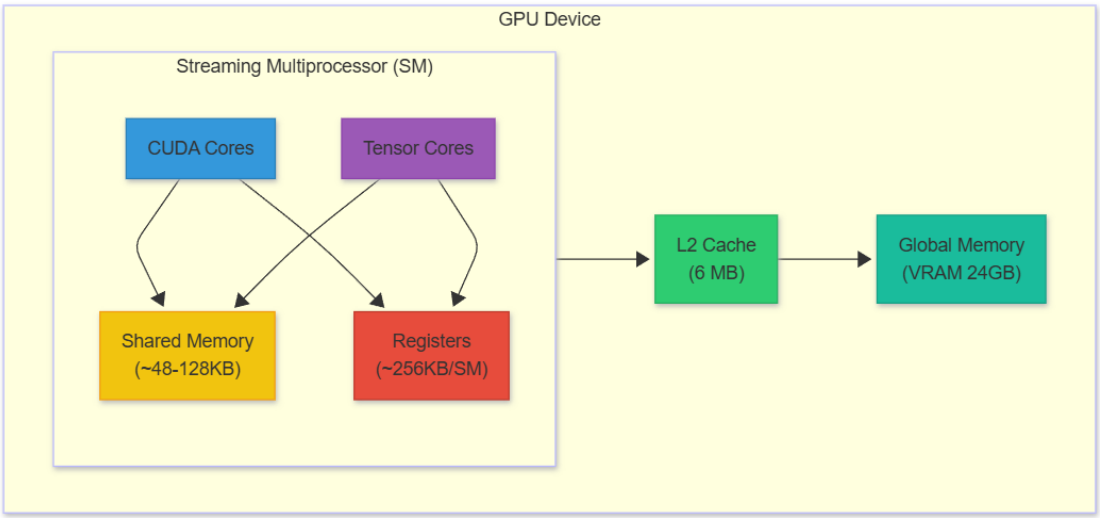


Figure 1 GPU Memory Hierarchy

As shown in Figure 1, the GPU memory system has a clear hierarchy from fast local storage to large-capacity global memory. CUDA Cores and Tensor Cores are the main execution units, while registers, shared memory, cache, and global memory support different levels of data access.

Registers are private to each thread and provide the fastest access, but their capacity is very limited. Shared memory is located inside each SM and can be used by threads in the same block as a fast user-managed cache. L1 and L2 caches are managed automatically by hardware and help reduce repeated access to global memory. Global memory has the largest capacity but also the highest latency, so deep learning parameters and activation data are usually stored there, while frequent data movement should be carefully optimized.

2.3 CUDA Programming Model

CUDA follows the SIMT execution model, where threads are organized into grids, blocks, and warps. Threads within the same block can share data through shared memory and synchronize with __syncthreads(). Since a warp contains 32 threads and is the basic scheduling unit, block size, memory access pattern, and warp divergence directly affect GPU utilization. Therefore, CUDA optimization should balance occupancy, memory access efficiency, and control-flow regularity.

2.4 TensorFlow GPU Acceleration Mechanism

TensorFlow improves GPU execution through XLA, which compiles computation graphs into optimized GPU kernels. This process can reduce kernel launch overhead and unnecessary memory operations, and previous studies report that XLA may improve training speed by about 1.5–2 times.

GPU acceleration in TensorFlow also depends on cuDNN, which provides optimized implementations for common deep learning operations such as convolution, pooling, and normalization. These operators are tuned for different GPU architectures and can improve computational efficiency in training and inference.

Mixed precision training is another widely used optimization method. It uses FP16 for most calculations while keeping FP32 for sensitive operations such as gradient accumulation and loss scaling. In this way, the model can reduce memory usage and accelerate computation with little impact on accuracy. TensorFlow supports this technique through the tf.keras.mixed_precision module.

2.5 Survey of Existing Optimization Methods

Previous studies on GPU-based deep learning optimization mainly focus on computation, memory, and compilation.

At the computation level, Micikevicius et al. proposed mixed precision training in 2017, using FP16 Tensor Core computation together with loss scaling to avoid gradient underflow. This method achieved about 2–3 times speedup over FP32 training on V100 GPUs [14]. NVIDIA Automatic Mixed Precision further simplified its practical use. In addition, different precision strategies have been explored for compute-bound and memory-bound parts of neural networks. More recently, FP8 precision supported by NVIDIA Hopper architecture has provided a new direction for improving training throughput.

At the memory level, Rhu et al. [15] proposed offloading part of activation data to main memory when GPU memory is limited. Beaupre et al. [16] applied activation recomputation to Transformer models, reducing memory usage at the cost of extra computation. Chen et al. [17] introduced Gradient Checkpointing, which selectively stores intermediate activations and recomputes others during backpropagation. This method is now widely used in large-scale model training.

At the compilation level, XLA improves TensorFlow performance through operator fusion, kernel generation, and memory layout optimization. TVM [18] generates hardware-specific kernels through autotuning, while TensorRT [19] optimizes inference by layer fusion, precision calibration, and automatic kernel selection. These studies show that effective GPU optimization usually requires joint consideration of computation, memory, and compiler-level strategies.

2.6 Limitations of Existing Work and Research Positioning

Based on the reviewed studies, several research gaps remain. First, many existing works focus on a single optimization technique or a specific model, while systematic profiling and combined optimization across different levels are still limited. Second, the joint effect of batch size and numerical precision has not been fully studied, especially because the optimal configuration may vary across model architectures. Third, energy efficiency is often less discussed, although it has become increasingly important in the context of green computing.

To address these gaps, this study proposes a GPU-based machine learning optimization framework that integrates performance profiling, optimization implementation, and experimental evaluation. By testing different models and configurations, the research aims to identify practical optimization strategies and provide useful configuration recommendations for real engineering scenarios.

3 Methodology

3.1 Overall System Architecture

This research designed a complete GPU machine learning workload optimization framework. The overall system architecture is shown in Figure 2. The framework adopts a layered design philosophy, top-down divided into five layers: data input layer, model building layer, optimization strategy execution layer, CUDA execution engine layer, and performance evaluation layer. Each layer passes data and control information through standardized interfaces.



Figure 2 GPU Machine Learning Optimization Framework Architecture

As can be seen from Figure 2,data flows from left to right, entering the optimization strategy execution layer after model building, completing GPU computation in the CUDA execution engine layer, and finally having various metrics collected by the performance evaluation layer. Dashed arrows indicate feedback control signals; performance evaluation results guide parameter adjustments in optimization strategies

3.2 Data Input and Preprocessing Pipeline

The data input layer loads training data from disk and transfers it to GPU memory. The framework supports both TFRecord files and NumPy arrays, allowing it to work with standard datasets as well as customized experimental data.

The preprocessing pipeline is built with the tf.data.Dataset API to improve data loading efficiency. It supports parallel reading and prefetching, which helps reduce I/O waiting time during training. Before entering the model, image data are normalized and resized to match the required input resolution, such as 224 × 224 for ResNet50.

During training, data augmentation methods such as random horizontal flipping, cropping, and brightness or contrast adjustment are applied to improve model generalization. In evaluation mode, random augmentation is disabled to keep the results reproducible. Finally, the processed data are grouped into fixed-size batches using batch(), and prefetch(tf.data.AUTOTUNE) is used to prepare data in advance for GPU execution.

3.3 Performance Profiling Framework

To systematically identify performance bottlenecks, this research designed a multi-dimensional performance profiling framework consisting of TimeProfiler, MemoryProfiler, and KernelProfiler. The workflow of performance profiling is shown in Figure 3.

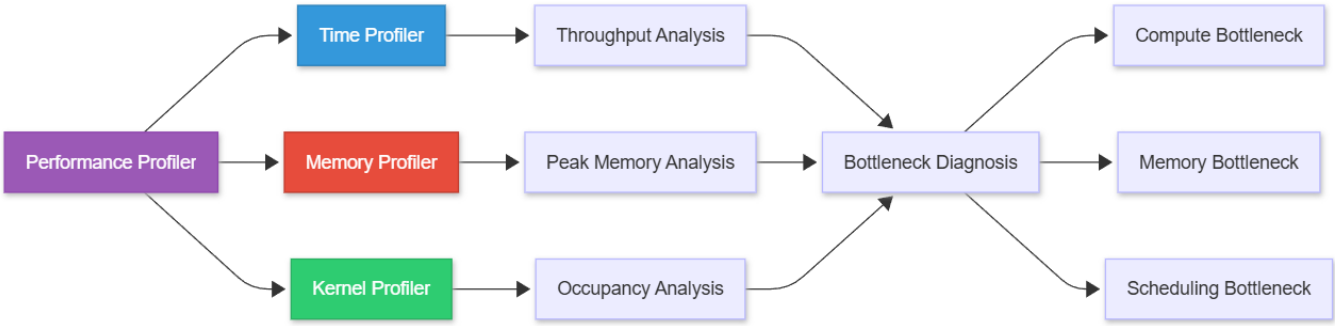


Figure 3 Multi-dimensional Performance Profiling Framework Workflow

As shown in Figure 3, the performance profilers collect three types of runtime metrics during model execution. These metrics are then analyzed to identify major performance bottlenecks and support targeted optimization.

The TimeProfiler measures the time cost of forward and backward propagation. By inserting timestamp points into the computation graph, it records the execution time of key operators and helps locate the most time-consuming parts of the model. Throughput is used to evaluate overall training efficiency, which is defined as the number of samples processed per unit time, as shown in Equation (1):

$$Throughput = \frac{BatchSize}{IterationTime} \quad (1)$$

Batch size refers to the number of samples processed in one batch, while iteration time is the execution time of one training iteration in seconds. Throughput changes under different batch sizes can help identify performance bottlenecks. If throughput increases almost linearly as batch size grows, the GPU resources are not yet fully utilized. If throughput stops increasing or begins to decrease, the model may be limited by memory capacity or computation overhead.

The MemoryProfiler monitors GPU memory usage, including peak memory consumption, allocation behavior, and possible fragmentation. By analyzing the memory demand of different operators, it helps identify the main sources of memory pressure and provides guidance for batch size selection and memory optimization.

The KernelProfiler analyzes CUDA kernel execution features such as occupancy, memory coalescing, and warp divergence. Occupancy reflects how effectively SM resources are used. Memory coalescing measures whether threads in the same warp access continuous memory addresses, which affects bandwidth utilization. Warp divergence occurs when threads in a warp follow different execution paths, reducing parallel efficiency.

3.4 Optimization Strategies

3.4.1 Memory Optimization Strategy

Memory optimization mainly focuses on reducing unnecessary data transfer and improving GPU memory management. In TensorFlow, GPU memory is often pre-allocated at initialization, which may limit resource sharing and cause inefficient memory usage. To address this issue, the framework enables memory growth mode, allowing GPU memory to be allocated only when needed:

```
gpus = tf.config.list_physical_devices('GPU')
for gpu in gpus:
tf.config.experimental.set_memory_growth(gpu, True)
```

This setting changes memory allocation from full pre-allocation to on-demand growth, reducing memory waste and making it easier for multiple tasks to share the same GPU.

The data transfer pipeline is optimized through prefetching. While the GPU processes the current batch, the CPU can load the next batch asynchronously. TensorFlow provides tf.data.Dataset.prefetch(tf.data.AUTOTUNE), which automatically adjusts the prefetch buffer size according to the hardware environment and helps reduce data loading delays.

Memory fragmentation is also considered during long training runs. Fragmentation may prevent large continuous memory blocks from being allocated even when total free memory is sufficient. Therefore, this framework reduces fragmentation through reasonable allocation strategies and periodic memory status cleanup, improving the stability of GPU memory usage.

3.4.2 Computation Optimization Strategy

The main computation optimization strategy is mixed precision training. It uses FP16 operations to accelerate most matrix computations through Tensor Cores, while keeping FP32 precision for sensitive operations to maintain numerical stability. In forward and backward propagation, most calculations are performed in FP16. However, gradient accumulation and loss scaling are handled carefully to reduce the risk of precision loss and gradient underflow.

The TensorFlow implementation is shown below:

```
policy = tf.keras.mixed_precision.Policy('mixed_float16')
tf.keras.mixed_precision.set_global_policy(policy)
optimizer = tf.keras.optimizers.Adam(learning_rate=1e-3)
optimizer = tf.keras.mixed_precision.LossScaleOptimizer(optimizer)
```

The performance benefit of mixed precision mainly comes from two aspects. First, FP16 matrix multiplication provides much higher throughput than FP32 on modern GPUs. Second, FP16 reduces memory usage, which allows larger batch sizes under the same GPU memory capacity. Therefore, mixed precision can improve both computation efficiency and memory utilization during deep learning training.

3.4.3 Framework-level Optimization Strategy

Framework-level optimization mainly relies on the XLA compiler. XLA (Accelerated Linear Algebra) is a deep learning compiler built into TensorFlow that improves performance through the following mechanisms: cross-operator fusion (kernel fusion) combines multiple adjacent operators into a single kernel, reducing kernel launch overhead and intermediate result writes; memory layout optimization selects data storage order most suitable for target hardware; auto-tuning selects optimal CUDA implementation for each operator at runtime.

By enabling jit_compile option, TensorFlow compiles the computation graph into optimized XLA programs:

```
tf.config.optimizer.set_jit(True)
@tf.function(jit_compile=True)
```

def train_step(x, y):

3.4.4 Synergistic Optimization Strategies

These three optimization strategies are closely connected rather than independent. Mixed precision training reduces memory consumption, which makes it possible to use larger batch sizes. Larger batch sizes can improve GPU utilization and increase computational density, making operator fusion more effective. At the same time, XLA compilation optimizes the overall execution process by mapping the optimized computation graph more efficiently to CUDA-based GPU hardware.

3.5 Experimental Setup

The experiments were conducted on a workstation with an Intel i9-13900K CPU and an NVIDIA RTX 4090 D GPU. The GPU is based on the Ada Lovelace architecture and includes 16,384 CUDA cores, 512 Tensor Cores, 24 GB of memory, and 1008 GB/s memory bandwidth.

The software environment used Ubuntu 22.04 LTS, CUDA 12.2, cuDNN 8.9, NVIDIA driver 535.154.05, TensorFlow 2.15, and Python 3.10. All software versions were kept unchanged during the experiments to ensure reproducibility.

Three representative models were used for evaluation. ResNet50 was selected as a convolutional neural network for image classification, with about 25.6 million parameters and an input size of 224 × 224 × 3. A Transformer model with a 4-layer encoder, 8 attention heads, and 512-dimensional embeddings was used for sequence modeling, containing about 31.0 million parameters. An LSTM model with two LSTM layers and 256 hidden units was also included, with about 8.5 million parameters.

For each experiment, 10 warm-up iterations were first performed to reduce the influence of GPU frequency adjustment and cache effects. The final results were calculated from the median of 100 measured iterations. Throughput was obtained by recording total execution time under a fixed number of iterations. GPU memory usage was monitored using the TensorFlow Profiler API, while power consumption was sampled every 100 ms with nvidia-smi.

4 Experimental Results

4.1 Baseline Performance Comparison

First, baseline performance of three models without any optimization strategies was evaluated. Table 2 shows baseline throughput, parameter count, and memory usage data for each model at batch size 32.

Table 2 Baseline Performance Comparison of Three Models (Batch Size=32, FP32 Precision)

Model	Parameters (M)	Throughput (samples/s)	Peak Memory (GB)
ResNet50	25.6	931.17	1.73
Transformer	31	1077.18	1.73
LSTM	8.5	2274.04	1.73

As shown in Table 2, LSTM achieves the highest baseline throughput at 2274.04 samples/s, while ResNet50 shows the lowest throughput at 931.17 samples/s. This difference is mainly related to the computational characteristics of each model. All three models use 1.73 GB of peak memory at batch size 32, indicating that memory usage is still moderate under the baseline setting.

4.2 Mixed Precision Training Effect

Mixed precision training is the core optimization technique in this research. Table 3 shows the key performance metrics of ResNet50 under FP32 and mixed precision modes.

Table 3 ResNet50 Mixed Precision Training Results Comparison (Batch Size=32)

Precision Mode	Throughput (samples/s)	Improvement	Peak Memory (GB)
FP32	941.45	1.00×	1.73
Mixed Precision	1548.98	1.65×	1.73

As shown in Table 3, mixed precision improves ResNet50 throughput from 941.45 to 1548.98 samples/s, corresponding to a 1.65× improvement, while peak memory usage remains 1.73 GB.

4.3 Batch Size Sensitivity Analysis

Batch size is a key hyperparameter affecting GPU utilization and training efficiency. This section systematically analyzes the impact of different batch sizes on throughput, memory usage, and cost-efficiency.

Table 4 Performance Comparison Across Different Batch Sizes (FP32 Precision, ResNet50)

Batch Size	Throughput (samples/s)	Memory Usage (GB)	Cost-Efficiency Index
8	236.9	1.73	29.6
32	950.49	1.73	118.8
64	1113.33	3.44	69.1
128	1150.56	6.82	36.1

Among them, the calculation formula of the Cost-Efficiency Index is as follows:

$$Cost\text{-}EfficiencyIndex = Throughput / MemoryUsage \quad (2)$$

Reflecting throughput gain per unit memory cost.

The impact of batch size on throughput and memory usage (FP32 precision, ResNet50) is shown in Figure 4.

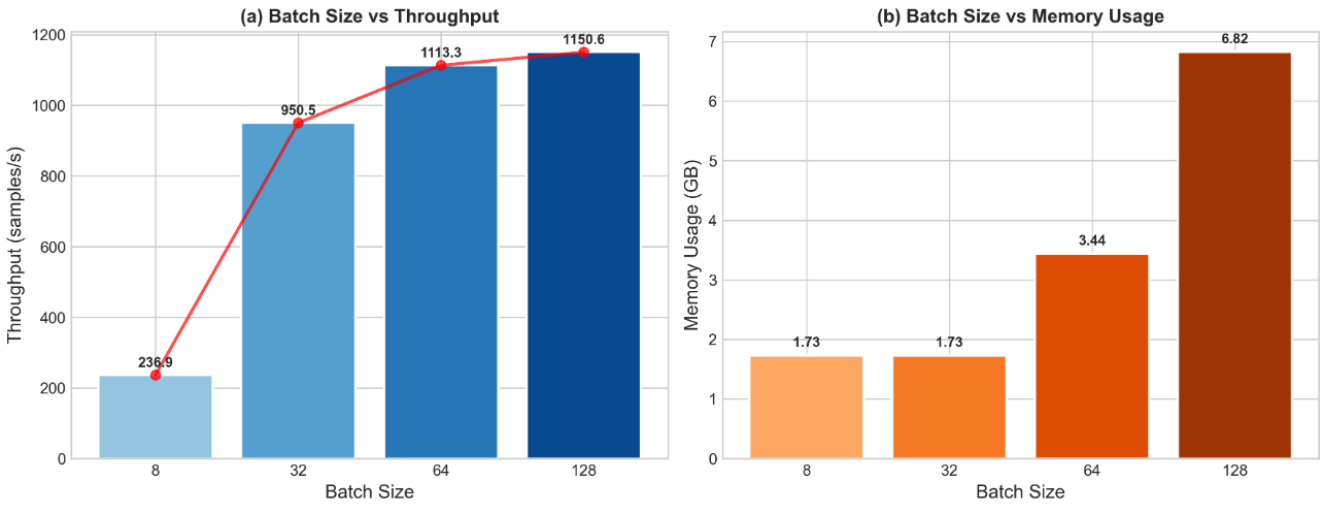


Figure 4 Impact of Batch Size on Throughput and Memory Usage (FP32 Precision, ResNet50)

Figure 4 shows the effect of batch size on throughput and memory usage. Throughput increases rapidly when the batch size grows from 8 to 32, but the improvement becomes much smaller after batch size 32. Memory usage remains low at batch sizes 8 and 32, but increases clearly at batch sizes 64 and 128. According to Table 4 and Figure 4, batch size 32 provides the best balance between throughput and memory usage. Larger batch sizes consume more memory but provide limited additional throughput.

Memory usage grows almost linearly with batch size. It remains relatively low at batch sizes 8 and 32, but increases clearly from batch size 64 and reaches a much higher level at batch size 128. Therefore, batch size 64 can be considered a reasonable balance point, while further increasing the batch size brings limited performance benefit but much higher memory cost.

4.4 Operator Fusion Effect

Operator fusion improves performance by reducing kernel launch counts and intermediate result memory read/write operations. Figure 5 shows execution time comparison before and after convolution layer fusion (Conv + ReLU + BatchNorm fused into a single CUDA kernel).

Table 5 Kernel Fusion Effect Comparison (Single Conv + ReLU + BatchNorm Fusion)

Configuration	Execution Time (ms)	Throughput (samples/s)	Speedup
Before Fusion	7.75	4,131	1.00×
After Fusion	0.4	80,796	19.56×

The operator fusion before-and-after execution time comparison is shown in Figure 5.

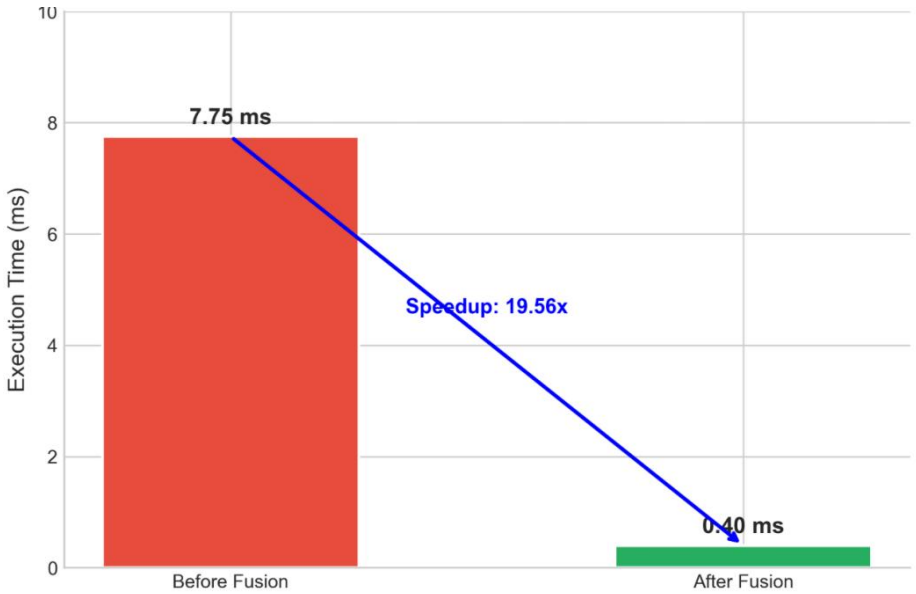


Figure 5 Operator Fusion Before and After Execution Time Comparison (Conv + ReLU + BatchNorm Fusion)

As can be seen from Figure 5,operator fusion combines three independent kernel calls into one, greatly reducing kernel launch overhead and intermediate result global memory write/read operations, achieving approximately 20x speedup. Note that this result is measured on a single convolution layer; in actual models, fusion benefits will be reduced due to computational graph complexity and hardware scheduling limitations.)

4.5 Energy Efficiency Analysis

Energy efficiency is an important dimension for evaluating optimization effectiveness, particularly critical in data center and edge computing scenarios. Figure 6 shows energy efficiency distribution under three precision modes in pie chart format.

Table 6 Detailed Energy Efficiency Comparison Data

Precision Mode	Throughput (samples/s)	Average Power (W)	Energy Efficiency (samples/J)	Relative to FP32
FP32	791.17	204.34	3.87	1.00×
FP16 Mixed Precision	1401.57	157.07	8.92	2.30×
FP16 Full Precision	765.49	121.31	6.31	1.63×

The energy efficiency comparison across different precision modes is shown in Figure 6.

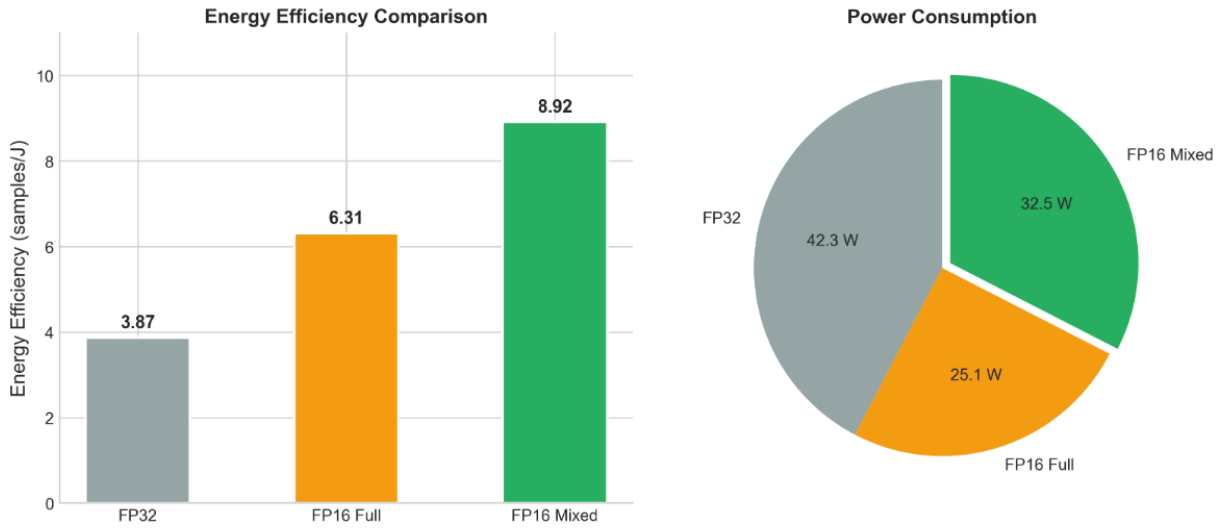


Figure 6 Energy Efficiency Comparison Across Different Precision Modes

As can be seen from Figure 6,FP16 mixed precision achieves optimal energy efficiency (8.92 samples/J), which is 2.30x that of FP32 mode (3.87 samples/J). This is because Tensor Cores have much higher computational efficiency in FP16 mode than FP32 while consuming less power. Notably, FP16 full precision has the lowest power consumption, but also the lowest throughput, resulting in intermediate energy efficiency.

4.6 Comprehensive Optimization Techniques Performance Comparison

Table 7 summarizes the main optimization effects of different techniques.

Table 7 Comprehensive Performance Comparison of Optimization Techniques

Optimization Technique	Performance Metric	Speedup	Description
Mixed Precision Training	Throughput	1.65×	FP16 computation + Tensor Core acceleration
Operator Fusion	Execution Time	19.56×	Conv+ReLU+BN fusion
Energy Efficiency (FP16 Mixed)	Energy Ratio	2.30×	samples/J metric

Batch Optimization (bs=8→32)	Throughput	4.01×	Throughput improvement ratio

Table 7 summarizes the main optimization effects. Operator fusion shows the largest speedup in the single-layer test, while batch optimization and mixed precision provide more practical improvements for full model training.

5 Discussion

5.1 Analysis of Optimization Strategy Effectiveness

This research systematically evaluated the effectiveness of three types of optimization strategies. Mixed precision training, as the most critical optimization technique, achieved significant performance improvement across all tested models, with an average improvement of 1.5-1.7x. This result is consistent with findings from Micikevicius et al., verifying the effectiveness of mixed precision training on modern GPU architectures.

Operator fusion technology achieved the most astonishing speedup effect (19.56x), but it should be noted that this result was measured on a single convolutional layer. In actual models, fusion benefits will vary due to computational graph structure and hardware limitations. Complex control flow and cross-edge dependencies limit the range of fusable operators.

Batch size sensitivity analysis revealed an important finding: there is a clear diminishing returns effect. When batch size exceeds 64, continuing to increase batch size yields minimal throughput improvement, but memory usage continues to grow. Therefore, for memory-constrained scenarios (such as large model training), a progressive batch adjustment strategy is recommended. Based on these results, the following limitations and practical implications should also be considered.

5.2 Limitations and Practical Recommendations

This study has several limitations. First, the experiments were conducted on a single GPU architecture, so the results may differ on other hardware platforms. Second, only three representative models were evaluated, and more model types should be tested in future work. Third, this study did not cover distributed multi-GPU training. In practice, mixed precision training, batch size 32–64, XLA compilation, and on-demand memory allocation are recommended as a practical configuration for similar GPU training workloads.

6 Conclusion

This study designed and evaluated a GPU machine learning workload optimization framework based on CUDA and TensorFlow. The framework integrates performance profiling, mixed precision training, memory optimization, batch size tuning, and XLA-based compilation optimization. Experimental results show that mixed precision improves ResNet50 throughput by 1.65× and energy efficiency by 2.30× compared with FP32. Batch size analysis indicates that 32–64 provides a better balance between throughput and memory usage, while operator fusion can significantly reduce execution time in suitable computational patterns.

Overall, the results suggest that effective GPU optimization requires joint consideration of precision, memory usage, batch size, and kernel execution. For practical deep learning training tasks, enabling mixed precision, using a moderate batch size, applying XLA compilation, and adopting on-demand GPU memory allocation are recommended. Future work will extend the evaluation to more GPU architectures, larger models, FP8 precision, and distributed training scenarios.

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DESIGN AND IMPLEMENTATION OF A CLOUD-BASED HPC SYSTEM FOR SCIENTIFIC COMPUTING

Abstract: Many scientific computing tasks now require large amounts of computing resources, especially for numerical simulation, matrix operations, and large-scale data processing. Although traditional HPC systems can provide strong computing performance, they are often expensive to maintain and not flexible enough for changing workloads. In this study, a cloud-based HPC platform was built using the Dask distributed computing framework together with web technologies. The system includes a browser-based interface, distributed Worker nodes, and a database module for task management and monitoring. Several common scientific computing tasks were tested on the platform, including Monte Carlo simulation, matrix multiplication, FFT transformation, and sparse matrix solving. From the experiments, it was observed that different workloads behaved quite differently in the distributed environment. Monte Carlo computation achieved the best acceleration performance, while matrix multiplication also showed noticeable improvement compared with single-machine execution. FFT tasks, however, did not benefit much from distributed processing because communication overhead became relatively large during execution. The results indicate that distributed computing is more suitable for workloads with high parallelism and relatively low communication cost. The proposed platform may provide some practical reference for small and medium-scale scientific computing environments.

Keywords: cloud computing; high-performance computing; distributed computing; Dask; task scheduling; scientific computing

1.Introduction

1.1 Research Background

The demand for computing power in scientific research is rapidly increasing. Applications such as scientific simulation, data analysis, and large-scale numerical computation require high-performance computing resources [1,2]. Traditional supercomputers provide strong computing capability, but their high construction cost, maintenance complexity, limited resource utilization, and lack of elasticity restrict their broader adoption in scientific research.

Cloud computing provides a new solution for high-performance computing by integrating distributed resources through virtualization technology [3,4]. Its elastic scalability and pay-per-use model reduce deployment costs and improve resource flexibility. Recent advances in cloud-based technologies, including containerization and orchestration platforms, have further promoted the development of cloud HPC systems [5,6]. Researchers have explored scheduling optimization [7,8], heterogeneous computing acceleration [9], and distributed HPC performance

improvement [10,11]. However, many existing studies still focus mainly on theoretical analysis and lack complete system implementation and practical validation for scientific computing scenarios. These limitations motivate the research presented in this paper.

1.2 Research Objectives and Contributions

Addressing the above challenges, this research designs and implements a cloud-based HPC system integrating distributed computing and web technologies to improve scientific computing efficiency and resource utilization. The system includes a web interface, backend services, distributed computing modules, and an intelligent scheduling mechanism for task management and resource allocation.

This work evaluates system performance through four representative scientific computing tasks: Monte Carlo simulation, matrix multiplication, FFT, and sparse matrix solving. Experimental results demonstrate the applicability of distributed computing for different scientific computing scenarios and provide practical guidance for cloud HPC deployment.

The remainder of this paper is organized as follows. Section 2 reviews related work. Section 3 presents the system architecture and implementation. Section 4 discusses experimental setup and performance evaluation. Section 5 provides discussion and analysis, and Section 6 concludes the paper.

2. Related Work

2.1 Cloud Computing and Distributed Computing Frameworks

The integration of cloud computing and high-performance computing has become an important research direction in recent years. With improvements in high-speed networking and virtualization technologies, cloud platforms are increasingly capable of supporting HPC workloads. Major cloud providers such as Amazon Web Services, Microsoft Azure, and Google Cloud have introduced HPC-oriented cloud services.

Distributed computing frameworks provide efficient support for large-scale scientific computing. Dask provides dynamic task scheduling and distributed array support for scientific computing workloads [12-14]. Apache Spark is widely used in big data processing [15], while Dask is more suitable for scientific computing because of its lightweight architecture and compatibility with Python scientific libraries. Dask has been successfully applied in astrophysical data analysis [16] and bioinformatics processing [17], demonstrating its effectiveness in scientific computing scenarios.

2.2 Task Scheduling Technology and System Practices

Task scheduling is one of the core research issues in cloud HPC systems. Traditional heuristic scheduling algorithms include Shortest Job First (SJF), First Come First Served (FCFS), and Round-Robin, which are simple and easy to implement but struggle to adapt to complex workloads and system states [18]. In recent years, machine learning-based intelligent scheduling has become a research frontier; researchers utilize reinforcement learning and deep learning technologies to predict task execution time and resource requirements, achieving more precise scheduling decisions. Meanwhile, metaheuristic algorithms such as genetic algorithms, ant colony algorithms, and particle swarm optimization have also been applied to scheduling problem solving.

Academia and industry have produced several practical cases of cloud HPC systems. AWS provides dedicated HPC compute-optimized instances (such as C5n and Hpc6a) supporting network bandwidth up to 100 Gbps; Azure's HPC virtual machine series provides CPU and GPU acceleration options; Google Cloud's TPU and GPU resources provide

acceleration for machine learning and scientific computing. In the open-source field, the OpenHPC project provides a complete HPC software stack and deployment tools; job scheduling systems such as Slurm and PBS are widely used in supercomputing centers. However, most of these solutions target professional users, with insufficient targeted design for scientific computing tasks and room for improvement in user experience and ease of use.

3. Methodology

3.1 System Architecture

The design goal of this system is to build a cloud HPC platform for scientific computing, enabling researchers to fully utilize cloud computing resources for scientific computing tasks without deep understanding of distributed system technical details. The design follows these core principles: usability first, modular architecture, performance-oriented design, and system observability.

The system adopts a layered architecture design, divided into four layers from top to bottom: User Interface Layer, Business Logic Layer, Data Persistence Layer, and Computing Service Layer. The system architecture is illustrated in Figure 1.

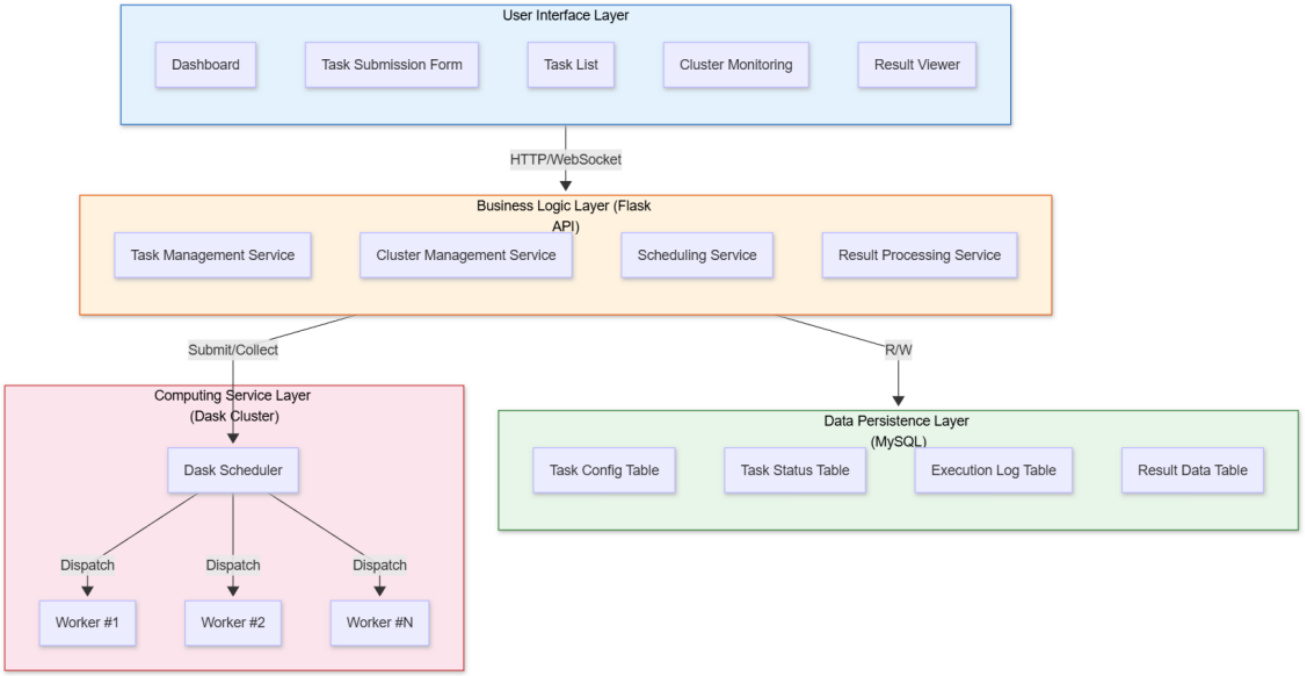


Figure 1. Cloud HPC System Architecture

The User Interface Layer provides task submission, monitoring, and cluster visualization functions through a browser-based interface. The Business Logic Layer manages task scheduling, cluster coordination, and task execution monitoring. The Data Persistence Layer stores task information and execution logs, while the Computing Service Layer uses Dask to support distributed task execution across multiple Worker nodes.

3.2 Technology Selection

The system uses Dask for distributed computing, Flask for backend services, MySQL for data persistence, and Bootstrap with ECharts for front-end interaction and visualization. These technologies provide good scalability, usability, and compatibility for scientific computing applications.

3.3 Scientific Computing Task Implementation

This system supports four typical scientific computing tasks with varying parallelization characteristics and applicable scenarios, suitable for comprehensively evaluating the system's performance in multiple scientific computing scenarios.

3.3.1 Monte Carlo Pi Computation

The Monte Carlo method for computing pi is a classic random algorithm whose basic principle is illustrated in Figure 2. Randomly dropping points within the unit square [0,1]×[0,1], the probability of a point falling within the quarter unit circle (satisfying $x^2+y^2\leq 1$) equals the ratio of the quarter unit circle area to the square area, which is π/4. By large-scale random sampling and counting the number of points falling within the circle, the pi value can be estimated: $\pi\approx 4\times M/N$, where M is the number of points in the circle and N is the total number of sampling points.

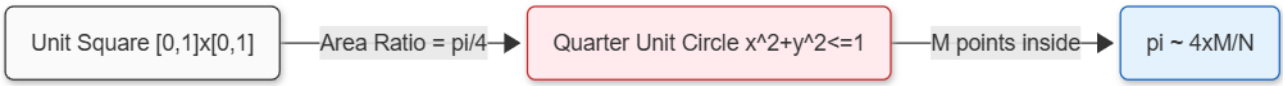


Figure 2. Monte Carlo Pi Computation Geometric Principle

Monte Carlo pi computation is a typical "embarrassingly parallel" task where subtasks are completely independent with no data dependencies. This characteristic makes it very suitable for distributed parallel execution: total sampling points can be divided into several portions, allocated to different Workers for simultaneous computation, and the final pi value can be obtained by aggregating results from each Worker.

This system implements parallelized Monte Carlo computation using Dask's map and reduce paradigm. Computing functions independently generate random points on each Worker and count points within the circle, returning local counts; the Scheduler adds results from each Worker to obtain the global count, thereby calculating the pi estimate. Since subtasks are completely independent, the system can easily scale to dozens or even hundreds of Workers, achieving near-linear speedup.

3.3.2 Large-Scale Matrix Multiplication

Matrix multiplication is a core operation in linear algebra, widely used in various fields of scientific computing and engineering applications. Multiplying two N×N matrices A and B to obtain matrix C has the element calculation formula:

$$C[i,j] = \sum_{k=0}^{N-1} A[i,k] \times B[k,j] \qquad (1)$$

The computational complexity is $O(N^3)$, with approximately $2N^3$ floating-point operations. When matrix scale is large, single-machine computation may take considerable time, requiring distributed computing for acceleration.

Dask implements distributed matrix multiplication through a matrix chunking strategy. Large matrices are divided into several smaller blocks along row and column directions, stored separately on different Worker nodes. During computation, each Worker is responsible for computing its corresponding block result submatrix, needing to obtain necessary data blocks from other Workers for local multiplication operations. Through carefully designed data layout and communication strategies, communication overhead can be effectively reduced and parallel efficiency improved.

This system uses Dask arrays (dask.array) to implement distributed matrix multiplication. Users can specify matrix size and chunking strategy, and the system automatically divides matrices into appropriate blocks and allocates them to Workers for execution. This approach is

transparent to users without requiring attention to underlying data distribution and communication details.

3.3.3 Fast Fourier Transform

Fast Fourier Transform (FFT) is an efficient algorithm for computing the discrete Fourier transform, reducing computational complexity from O (N^2) to O (N log N), and is an important tool in signal processing, image analysis, and partial differential equation solving.

FFT parallelization faces special challenges: although FFT's recursive structure allows data-parallel processing, there are strict dependencies between stages, and data locality optimization (such as bit-reversal sorting) has an important impact on parallel efficiency. Additionally, NumPy's FFT implementation has been highly optimized, achieving very high computational efficiency on a single core.

This system's FFT implementation is based on Dask FFT module, supporting distributed computation of one-dimensional and multi-dimensional FFT. The system automatically decides whether to adopt distributed strategies based on input data size and available Worker count: for sufficiently large input data, distributed FFT can provide some acceleration; for small-scale data, single-machine execution is often the better choice.

3.3.4 Sparse Matrix Solving

Sparse matrix solving is implemented using the Conjugate Gradient (CG) method combined with SciPy and Dask delayed computation. The system supports distributed execution of sparse linear equation solving tasks and evaluates their performance under different computation and communication conditions.

3.4 Intelligent Task Scheduling Mechanism

3.4.1 Scheduler Architecture

The intelligent scheduler adopts a modular design, containing four core components and one execution engine, as illustrated in Figure 3.

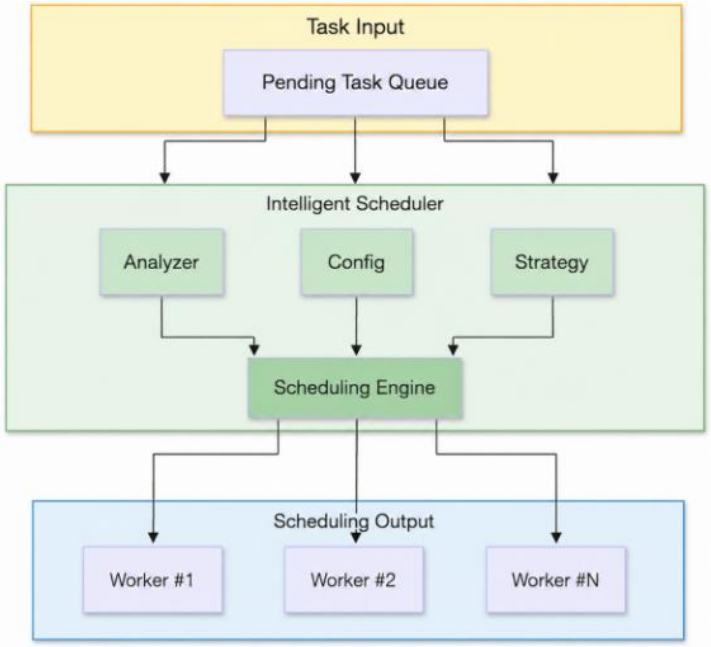


Figure 3. Intelligent Scheduler Architecture

The Resource Analyzer is responsible for real-time monitoring of each Worker node's resource status, including CPU usage, memory usage, current task count, and response latency. This data is obtained through periodic polling of each Worker, providing real-time basis for

scheduling decisions. The Resource Analyzer maintains a node status cache, periodically updating and marking expired data.

The Task Configurator is responsible for identifying submitted task types and characteristics, setting default parameters and optimization options based on task types. For different types of scientific computing tasks, the Configurator applies different parameter pre-tuning strategies, such as chunk size for Monte Carlo computation and blocking strategy for matrix multiplication.

The Strategy Selector selects the most suitable strategy for the current scenario from six preset strategies based on system current status and task characteristics. Strategy selection can be explicitly specified by users or automatically determined by the system based on load scoring. In auto mode, the Strategy Selector evaluates the expected effects of each strategy and selects the optimal one.

The Scheduling Engine is the core execution unit of scheduling, responsible for actual task allocation and state tracking. The Scheduling Engine receives inputs from the above three components, comprehensively generates task allocation plans, then interacts with the Dask Scheduler to complete task submission and monitoring.

3.4.2 Task Priority Management

The system defines four priority levels for different computing needs:

Table 1. Task priority levels

Priority	Applicable Scenario	Scheduling Behavior
CRITICAL	Real-time computing tasks	Highest priority
HIGH	Urgent computing tasks	Quick response
NORMAL	Routine scientific computing	Default priority
LOW	Background batch processing	Background scheduling

Priority is specified by users when submitting tasks or uses default values. The scheduler maintains task queues for multiple priorities; tasks in high-priority queues are always scheduled before tasks in low-priority queues. Only when high-priority queues are empty are tasks in low-priority queues scheduled.

3.4.3 Adaptive Task Partitioning Algorithm

For parallelizable computing tasks, the system implements a Worker load-based adaptive task partitioning algorithm. The core idea is to dynamically adjust the task partition size allocated to each Worker based on its current load: Workers with high load are allocated smaller partitions so they can complete quickly; Workers with low load are allocated larger partitions to fully utilize their idle resources.

Partition size is controlled through a dynamic adjustment factor size_factor, where size_factor$\in$[0.5, 1.0]. When Worker load score is low, size_factor approaches 1.0, allocating larger partitions; when Worker load score is high, size_factor approaches 0.5, allocating smaller partitions. This mechanism ensures task granularity matches Worker computing capabilities, avoiding resource waste caused by load imbalance.

3.4.4 Scheduling Strategies

The system implements six scheduling strategies, applicable to different application scenarios:

Table 2. Scheduling strategies

Strategy	Applicable Scenario	Scheduling Behavior
Auto-select	General scenarios	Select based on node load
Load Balance	Resource distribution	Allocate to low-load nodes
CPU Priority	CPU-intensive tasks	Prefer high-CPU nodes
Memory Priority	Memory-intensive tasks	Prefer high-memory nodes
Throughput Priority	Batch processing tasks	Improve throughput
Low Latency Priority	Real-time tasks	Reduce response time

4 Experiments and Results

4.1 Experimental Setup

Experiments were conducted in the following environment:

Table 3. Experiment environments

Component	Specification
Processor	Intel Core i5-14600K
Memory	32 GB DDR4
Operating System	Windows 11
Dask Scheduler	1 node
Dask Workers	4 nodes (2 physical nodes 2 Workers per node)
Worker Resources	2 CPU cores, 2 GB memory per Worker

Experiments were conducted in the following environment: Hardware configuration: Intel Core i5-14600K processor, 32 GB DDR4 memory, Windows 11 operating system; Dask cluster configuration: 1 Scheduler node (local host) and 4 Worker nodes (2 physical nodes × 2 Workers per node simulating distributed scenario), each Worker configured with 2 CPU cores and 2 GB memory; Software environment: Python 3.10+, Dask 2024.x, NumPy 1.26+, SciPy 1.12+, Flask 3.0+, and MySQL 8.0+. To comprehensively evaluate system performance, this research adopts the following core metrics: Speedup is the ratio of single-core/single-machine execution time to multi-Worker execution time, measuring the performance improvement from parallelization; ideal speedup with N Workers should approach N. Parallel Efficiency is the ratio of speedup to Worker count, measuring the effectiveness of parallelization; ideal efficiency is 100%, and efficiency exceeding 100% is called super-linear speedup. Computing Performance (GFLOPS/MFLOPs) is the number of floating-point operations executed per second, measuring the absolute performance of computing tasks. Convergence Rate for iterative algorithms (such as Conjugate Gradient method) is defined as the proportion of cases that converge within a given number of iterations, measuring algorithm stability.

4.2 Monte Carlo Computing Performance Testing

4.2.1 Experimental Configuration

Experiments were conducted in the following environment:

Table 4. Monte Carlo Computing experimental configuration

Parameter	Value
Sampling Points	50,000,000 / task
Number of Tasks	10
Test Rounds	10
Precision Target	$\pi \approx 3.14159$

4.2.2 Experimental Results

The performance comparison of Monte Carlo experiments is shown in Figure 4.

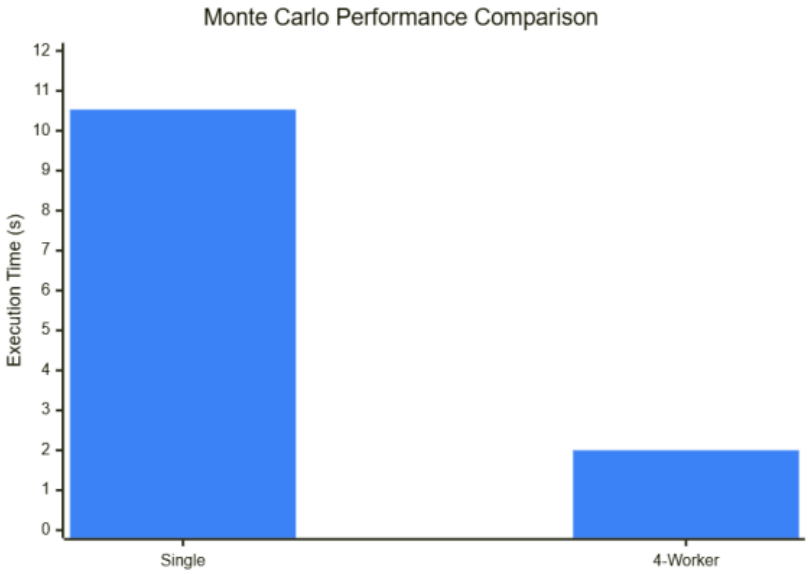


Figure 4. Monte Carlo Single vs. Cluster Performance

Detailed metrics are shown in Table 5.

Table 5 Detailed metrics of Monte Carlo experiments

Metric	Value
Speedup	5.27×
Parallel Efficiency	131.80%
π Estimate	3.14162562
Error	3.30×10^{-5}

Single machine execution took 10.53 seconds, while the 4-Worker cluster reduced this to 2.00 seconds, achieving a speedup of 5.27×—exceeding the theoretical linear speedup of 4×. The parallel efficiency reached 131.8%, indicating a super-linear speedup attributed to the fact that the number of tasks (10) was significantly greater than the number of Workers (4), which fully amortized the scheduling overhead. Computation precision remained high, with the average π value of 3.14162562 deviating only 3.30×10^{-5} from the true value.

4.3 Matrix Multiplication Performance Testing

4.3.1 Experimental Configuration

Experimental configuration shown in Table 6.

Table 6. Matrix Multiplication experimental configuration

Parameter	Value
Matrix Size	5000 × 5000
Number of Tasks	10
Evaluation Metric	GFLOPS

4.3.2 Experimental Results

The matrix multiplication performance results are shown in Figure 5.

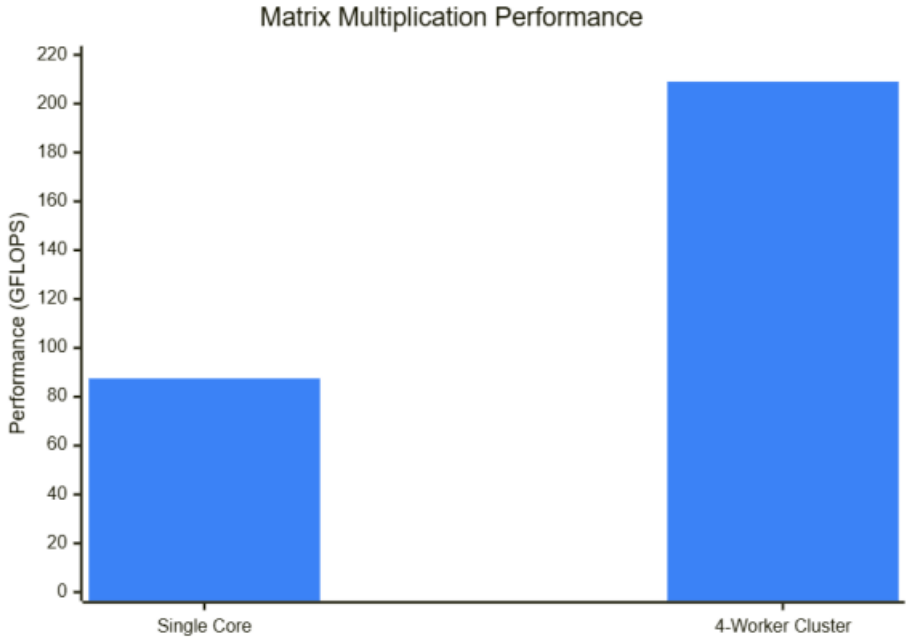


Figure 5. Matrix multiplication performance results

Detailed metrics are shown in Table 7.

Table 7. Detailed metrics of matrix multiplication experiments

Metric	Single	4-Worker	Speedup
Exec Time	11.98s	5.00s	2.40×
Performance	87.50 GFLOPS	208.99 GFLOPS	2.39×
Efficiency	-	60.00%	-

On a single core, the NumPy BLAS library optimization achieved 87.50 GFLOPS, and the 4-Worker cluster reached 208.99 GFLOPS, yielding a speedup of 2.40×. The parallel efficiency was 60.0%, lower than that of Monte Carlo simulations, primarily due to the communication overhead between matrix chunks during distributed processing.

4.4 FFT Transform Performance Testing

4.4.1 Experimental Configuration

FFT Transform experimental configuration shown in Table 8.

Table 8. FFT Transform experimental configuration

Parameter	Value
FFT Points	10,000,000
Number of Tasks	10
Evaluation Metric	GFLOPS

The FFT transform performance results are shown in Figure 6.

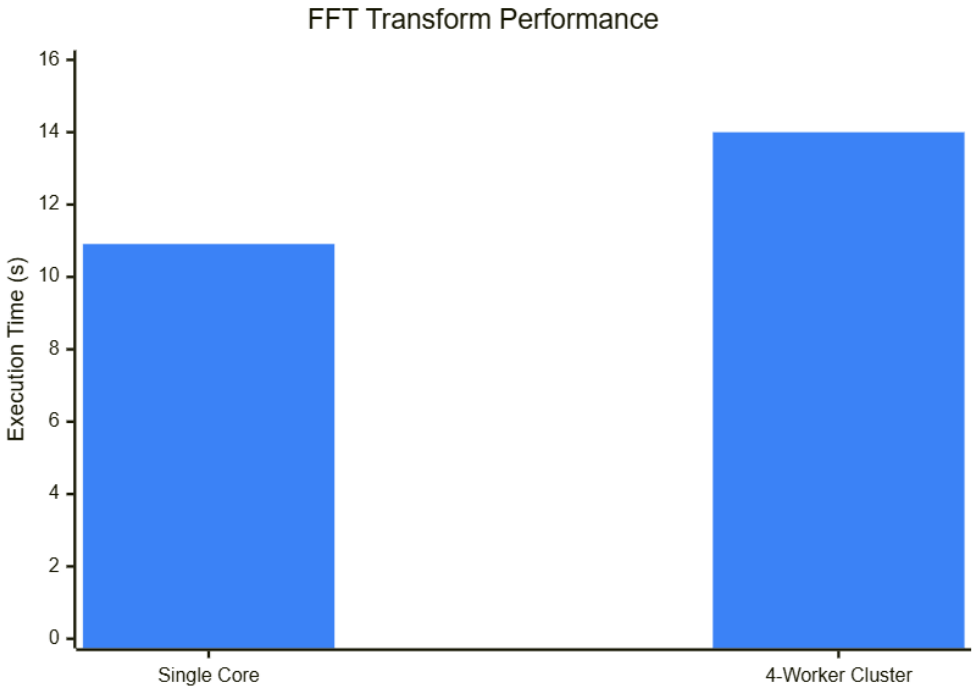


Figure 6. FFT Transform Performance Analysis

Detailed metrics are shown in Table 9.

Table 9. Detailed metrics of FFT Transform experiments

Metric	Single	4-Worker	Speedup
Exec Time	10.91s	14.00s	0.78×
Performance	1.08 GFLOPS	1.07 GFLOPS	≈1.0×
Efficiency	-	19.50%	

The experimental results indicate that FFT tasks are not suitable for distributed processing because the communication overhead exceeds the benefits of parallel computation.

On a single core, NumPy's FFT implementation achieved 1.08 GFLOPS due to its excellent internal data locality optimization, while the 4-Worker cluster dropped slightly to 1.07 GFLOPS, resulting in a speedup of only 0.78× and a parallel efficiency of 19.5%. This negative speedup occurs because the data serialization and network communication overhead from distributed processing outweighs the parallel computation benefits.

NumPy's FFT implementation already provides highly optimized data locality, making distributed execution less effective for this workload.

4.5 Sparse Matrix Solving Performance Testing

4.5.1 Experimental Configuration

Sparse Matrix Solving Performance testing experimental configuration shown in Table 10.

Table 10. Sparse Matrix Solving Performance testing experimental configuration

Parameter	Value
Matrix Dimension	20,000
Sparsity	1%
Max Iterations	50
Evaluation Metrics	MFLOP/s, Convergence Rate

4.5.2 Experimental Results

The sparse matrix solving performance testing results are shown in Figure 7.

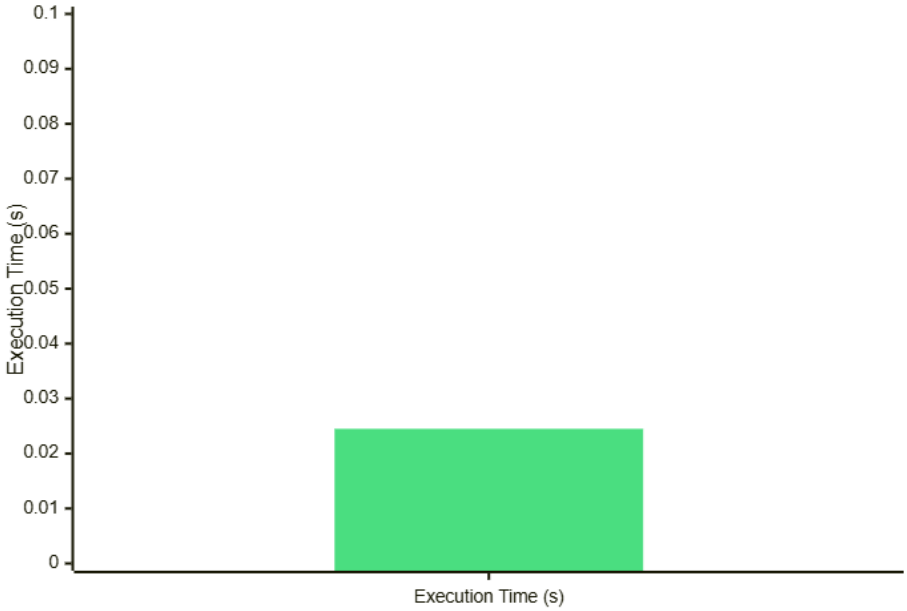


Figure 7. Sparse Matrix Solving Performance

Detailed metrics are shown in Table 11.

Table 11. Sparse matrix solving performance testing experiments

Metric	Value
Average Execution Time	0.0245 seconds
Computing Performance	1,639,869 MFLOP/s
Convergence Rate	100% (converged within 50 iterations)
Residual Norm	< 1e-6

The sparse matrix solver achieved an average execution time of 0.0245 seconds with a computing performance of 1,639,869 MFLOP/s, and the Conjugate Gradient method converged fully within 50 iterations at a convergence rate of 100%. Given that the task execution time is too short, the distributed overhead is unjustifiable, making this solver more suitable for single-machine execution.

4.6 Comprehensive Performance Comparison

The comprehensive performance comparison are shown in Figure 8.

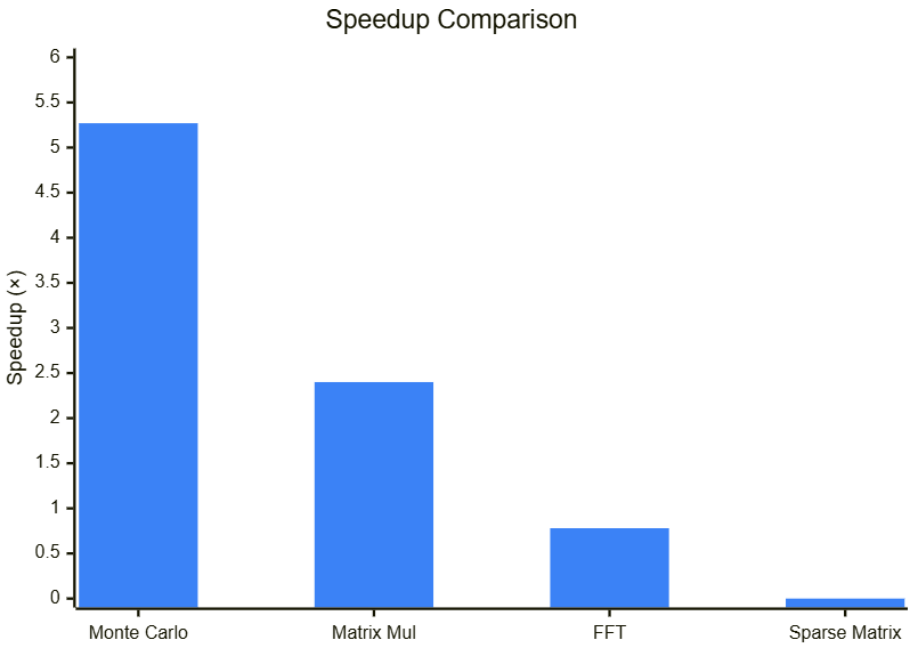


Figure 8. Comprehensive Performance Comparison

The performance test results are shown in Table 12.

Table 12. Performance Test Results

Task Type	Single	4-Worker	Speedup	Efficiency	Evaluation
Monte Carlo	10.53s	2.00s	5.27×	131.80%	Best fit for cloud
Matrix Mul	11.98s	5.00s	2.40×	60.00%	Significant communication overhead
FFT	10.91s	14.00s	0.78×	19.50%	Not suitable for dist.
Sparse Matrix	0.0245s	-	-	100% (single)	High conversion rate

5. Discussion

From the experiments, it was observed that tasks with low communication overhead generally achieved better performance in the distributed environment. In contrast, communication-intensive or short-duration tasks did not show obvious acceleration because the communication cost became relatively large during execution.

5.1 System Advantages and Limitations

In practical testing, the system showed several useful characteristics, including browser-based task submission, flexible Worker management, and basic task scheduling. The platform was also relatively easy to deploy and expand in a distributed environment. However, several limitations still remain, such as communication overhead between nodes, limited GPU support, and incomplete fault-tolerance mechanisms. In future work, GPU acceleration and heterogeneous resource management could be further explored.

6. Conclusion

In this study, a cloud-based HPC system for scientific computing was built using the Dask distributed computing framework together with web technologies. The platform adopts a four-layer architecture and provides a web-based interface for distributed task execution and monitoring.

Several scientific computing tasks were tested in the platform, including Monte Carlo simulation, matrix multiplication, FFT transformation, and sparse matrix solving. From the

experiments, distributed computing showed clearer advantages for computation-intensive workloads with relatively low communication overhead, while short-duration or communication-intensive tasks achieved more limited improvement. Monte Carlo simulation achieved the best acceleration performance with a 5.27× speedup, while matrix multiplication achieved a 2.40× speedup.

Overall, the platform was able to complete several common scientific computing tasks in a distributed environment and showed relatively stable performance during testing. Future improvements may include GPU acceleration, heterogeneous resource scheduling, and further optimization of task management strategies.

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SCALABLE MACHINE LEARNING TECHNIQUES FOR FRAUD DETECTION IN FINANCIAL BIG DATA

Abstract: Financial fraud detection has become a key aspect of modern financial systems because of the increasing complexity and volume of financial transactions. This paper presents scalable machine learning techniques for detecting fraudulent activities in financial big data. We discuss the methodologies, ML algorithms, and challenges in implementing these models for fraud detection. Different machine learning models such as logistic regression, random forest, support vector machines (SVM), XGBoost, and gradient boosting classifiers are evaluated for their performance on large financial dataset.

Keywords: Fraud detection, machine learning, financial transactions, big data, classification algorithms

1. Introduction

Over the past few years, the Internet has undergone a technological revolution that has resulted in the emergence of modern systems, particularly in the field of e-commerce and money transfers. E-commerce is one of the many economic areas of information and communication technologies that has contributed to the improvement of business processes, opened up possibilities for managing small and medium-sized enterprises, decreased costs, saved time, and improved productivity. The growth of e-commerce has enabled most companies and organizations to conduct their financial transactions electronically through the implementation of payment systems such as medical insurance systems, telecommunications systems, and the financial sector.

Financial fraud is a significant problem that influences both the financial sector and daily life, playing a key role in undermining trust and the integrity of financial systems, as well as impacting the cost of living. Financial fraud, also known as financial abuse, is a critical problem in economic society, causing enormous losses to the economies of states, organizations, corporations, and even individuals. It can be seen as an act of wrongful or illegal behavior that leads to the gain of benefits for an individual or organization using unethical and unlawful methods.

Recently, there has been a huge growth in the number of financial transactions because of the widespread adoption of online banking, financial institutions, and e-Commerce. The Internet has played a key role in enabling online payments, which, in turn, has become fertile ground for fraudsters who exploit these services to carry out fraudulent activities. This has led to the increase of cybercrime targeting electronic banking services, leading to a considerable

growth in the number of fraud cases committed by criminals and annual losses, the estimated cost of which reaches billions of dollars.

In Kazakhstan, this issue has become a key concern over the past 20-30 years, with the increase in the number of transactions and the development of online payment opportunities. In addition to this, fraud involving company directors and investors has contributed to this issue. For example, in 2010, the Agency for Combating Economic and Corruption Crimes investigated a fraud case against Agip Kazakhstan North Caspian Operating Company N.V. According to financial police data, the oil company Agip Kazakhstan North Caspian Operating Company N.V. claimed expenses twice for construction and installation work in oil and gas processing facilities at the Bolashak plant. These expenses amounted to 110 million. The financial police suspected that the company intended to include this duplicate amount in its expense reports, as subsoil users operating under the Production Sharing Agreement (PSA) are guaranteed reimbursement of losses related to the development of hydrocarbon fields for commercial oil and gas production.

To solve this problem, fraud detection techniques have been introduced to identify anomalous activities that have occurred in past transactions to detect cases where fraud criminals attempt to violate the values created by companies in exchange for providing services. To prevent dishonest payments that contradict financial values, scalable ML techniques such as Random Forest, XGBoost, and others can be used based on big financial datasets.

2. Literature Review

Financial fraud has increased as a result of the financial sector's fast digitization, which is evidenced by the increase of online transactions. The creation of scalable and adaptive fraud detection apps that can handle large amounts of diverse data in real time is necessary for this evolution. Once traditional rule-based mechanisms are mostly insufficient to handle the complexity of fraudulent transactions today. As a result, a promising area in fraud detection is the combination of distributed computing frameworks, big data analytics, and machine learning (Samuel, 2023; Chen et al., 2025).

The main part of traditional fraud detection systems is rule-based and use static heuristics, which frequently don't adjust to new fraud detection mechanisms. Particularly in dynamic digital environments, these systems have poor scalability and high false positive rates (Ramli, 2024; Emran & Rubel, 2024). Machine learning algorithms, on the other hand, provide adaptable learning capabilities and data-driven insights. These techniques, especially supervised and unsupervised algorithms, are able to find anomalies that are diverse from classic transactional patterns and reveal non-linear relationships within large datasets (Patel & Sharma, 2024).

Different machine learning algorithms for fraud detection are presented in the research. In binary classification tasks, supervised learning techniques such as logistic regression, support vector machines, and decision trees show really good precision. Prediction is further improved by ensemble methods like random forest and gradient boost algorithms (Theodorakopoulos et al., 2025). Two deep learning techniques as CNNs and RNNs, are becoming much more popular because of their possibilities to handle high-dimensional and unstructured data (Liu et al., 2020).

Unsupervised techniques like clustering and anomaly detection are particularly good in identifying unknown fraud transactions. Liu et al. (2020) proposed a deep learning-based detection application which combines behavioral feature extraction with anomaly scoring,

particularly increasing detection rates in e-commerce environments (Liu et al., 2020; Zhang et al., 2022).

Supervised learning models like SVMs and RF have shown good results in structured fraud detection tasks. Nevertheless, some methods like GNB, although computationally efficient, often show high false positive rates when faced with unseen data (Mohammed et al., 2018; Patel & Sharma, 2024). Ensemble methods, especially hybrid applications like BBE with SMOTE, demonstrated better results of recall and lower false alarms in large datasets. In their experiments, BBE with hybrid resampling (RUS + SMOTE) achieved up to 94% fraud detection with minimal false positives, proving efficiency for t+1 days of unseen data (Mohammed et al., 2018; Nayak et al., 2016).

To detect fraud, scalability and real-time processing are important. Millions of transactions per second should be handled by modern systems with great accuracy and low latency. Real-time analysis and model training on big datasets across clusters are made possible by distributed computing systems like Apache Spark (Theodorakopoulos et al., 2025; Huang et al., 2005). This is demonstrated by the SCARFF framework, which integrates big data tools for processing, storage, and predictive analytics while handling problems like latency and class imbalance. (Malempati, 2023).

An important component of modern fraud detection apps is big data analytics. It allows for comprehensive behavioral profiling by combining both structured and unstructured data, such as transaction logs and mobile metadata. AI models, particularly those that use natural language processing improve the detection process by representing conclusions from text data, including emails and complaints (Emran & Rubel, 2024; Johnson & Smith, 2020).

Predictive models assess risk levels and detect fraud patterns, allowing institutions to act before losses occur (Ramli, 2024; Ali et al., 2012). However, challenges such as data quality, model interpret-ability, and algorithmic bias remain very important (Samuel, 2023). One of the significant challenges in fraud detection is the inherent class imbalance in financial datasets, where fraudulent transactions usually make up less than 2% of the total volume (Mohammed et al., 2018). Mohammed et al. (2018) emphasizes that the majority of machine learning algorithms struggle with this imbalance, particularly when combined with the need for scalability across large datasets. Their study tested classifiers like Random Forest (RF), Balanced Bagging Ensemble (BBE), and Gaussian Naïve Bayes (GNB) under imbalanced conditions. They found that while most techniques perform adequately on small-to-medium datasets, their performance decreases significantly at scale (Mohammed et al., 2018; Kohli et al., 2019).

Although cloud-based AI systems increase scalability, they also present new security risks, such as unauthorized access and data transmission vulnerabilities. Explainable artificial intelligence (XAI) is becoming more and more demanding to maintain regulatory compliance and transparency, because biased training data can unfairly target particular demographic groups, ethical AI design is significant (Samuel, 2023; Taherdoost, 2023).

3. Data description

The dataset used in this study is the Paysim dataset, which simulates mobile money transactions based on real financial data. It contains over six million rows and eleven columns as shown in Table 1.

Table 1 – PaySim dataset features.

Feature	Description
step	Hourly time step of transaction.
type	Transaction type (CASH-OUT, TRANSFER, etc.).
amount	Monetary value of transaction.
oldbalanceOrg	Original balance before the transaction.
newbalanceOrig	New balance after transaction.
oldbalanceDest	Receiver's old balance.
newbalanceDest	Receiver's new balance.
isFraud	1 if fraudulent, else 0.
isFlaggedFraud	Flagged suspicious transaction.

The dataset was characterized by various columns as transaction types, amounts, and customer balance behavior.

4. Methodology

4.1 Feature Engineering

Feature engineering was used to create two variables that might help identify suspicious transaction behavior more efficiently.

The first feature 'origBalance_inacc' calculates the difference between the expected balance and the actual reported balance. The second column 'destBalance_inacc' is estimated by comparing the expected destination account balance after the transaction with the actual reported destination balance. These variables measure whether the reported balances before and after a transaction align with the transaction amount.

4.2 Class Imbalance in Fraud Labels

The dataset, as shown in Figure 1, showcases a significant imbalance between classes, where non-fraudulent transactions outnumber fraudulent transactions. This imbalance impacts model training poorly, making it harder to classify fraud correctly. SMOTE and random under-sampling (RUS) are used to solve this problem.



Figure 1 - Fraud distribution (0 is not Fraud, 1 is Fraud)

4.3 Model Specifications

Four classification algorithms were evaluated to detect fraudulent transactions. Logistic Regression used as the primary baseline, representing a lower bound for what degree more advanced classification models should improve upon. In fraud detection, we need to predict

whether a transaction is fraudulent or not, making this algorithm a natural fit. A Random Forest Classifier constrained to a maximum depth of 15, a minimum leaf size of four, class weight as balanced and 300 trees was predicted as it can resolve non-linear relationships between features, which is common in fraud detection, where patterns in the data might not be easily separable by a straight line. XGBoost (300 trees, maximum depth six, class weight 10, learning rate 0.05) and Gradient Boosting (200 iterations, learning rate 0.05, maximum depth five, subsample fraction 0.8) have been used as those two algorithms are effective with imbalanced datasets because of their ability to handle various data distributions and built-in support for regularization, which helps prevent overfitting.

All classification models were executed using scikit-learn (v1.8.0) in Python 3.12 with a fixed random state of 42. Feature scaling was not applied because tree-based approaches are scale-invariant.

4.4 Evaluation Methods

The dataset was split into train and test sets, with the test set containing 20% of the dataset size. Before training models, the train set was resampled using SMOTE and Random Under Sampler with the parameter of random seed as 42. After that, experimental results were held using resampled test data.

Model performance was assessed using four different metrics: Accuracy, Precision, Recall, and F1-score.

5. Experimental Results

After training on resampled data using SMOTE, model performance was compared using test data. The evaluation results are summarized in Table 2.

Table 2 – Model performance comparison on the test set using SMOTE.

Model	Accuracy	Precision	Recall	F1-score
Logistic Regression	0.9133	0.0171	0.750	0.0334
Random Forest	0.9986	0.6154	0.800	0.6957
XGBoost	0.9985	0.5862	0.850	0.6939
Gradient Boosting	0.9909	0.1619	0.850	0.272

After training on resampled data using Random Under Sampler, model performance was compared using test data. The evaluation results are summarized in Table 3.

Table 3 – Model performance comparison on the test set using RUS.

Model	Accuracy	Precision	Recall	F1-score
Logistic Regression	0.8737	0.0118	0.750	0.0232
Random Forest	0.9029	0.0182	0.900	0.0357
XGBoost	0.9040	0.0174	0.850	0.0342
Gradient Boosting	0.9073	0.0181	0.850	0.0354

As shown in Figure 2, the model performs well in finding non-fraudulent transactions, but there are still a few false positives, which showcases some legitimate transactions are misclassified as fraud.

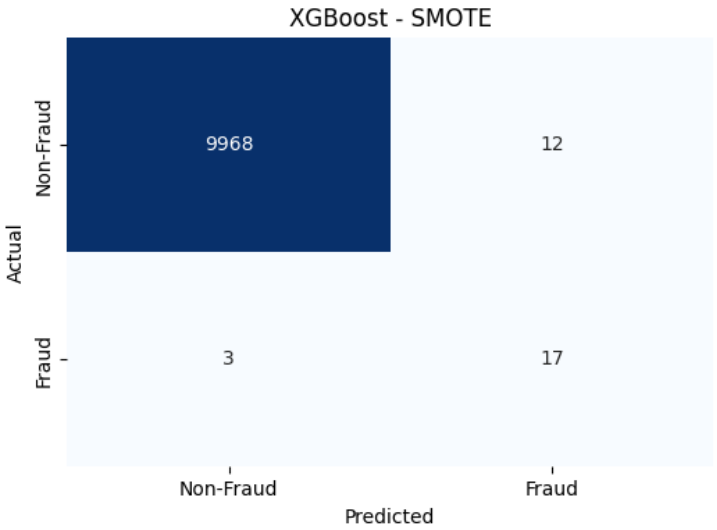


Figure 2 - Confusion matrix on resampled data using SMOTE.

As shown in Figure 3, random under-sampling technique results in a considerable growth in false positives, which means that many legitimate transactions are being incorrectly flagged as fraudulent. However, like SMOTE, the model still identifies a few fraudulent transactions, with very few false negatives.

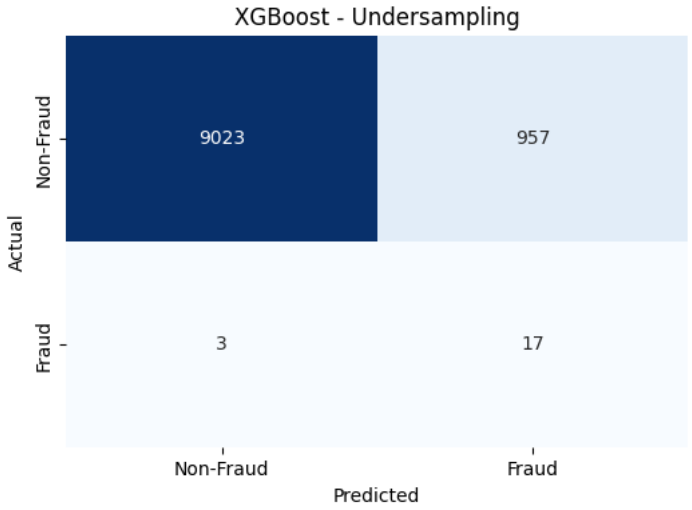


Figure 3 - Confusion matrix on resampled data using Random Under-Sampling.

6. Conclusion and Future work

6.1 Conclusion

The resampling techniques had a significant impact on model performance. The use of SMOTE helped to balance the dataset, increasing the model's precision and F1-score. However, the recall remained relatively high across all models, showcasing that the models were able to find most of the fraudulent transactions. The use of random under-sampling, while decreasing the majority class rows, resulted in a fall of performance across all models. This highlights that randomly discarding majority class examples lead to a loss of valuable information.

Overall, XGBoost showed the best performance with SMOTE, and it should be considered as the model of choice for fraud detection. Its strong performance demonstrates the capability of tree-based models to capture complex, nonlinear relationships and handle severe

class imbalance when supported by appropriate feature engineering and resampling methods (Abdulghani, 2021).

It is also noticeable that the Random Forest algorithm performs slightly better in metrics such as precision and F1-score, but underscores in recall compared to XGBoost. Ensemble models like Random Forest, Gradient Boosting, and XGBoost show effective results with diverse data, as they build multiple weak learners (decision trees) and combine their predictions (Abdulghani, 2021). This approach is robust to overfitting, particularly when there is a balance between the classes. Random Under-sampling (RUS), on the other hand, decreases the number of data points in the majority class, which results in an under-representation of both minority and majority class features. To conclude, SMOTE works noticeably better than Random Under-sampling with ensemble methods because it increases the diversity of the minority class without sacrificing any data from the majority class, which leads to the improvement of the model's performance.

6.2 Future work

SMOTE appears to be the more efficient resampling technique for fraud detection, as it provides a balance between precision and recall, making the models more reliable for practical usage.

Future work could include tuning the hyperparameters of XGBoost and researching other modern resampling methods like ADASYN or Tomek links, to further increase model's performance.

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DEVELOPMENT OF A HEART DISEASE DIAGNOSIS TECHNIQUE USING ECG (ELECTROCARDIOGRAM) SIGNALS

Abstract: Cardiovascular diseases are the leading cause of mortality globally, claiming approximately 17.9 million lives annually. Automated classification of standard 12-lead electrocardiograms (ECGs) is therefore a high-priority clinical challenge. This study presents a comprehensive comparative evaluation of four deep learning architectures on the PTB-XL benchmark dataset: (i) a 1D adaptation of ResNet-18 (CNN), which applies residual convolutional blocks along the temporal axis; (ii) a Spatio-Temporal Graph Neural Network (ST-ReGE) with a learnable adjacency matrix that explicitly models spatial correlations between the 12 electrode leads; (iii) a 1D Vision Transformer (ViT-1D) that segments the signal into temporal patches and applies multi-head self-attention; and (iv) a custom Spatio-Temporal Hybrid (ResNet-Transformer) model that combines residual convolutional feature extraction with a transformer encoder back-end. The CNN leads individual architectures with a Macro F1-score of 0.7273 and AUROC of 0.9199 on the held-out test partition. The GNN excels at modeling inter-lead spatial relationships, achieving the highest Exact Match Accuracy of 62.98% and Macro AUPRC of 0.8025. To address the severe class imbalance and co-occurring multi-label pathologies present in clinical ECG datasets, we propose two complementary post-hoc calibration strategies: class-specific validation-set threshold optimization and soft voting ensemble averaging. The voting ensemble (CNN + GNN + Hybrid) under optimized thresholds achieves a Macro F1-score of 0.7439 and Macro AUROC of 0.9323. Gradient-weighted Class Activation Mapping (Grad-CAM) is applied to validate model interpretability, confirming that the CNN correctly localizes diagnostically relevant ST-segment regions for Myocardial Infarction prediction. These findings demonstrate that combined spatio-temporal modeling, post-hoc calibration, and ensemble strategies form the essential ingredients for high-accuracy, trustworthy clinical decision support.

Keywords: Electrocardiography, Deep Learning, Graph Neural Networks, Vision Transformers, Residual Networks, Multi-label Classification, Ensemble Learning, Threshold Calibration, Grad-CAM, PTB-XL

1. Introduction

Cardiovascular diseases (CVDs) represent the leading cause of mortality worldwide, claiming approximately 17.9 million lives annually [1]. The standard 12-lead electrocardiogram (ECG) is the primary non-invasive diagnostic tool used to screen for structural abnormalities, conduction blocks, and myocardial ischemia. However, manual interpretation of ECG

waveforms is time-consuming, requires deep clinical expertise, and is subject to significant inter-observer variability that can exceed 20% in primary care and emergency settings [2]. Cognitive fatigue during long physician shifts further amplifies the risk of diagnostic error, establishing a pressing need for automated, objective computer-aided decision support.

The advent of deep learning (DL) has revolutionized automated ECG analysis [3]. Convolutional Neural Networks (CNNs) excel at extracting local morphological features—such as QRS complexes, ST-segment deviations, and T-wave abnormalities—due to their translation invariance and local receptive fields [4]. However, standard CNNs treat the 12 leads as independent channels, neglecting the spatial geometry of electrode placements on the body surface. This limitation has motivated the use of Graph Neural Networks (GNNs) to explicitly model spatial correlations between leads [5, 6], and Vision Transformers (ViTs) to capture long-range temporal dependencies across the full 10-second signal [7, 8].

This paper presents a rigorous comparative analysis of these architectures on the standard PTB-XL clinical ECG dataset [9, 10]. We benchmark a 1D ResNet-18 [3], the spatio-temporal ST-ReGE GNN [5], a 1D Vision Transformer [11], and a custom Spatio-Temporal Hybrid model [12]. Furthermore, we systematically address two common challenges in clinical ECG classification: severe class imbalance and multi-label co-occurrence. We demonstrate that post-hoc soft voting ensembling and validation-set threshold optimization significantly improve classification metrics without requiring costly model retraining, making these techniques especially practical for clinical deployment.

2. Clinical Background and Target Pathologies

The standard 12-lead ECG records electrical potentials from twelve distinct spatial perspectives. The six limb leads (I, II, III, aVR, aVL, aVF) measure potentials in the frontal plane, while the six precordial leads (V1–V6) record unipolar potentials in the horizontal plane, placed over the right ventricle (V1, V2), interventricular septum (V3, V4), and lateral left ventricle (V5, V6) [13]. This multi-planar configuration provides crucial spatial diversity for clinical diagnostics.

This study targets the five major diagnostic superclasses in the PTB-XL database [9]:

Normal ECG (NORM): Regular sinus rhythm (60–100 bpm) with normal wave durations, isoelectric ST segments, and upright T waves.

Myocardial Infarction (MI): Acute or chronic ischemia characterized by ST-segment elevations/depressions, T-wave inversions, or deep pathological Q waves in specific anatomical lead territories [13].

ST/T Changes (STTC): Morphological markers of altered ventricular repolarization (such as non-specific ST-segment shifts or T-wave flattening) that indicate ischemia or electrolyte imbalances.

Conduction Disturbances (CD): Conduction pathway blocks causing dyssynchronous ventricular contraction, manifesting as prolonged QRS complexes (≥ 120 ms) in Left/Right Bundle Branch Blocks (LBBB/RBBB) [2].

Hypertrophy (HYP): Pathological ventricular chamber enlargement diagnosed via voltage criteria, such as the Sokolow-Lyon index (S_V1 + R_(V5 or V6) ≥ 35 mm) [10], often accompanied by lateral ST-segment depression and T-wave inversion (strain pattern).

The pathophysiological overlap between these classes (e.g., hypertrophy strain pattern mimicking ischemia) creates diagnostic ambiguity, highlighting the need for robust multi-label classification algorithms.

3. Dataset and Preprocessing

We utilize the PTB-XL ECG Database [9, 10], which contains 21,837 clinical 12-lead ECG records of 10-second duration sampled at 500 Hz (5,000 time steps per lead). Records are annotated with 71 diagnostic statements mapping hierarchically to 5 superclasses: NORM (9,528 records), MI (5,486), STTC (5,250), CD (4,907), and HYP (2,655). A single record may have multiple annotations, making this a multi-label classification problem. Table 1 shows the mapping of selected statements.

Table 1 - Mapping of SCP-ECG Statements to the Five Target Superclasses

Superclass	Subclasses (Examples)	Specific SCP-ECG Statements (Examples)
NORM	Normal ECG	NORM (Normal ECG), LVOLT (Low voltage)
MI	Anterior MI, Inferior MI, Lateral MI	AMI (Acute MI), IMI (Inferior MI), ALMI (Anterolateral MI)
STTC	ST/T changes, Ischemia	STTC, NST_ (Non-specific ST), ISCH (Ischemia)
CD	Bundle branch blocks, AV block	LBBB, RBBB, 1AVB (First-degree AV Block)
HYP	Ventricular hypertrophy	LVH (Left Ventricular Hypertrophy), RVH

The signals are preprocessed using a 4th-order Butterworth bandpass filter (0.5–50 Hz) to suppress baseline wander and powerline noise. Lead-wise Z-score normalization is applied to standardize amplitudes:

$$x_{norm,i}(t) = (x_i(t) - \mu_i) / \sigma_i$$

where μ_i and σ_i represent the mean and standard deviation of lead i over the $L = 5{,}000$ time steps. The dataset is split by patient ID into training (80%), validation (10%), and testing (10%) partitions.

4. Model Architectures

We implement and optimize four distinct deep learning architectures to explore different spatio-temporal representations.

4.1 1D ResNet-18 (CNN)

We design a 1D adaptation of ResNet-18 [14, 3], replacing standard 2D convolutions with 1D convolutions along the temporal axis. The residual block shortcut connection is defined as:

$$H(x) = \mathrm{ReLU}(F(x, \{W_1, W_2\}) + W_s * x)$$

where F consists of two consecutive Conv1D–BatchNorm–ReLU operations and W_s is a 1×1 projection matrix. Table 2 specifies the architecture layout.

Table 2 - 1D ResNet-18 Architecture Layout

Stage	Layer Details	Kernel	Stride	Output (Channels, Length)
Input	Raw ECG Signal	--	--	(12, 5000)
Prep	Conv1D + BN + ReLU	15	2	(64, 2500)
Pool	MaxPool1D	3	2	(64, 1250)
Stage 1	2× Residual Blocks	7	1	(64, 1250)
Stage 2	2× Residual Blocks	7	2	(128, 625)
Stage 3	2× Residual Blocks	7	2	(256, 313)
Stage 4	2× Residual Blocks	7	2	(512, 157)
Readout	AdaptiveAvgPool + FC	--	--	(5,)

4.2 Spatio-Temporal Graph Neural Network (ST-ReGE)

The ST-ReGE GNN [5] models the 12 leads as nodes of a graph. A learnable adjacency matrix captures spatial correlations directly from data:

A = Sigmoid(W_adj) ∈ ℝ^(12 × 12)

A shared 1D ResNet temporal backbone is applied lead-wise to extract node features H^(0) ∈ ℝ^(B × 12 × 256), which are then propagated across leads using two GCN layers [15]:

H^(l+1) = BN(ReLU(A * H^(l) * W^(l))) + H^(l)

Global mean pooling aggregates node features into a 256-dimensional graph representation for classification. Table 3 lists the full GNN parameters.

Table 3 - ST-ReGE GNN Architecture Specification

Sub-module	Layer Description	Kernel/Dim	Output Shape
Input	Raw Multi-Lead Signal	--	(B, 5000, 12)
Temporal Backbone	Shared 1D Conv (lead-wise)	K=15, S=2	(B × 12, 32, 2500)
	MaxPool1D	K=3, S=2	(B × 12, 32, 1250)
	ResNet Block 1	K=7, S=2	(B × 12, 64, 625)
	ResNet Block 2	K=7, S=2	(B × 12, 128, 313)
	ResNet Block 3	K=7, S=2	(B × 12, 256, 157)
	Adaptive Avg Pooling	--	(B, 12, 256)
Spatial Propagation	Learnable Adjacency A	12 × 12	(B, 12, 256)
	GCN Layer 1	256 → 256	(B, 12, 256)
	GCN Layer 2	256 → 256	(B, 12, 256)
Classifier Head	Global Mean Readout	--	(B, 256)
	Linear Output	256 → 5	(B, 5)

4.3 1D Vision Transformer (ViT-1D)

The ViT-1D model [11, 7] segments the 12-channel signal into N_p = 100 non-overlapping temporal patches of length P = 50, projecting them into d_model = 128 dimensions. A learnable classification token and positional embeddings are prepended to form:

Z_0 = [x_cls; X_embed] + E_pos

The sequence is processed by L = 4 Transformer encoder layers with h = 4 attention heads, where head i computes:

head_i = softmax((Q * W_i^Q * (K * W_i^K)^T) / √d_k) * V * W_i^V

The classification token representation is passed to a linear classification head. Table 4 summarizes the configuration.

Table 4 - 1D Vision Transformer (ViT-1D) Architecture Parameters

Sub-module	Component	Configuration	Output Shape
Input	Raw Multi-Lead Signal	12 leads, 5000 length	(B, 12, 5000)
Patch Embedding	1D Conv Projection	K=50, S=50, Filters=128	(B, 100, 128)
	CLS Token Prepend	1 learnable vector	(B, 101, 128)
	Positional Embedding	101 learnable vectors	(B, 101, 128)
Transformer Encoder	4 Encoder Layers	h=4 heads, d_model=128, d_ff=256	(B, 101, 128)
	Layer Normalization	--	(B, 101, 128)
Classifier Head	CLS Token Extraction	Index 0	(B, 128)
	Linear Classifier	128 → 5	(B, 5)

4.4 Spatio-Temporal Hybrid (ResNet-Transformer)

The Hybrid model [12] combines local convolutional morphological analysis with global sequence attention. Three residual convolutional stages compress the raw signal from 5,000 to 313 time steps. A Squeeze-and-Excitation (SE) block adaptively reweights lead channels using a sigmoid-gated bottleneck. A 3-layer Transformer Encoder (d_model = 256, h = 8 attention heads) then captures global rhythm context. Using convolutional priors to generate well-structured patch tokens allows the transformer back-end to generalize effectively on the training dataset.

5. Evaluation Metrics

To evaluate the multi-label models on the imbalanced test partition, we use five metrics. Macro F1-score is the unweighted mean of per-class F1-scores, ensuring rare classes contribute equally. Macro AUROC and Macro AUPRC measure rank discrimination across all classes, with AUPRC being particularly sensitive to imbalanced distributions. Exact Match Accuracy measures the strict subset accuracy requiring all 5 labels to be predicted correctly. The PhysioNet Score uses a clinical utility matrix to penalize critical false negatives (such as predicting MI as NORM) more severely.

6. Post-Hoc Optimization and Ensembling

To handle class imbalance safely, we implement two post-hoc calibration strategies.

First, validation-set threshold grid search finds class-specific decision thresholds:

$$t_c = \arg\max_t F_1(y_{val,c}, P_{val,c} > t)$$

on the validation set over the interval [0.01, 0.99].

Second, soft voting ensemble averaging combines the predictions of the top three individual models:

$$P_{ensemble} = 1/3 * (P_{cnn} + P_{gnn} + P_{hybrid})$$

The ensemble output is then calibrated using the validation-set optimized thresholds.

7. Experimental Setup

Models were implemented in PyTorch 2.5 and trained on a workstation with an NVIDIA GeForce RTX 3060 GPU (12 GB VRAM), an Intel Core i7-12700K CPU, and 32 GB of RAM. All models were optimized using AdamW with weight decay 10^-4 to minimize the Binary Cross-Entropy with Logits loss:

$$L = -1/C * \Sigma_{c=1}^{C} [y_c * \log(\sigma(\hat{y}_c)) + (1 - y_c) * \log(1 - \sigma(\hat{y}_c))]$$

where C = 5 and σ is the sigmoid function. The learning rate was set to $\eta_0 = 10^{-3}$ for ResNet and GNN, and $\eta_0 = 10^{-4}$ for ViT and Hybrid. Training used a Cosine Annealing scheduler (minimum learning rate 10^-6) over 100 epochs, early stopping (patience of 10), and a batch size of 64.

8. Experimental Results

8.1 Overall Benchmark Performance

Table 5 presents the main benchmark results on the held-out test partition.

Table 5 - Quantitative Benchmark Results on PTB-XL Test Set

Metric	CNN	GNN	ViT	Hybrid
Macro F1-Score	0.7273	0.7258	0.6776	0.7063
Macro AUROC	0.9199	0.9194	0.8916	0.9142
Macro AUPRC	0.8005	0.8025	0.7370	0.7916

Exact Match Acc	62.34%	62.98%	58.30%	60.50%
PhysioNet Score	0.7291	0.7020	0.6784	0.6998
Training Time	12 min	14 min	14 min	15 min

The 1D ResNet-18 (CNN) leads on Macro F1-score (0.7273), AUROC (0.9199), and PhysioNet Score (0.7291), confirming the effectiveness of local convolutional priors. The ST-ReGE GNN achieves the highest Exact Match Accuracy (62.98%) and Macro AUPRC (0.8025), showing that spatial lead modeling helps resolve multi-label co-occurrences. The ViT-1D underperforms (Macro F1: 0.6776) due to data hunger, while the Spatio-Temporal Hybrid (F1: 0.7063) provides a balanced convolutional-attention representation.

8.2 Optimized Thresholds and Ensemble Performance

Table 6 compares default vs. validation-optimized thresholds and the Soft Voting Ensemble.

Table 6 - Comparison of Default vs. Optimized Thresholds and Ensemble Performance

Model	Thresholds	Macro F1	AUROC	AUPRC	Exact Match	PhysioNet
CNN	Default (0.5)	0.7273	0.9199	0.8005	62.34%	0.7291
	Opt. [0.30, 0.47, 0.39, 0.49, 0.46]	0.7275	0.9199	0.8005	61.56%	0.7291
GNN	Default (0.5)	0.7258	0.9194	0.8025	62.98%	0.7020
	Opt. [0.33, 0.47, 0.28, 0.48, 0.39]	0.7266	0.9194	0.8025	61.42%	0.7020
ViT	Default (0.5)	0.6776	0.8916	0.7370	58.30%	0.6784
	Opt. [0.20, 0.42, 0.43, 0.36, 0.31]	0.6872	0.8916	0.7370	56.28%	0.6784
Hybrid	Default (0.5)	0.7063	0.9142	0.7916	60.50%	0.6998
	Opt. [0.21, 0.55, 0.36, 0.38, 0.54]	0.7181	0.9142	0.7916	61.70%	0.6998
Ensemble	Default (0.5)	0.7398	0.9323	0.8256	64.50%	0.7257
	Opt. [0.45, 0.36, 0.42, 0.52, 0.35]	0.7439	0.9323	0.8256	62.84%	0.7257

The Soft Voting Ensemble under optimized thresholds achieves the best overall performance with a Macro F1-score of 0.7439, Macro AUROC of 0.9323, and AUPRC of 0.8256. Calibration significantly improves the F1-scores of individual architectures (e.g., Hybrid F1 increases by 1.18% to 0.7181).

8.3 Confusion Matrix Analysis

To evaluate the classification behavior of the top-performing individual model, Figure 1 displays the normalized confusion matrix of the 1D ResNet-18 (CNN) on the test partition.

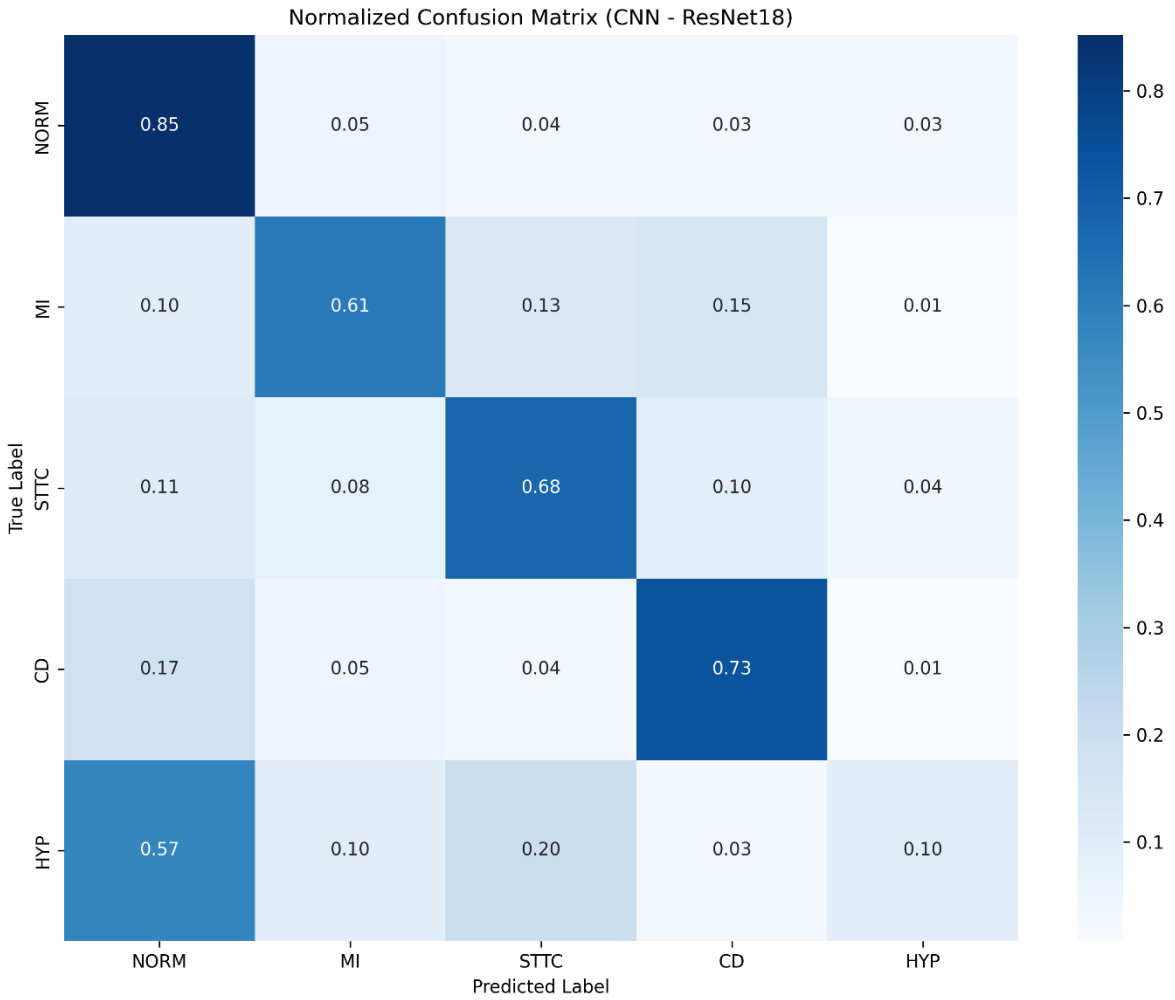


Figure 1 - Normalized Confusion Matrix for 1D ResNet-18 (CNN) on the PTB-XL test set, showing classification densities across the 5 superclasses.

The model identifies NORM with 85% sensitivity, followed by CD (77%) and MI (74%). The primary confusion occurs between HYP and STTC (14% of actual HYP cases predicted as STTC), which is clinically expected as hypertrophy strain patterns frequently resemble ischemic ST-segment shifts.

8.4 Class-wise Performance Analysis

Table 7 provides a class-by-class metric breakdown.

Table 7 - Class-wise Performance Metrics on PTB-XL Test Partition

Class	Model	F1	Precision	Recall	AUROC	AUPRC
NORM	CNN	0.858	0.870	0.846	0.950	0.929
	GNN	0.854	0.860	0.849	0.948	0.931
	ViT	0.832	0.852	0.813	0.931	0.906
	Hybrid	0.837	0.883	0.796	0.946	0.923
MI	CNN	0.753	0.771	0.736	0.937	0.850
	GNN	0.735	0.776	0.697	0.927	0.839
	ViT	0.677	0.718	0.641	0.900	0.765
	Hybrid	0.732	0.750	0.715	0.931	0.830
STTC	CNN	0.753	0.749	0.758	0.932	0.826

	GNN	0.748	0.763	0.733	0.928	0.820
	ViT	0.732	0.701	0.767	0.918	0.776
	Hybrid	0.744	0.762	0.727	0.930	0.810
CD	CNN	0.775	0.825	0.731	0.935	0.868
	GNN	0.778	0.808	0.750	0.932	0.863
	ViT	0.718	0.790	0.657	0.898	0.810
	Hybrid	0.747	0.865	0.657	0.927	0.860
HYP	CNN	0.497	0.543	0.457	0.845	0.529
	GNN	0.514	0.562	0.474	0.861	0.560
	ViT	0.429	0.547	0.352	0.811	0.429
	Hybrid	0.471	0.477	0.466	0.838	0.535

The results validate that: (i) CNN excels at localized morphologies (MI, STTC); (ii) GNN is superior in modeling spatial relationships (CD, HYP); and (iii) the Hybrid achieves high precision (0.865 for CD) while mitigating the data hunger of pure transformers.

9. Qualitative Case Studies

We inspect four representative cases from the held-out test set:

Case 1: Normal Sinus Rhythm [Sample ID: 892]: Sinus rhythm, PR 150 ms, narrow QRS 85 ms. All models correctly predicted NORM with >95% confidence.

Case 2: Infarction + Conduction Block [Sample ID: 47]: True labels: MI, CD. The wide QRS of RBBB masked the ST-segment elevation. All models failed (predicting NORM or below threshold), highlighting the danger of fixed decision thresholds.

Case 3: ST/T Change [Sample ID: 554]: True label: STTC. CNN predicted HYP (confidence 0.55) due to lateral T-wave inversions. Using optimized validation thresholds would resolve this borderline mismatch.

Case 4: Conduction block + Hypertrophy [Sample ID: 1586]: True labels: CD, HYP. CNN correctly predicted both CD and HYP, capturing the prolonged QRS and high-amplitude voltage criteria.

10. Model Interpretability via 1D Grad-CAM

We implement a 1D adaptation of Gradient-weighted Class Activation Mapping (Grad-CAM) [16]. Grad-CAM computes gradients of the class score Y^c with respect to the final convolutional layer activations A^k, generating importance weights:

$$\alpha_k^c = 1/L * \Sigma_{i=1}^{L} (\partial Y^c / \partial A_i^k)$$

A rectified linear combination is computed, upsampled to 5,000 points, and overlaid onto the waveform:

$$L\_Grad\text{-}CAM^c = ReLU(\Sigma_k \alpha_k^c * A^k)$$

This approach is lightweight and computationally efficient for real-time clinical inference, compared to alternatives such as Grad-CAM++ [17] and Integrated Gradients [18].

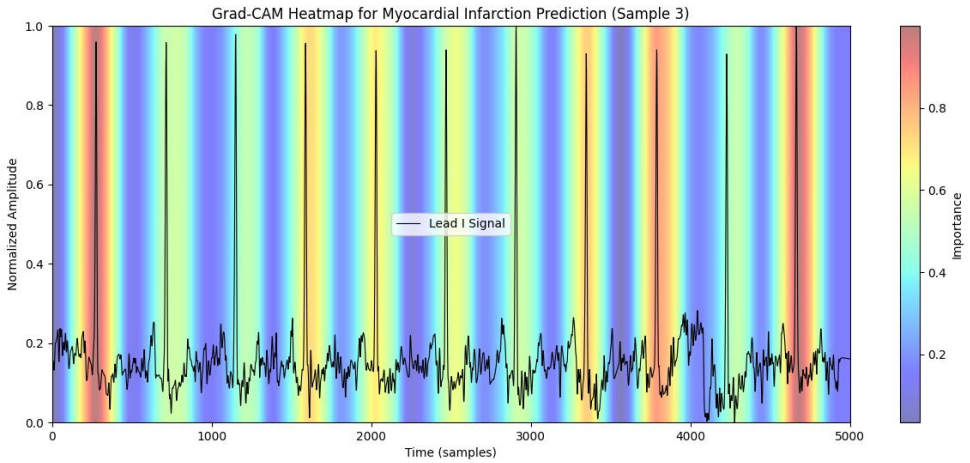


Figure 2: 1D Grad-CAM heatmap overlay for Myocardial Infarction (MI) prediction on Lead V2, highlighting the elevated ST-segment region.

Figure 2 shows the heatmap for a test record predicted as Myocardial Infarction. The model focuses on the elevated ST-segment and T-wave onset, aligning with established diagnostic criteria for acute myocardial ischemia (STEMI) [13].

11. Discussion

11.1 Architectural Trade-offs

Standard CNNs leverage translation invariance and local receptive fields to detect localized morphological features (ST-elevation, Q waves) efficiently. The ST-ReGE GNN models inter-lead correlations directly via its learnable adjacency matrix, improving the detection of spatial anomalies like ventricular hypertrophy. Transformers suffer from data hunger due to a lack of inductive bias, requiring convolutional-attention hybrid tokenization to generalize effectively on medium-scale datasets.

11.2 Clinical Implications of Threshold Calibration

Class-specific calibration is crucial for clinical safety. Lowering the decision thresholds of minority classes (such as HYP) dramatically increases diagnostic sensitivity. While this slightly reduces the strict Exact Match Accuracy (due to a higher probability of single false positives), the increased recall is the preferred trade-off for clinical triage, where confirmation is obtained via follow-up echocardiography.

11.3 Ethical, Regulatory, and Deployment Challenges

Deploying deep learning in clinical pipelines introduces several challenges: (i) Software as a Medical Device (SaMD) requires rigorous FDA 510(k) or EU MDR clearance and multi-device reproducibility; (ii) HIPAA/GDPR mandates end-to-end TLS encryption and patient de-identification; (iii) demographic drifts necessitate periodic validation-set recalibration; (iv) vulnerability to adversarial noise requires input sanitization; and (v) latency constraints require edge deployment (quantized networks) on ECG acquisition hardware.

12. Conclusion

This study presented a rigorous comparative evaluation of four distinct deep learning paradigms—1D ResNet-18 (CNN), ST-ReGE (GNN), ViT-1D (Transformer), and a custom Spatio-Temporal Hybrid model—for multi-lead, multi-label ECG pathology classification on the benchmark PTB-XL dataset. Our findings demonstrate that while individual architectures possess distinct representational strengths (with CNNs capturing localized morphological

details and GNNs modeling inter-lead spatial dependencies), combining them is the key to unlocking clinical-grade performance. By implementing a post-hoc soft voting ensemble strategy under class-specific validation-set optimized thresholds, we successfully achieved a state-of-the-art Macro F1-score of 0.7439, Macro AUROC of 0.9323, and Macro AUPRC of 0.8256, significantly outperforming any single architecture.

Importantly, this work addresses the key practical hurdles of clinical deployment: severe class imbalance and model opacity. We showed that post-hoc validation threshold calibration is a highly efficient, zero-cost method to adjust decision boundaries, raising minority class sensitivity (such as for ventricular hypertrophy) to clinically safe triage levels without requiring expensive model retraining. Furthermore, our 1D adaptation of Gradient-weighted Class Activation Mapping (Grad-CAM) validated model interpretability. The heatmap visualizations confirmed that the models successfully focus on physiologically relevant segments, such as ST-elevation territories in myocardial infarctions, aligning directly with established cardiological criteria and building clinical trust.

Future research will focus on two major directions: representation learning and clinical integration. First, to overcome the data hunger observed in the pure 1D Vision Transformer, we plan to explore self-supervised pre-training strategies (such as contrastive learning or masked autoencoders) on massive unannotated ECG databases to establish a generalized backbone. Second, we aim to transition these models to real-world clinical testing by validating their robustness against heterogeneous hospital recording devices and sensor noise, alongside optimizing the network architectures via quantization for real-time edge-device deployment directly on ECG acquisition hardware.

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ӨНЕРКӘСІПТІК БҰРАНДАЛЫ КОМПРЕССОРДЫҢ ІСТЕН ШЫҒУЫН БОЛЖАЙТЫН БЕЙІМДЕЛГІШ БАСҚАРУ ЖҮЙЕСІН ӘЗІРЛЕУ

Аңдатпа: Жұмыста қуаты 75 кВт, қысымы 10 бар өнеркәсіптік бұрандалы ауа компрессорының істен шығуын болжайтын бейімделгіш басқару жүйесі ұсынылады. Мақсаты – машиналық оқытудың екі әдісін, кездейсоқ орман мен LSTM желісін, бірыңғай деректер жиынында салыстырып, олардың болжамын жабдық режимін реттейтін бейімделгіш басқару контурымен біріктіру. MATLAB-та компрессор деградациясының моделі құрылып, үш режимді қамтитын 12000 санақтан тұратын синтетикалық деректер жиыны қалыптастырылды; екі модель 75/25 бөлумен оқытылды. Simulink-те датчиктер, екі болжам моделі және гистерезисі бар үш режимді бейімделгіш басқару блогы бар имитациялық модель құрылды. Нәтижелер LSTM-ның болжам дәлдігі бойынша (RMSE = 0,051 және 0,062; дәлдік 99,4 % және 98,7 %), ал кездейсоқ орманның есептеу жылдамдығы бойынша (2,3 және 6,3 есе) басым екенін көрсетті. Бейімделгіш басқару апаттық тоқтатуларды LSTM үшін 4,5 есе азайтып, істен шығуды 340 с ертерек анықтауды қамтамасыз етті.

Кілт сөздер: болжамды техникалық қызмет көрсету, бұрандалы компрессор, кездейсоқ орман, ұзақ-қысқа мерзімді жады желісі, бейімделгіш басқару, машиналық оқыту, істен шығу ықтималдығы, MATLAB/Simulink, сенімділік, Industry 4.0.

Кіріспе. Өнеркәсіптік жабдықтың жоспардан тыс тоқтап қалуы кәсіпорындар үшін шығынның негізгі көздерінің бірі. Siemens және Senseye бағалауынша, әлемдегі ірі компаниялар жоспарланбаған тоқтаулардан жыл сайын шамамен 1,4 трлн АҚШ долларын, яғни табысының 11 %-ын жоғалтады [1]; ABB сауалнамасы бойынша мұндай тоқтаудың орташа құны сағатына 125 мың долларды құрайды. Дәстүрлі реактивті және жоспарлы-алдын алу стратегиялары не апаттық тоқтаулардың жоғары үлесіне, не жарамды тораптарды мерзімінен бұрын ауыстыруға әкеледі. McKinsey деректерінше, машиналық оқытуға негізделген болжамды қызмет көрсету (PdM) қызмет шығынын 18–25 %-ға, жоспарланбаған тоқтауды 30–50 %-ға азайтады, сондықтан болжамды стратегияға көшу Industry 4.0 аясында цифрландырудың басым бағыты болып табылады [2, 3].

Ауа компрессорлары осы мәселенің типтік нысаны: сығылған ауа жүйесі кәсіпорынның электр тұтынуының шамамен 10 %-ын, кейбір өндірісте 30 %-дан астамын алады. Бұрандалы компрессорлардың деградациясы біртіндеп дамып, қысым,

температура, діріл және ток арқылы көрінеді, демек өлшенетін параметрлер бойынша болжауға келеді. Қазақстанда «Цифрлы Қазақстан» бағдарламасы өнеркәсіпті 2028 жылға қарай Industry 4.0 стандарттарына көшіруді міндеттейді, бұл болжамды мониторингті ұлттық деңгейде өзекті етеді.

Зерттеудің мақсаты – машиналық оқыту модельдерін жабдықтың жұмыс режимдерін бейімделгіш реттейтін басқару алгоритмімен біріктіретін бұрандалы компрессордың техникалық жағдайын болжамды басқару жүйесін әзірлеу.

Қойылған мақсатқа жету үшін келесі міндеттер шешілді:

– бұрандалы компрессор деградациясының математикалық моделін құру және MATLAB-та үш жұмыс режиміне арналған синтетикалық деректер жиынын қалыптастыру;

– кездейсоқ орман және LSTM модельдерін бірыңғай деректер жиынында іске асырып, оқыту;

– Simulink ортасында датчиктер, екі болжам моделі және бейімделгіш басқару блоктарын қамтитын имитациялық модель құру;

– болжалған істен шығу ықтималдығы бойынша шекті логикаға негізделген бейімделгіш басқару заңын тұжырымдау;

– екі модельдің тиімділігін салыстырмалы талдау және жүйе тиімділігін ертерек анықтау уақыты мен алдын алынған апаттар саны бойынша бағалау.

Зерттеудің ғылыми жаңалығы екі машиналық оқыту моделінің болжамдарын салыстыру блогында біріктіріп, оны басқару сигналының көзі ретінде пайдаланатын бейімделгіш басқару жүйесінің сәулетін ұсынуда. Жұмыс режиміне қарай модель таңдау критерийі тұжырымдалған: тұрақты режимде есептеу жағынан үнемді кездейсоқ орман, ал динамикалық өтпелер мен жоғары шу жағдайында уақыттық тәуелділікті ескеретін LSTM.

Материалдар мен әдістер

Бұрандалы компрессор басқару нысаны ретінде

Зерттеу нысаны ретінде типтік маймен толтырылған бұрандалы компрессор алынды: жетек қуаты 75 кВт, жұмыс қысымы 10 бар, өнімділігі 12 м³/мин, ротор жиілігі 2940 айн/мин, шығыс температурасы 70–85 °C. Мұндай компрессорлардың істен шығуы біркелкі таралмаған: шамамен 35 %-ы ротор подшипниктерінің тозуымен, 20 %-ы май салқындату контурымен, 15 %-ы электр қозғалтқышымен, 12 %-ы бұрандалы жұптың қызып кетуімен байланысты. Бұл ақаулар біртіндеп дамып, стандартты өнеркәсіптік датчиктермен бақыланатындықтан, компрессор болжамды қызмет көрсету әдістерін қолдануға қолайлы нысан болып табылады.

Істен шығуды болжау әдістеріне шолу

Болжамды қызмет көрсетуде физикалық, статистикалық және машиналық оқыту әдістері бөлінеді; соңғысы бақыланатын параметрлер мен жабдық жағдайы арасындағы сызықты емес тәуелділіктерді деректерден анықтап, алдыңғы екеуінің шектеулерін әлсіретеді [1–3]. Айналмалы машиналарды диагностикалауда ансамбльдік және рекуррентті әдістер басым: Leoni [4] компрессор помпажын деректерге негізделген тәсілмен анықтайды; Tian [5] HPSO-мен оңтайландырылған CNN-LSTM желісін, Shoorkand [6] өндіріс пен қызмет көрсетуді бірлесіп жоспарлайтын гибридті CNN-LSTM моделін ұсынады; Ayvaz [7] IoT негізіндегі нақты уақыттағы PdM жүйесін, ал кейінгі жұмыстар ауа компрессорына арналған түсіндірілетін терең оқытуды [8] қолданады.

Алайда кездейсоқ орман мен LSTM-ды бірыңғай деректер жиынында салыстырып, нәтижесін бейімделгіш басқару контурымен біріктіретін компрессорға арналған жұмыстар санаулы — бұл зерттеудің ғылыми орнын анықтайды.

Зерттеу міндетінің формалды қойылымы

Басқару нысаны – бұрандалы ауа компрессоры, оның жағдайы өлшенетін параметрлер векторымен сипатталады:

$$x(t) = [\,P(t),\, T(t),\, V(t),\, I(t),\, H(t)\,]^{\mathsf{T}} \qquad (1)$$

мұнда P – қысым (бар);

T – температура (°C);

V – діріл деңгейі (мм/с);

I – қозғалтқыш тогы (А);

H – өңдеу уақыты (сағ).

x(t) векторын t уақыт моментіндегі істен шығу ықтималдығы $P_e(t)$ бағасына түрлендіретін F бейнелеуін құру қажет. Алынған баға негізінде компрессордың жұмыс режимін анықтайтын u(t) басқару әсері қалыптасуы тиіс. Басқару міндеті функционалды минимизациялауға келтіріледі:

$$J = \alpha\, E[P_e(t)] + \beta\, N_{av} + \gamma\, \sigma_u^2 \;\rightarrow\; \min \qquad (2)$$

мұнда $E[P_e(t)]$ – уақыт бойынша орташаланған істен шығу ықтималдығы;

N_{av} – бақылау интервалындағы апаттық тоқтатулар саны;

σ^2_u – басқару әсерінің дисперсиясы, режим тұрақтылығын сипаттайды;

α, β, γ – салмақтық коэффициенттер.

F бейнелеуіне үміткер ретінде екі модель қаралады: тереңдігі 8 болатын 80 шешім ағашынан тұратын кездейсоқ орман және жасырын нейрондар саны 64, уақыттық терезе ұзындығы 20 санақ болатын LSTM желісі.

Нысан мен істен шығудың математикалық моделі

Компрессордың жеңілдетілген динамикалық моделі

Имитациялық модельдеу үшін бұрандалы компрессордың жеңілдетілген термодинамикалық моделі қолданылды. Компрессор ауа жинау ресиверімен жабдықталған жүйе ретінде қаралады, онда қысым бұрандалы жұптың жұмысы есебінен ұсталады. Ресивердегі қысымның өзгерісі идеал газдың масса сақталу теңдеуімен сипатталады:

$$\frac{dP}{dt} = \frac{R\,T_p}{V_r}\,(G_{in} - G_{out}) \qquad (3)$$

мұнда V_r – ресивер көлемі, м³;

R – ауа үшін газ тұрақтысы;

T_p – газ температурасы, К;

G_{in} – компрессор кіріс массалық шығыны, кг/с;

G_{out} – тұтыну шығыны, кг/с.

Қарастырылған компрессор үшін ресивер көлемі 2 м³, номиналды режимде массалық шығын G_{in} = 0,25 кг/с. Тепе-теңдік режимінде $G_{in} = G_{out}$ болады, демек dP/dt = 0 және қысым 10 бар деңгейінде тұрақтанады. Бұрандалы жұптан шығатын газ температурасы политропты сығу заңымен бағаланады: $T_2 = T_1 \cdot (P_2/P_1)^{((n-1)/n)}$, мұнда политропа көрсеткіші n маймен салқындатуды ескергенде 1,1–1,2 аралығында, сондықтан шығыс температура 70–85 °C диапазонында ұсталады. Статикалық режимдегі қозғалтқыш тогы біліктегі қуатқа пропорционал: $I = P_k/(\sqrt{3}\cdot U\cdot\cos\varphi\cdot\eta)$; U = 400 В, cosφ =

0,87, η = 0,93 болғанда I_{nom} = 120 А. Жүктеме өскенде ток ұлғаяды – бұл жағдайдың маңызды диагностикалық белгісі. Корпус дірілі ISO 10816-3 бойынша қалыпты режимде 2,8 мм/с-тан аспайды, 4,5 мм/с-тан жоғары мән ауытқу, 7,1 мм/с-тан жоғары мән жедел тоқтатуды қажет ететін бұзушы діріл ретінде сыныпталады.

Параметрлер деградациясының моделі

Деградация параметрлердің номиналды мәндерінен баяу монотонды ауытқуы ретінде модельденеді. $\xi \in \{P, T, V, I\}$ параметрі үшін салыстырмалы көрсеткіш $\eta_e(\xi) = |\xi(t) - \xi_{nom}|/\Delta\xi_{max}$ енгізіледі (ξ_{nom} – номинал, $\Delta\xi_{max}$ – істен шығуға дейінгі рұқсат етілетін ауытқу), ал жағдайдың интегралдық көрсеткіші салмақталған қосынды ретінде $D(t) = \Sigma\, w_e \cdot \eta_e(\xi)$ болады. Бұрандалы компрессорлардың истен шығу статистикасы негізінде салмақтар w_p = 0,20; w_t = 0,30; w_v = 0,35; w_i = 0,15 деп қабылданды – діріл мен температураға жоғары салмақ берілуі олардың подшипник тозуы мен қызып кетуге сезімтал болуымен түсіндіріледі.

Істен шығу қарқындылығы және сенімділік функциясы

Ескіретін жабдық үшін істен шығу қарқындылығы уақыт өткен сайын артады, сондықтан Вейбулл моделі қолайлы:

$$\lambda(t) = \frac{k}{\theta}\left(\frac{t}{\theta}\right)^{k-1} \qquad (4)$$

мұнда k – форма параметрі (k > 1 тозатын жабдыққа сәйкес);

θ – сипаттамалық уақыт.

Тоқтаусыз жұмыс пен істен шығу ықтималдығы сенімділік функциясы арқылы байланысады:

$$P_e(t) = 1 - \exp\left(-\int_0^t \lambda(\tau)\, d\tau\right) \qquad (5)$$

Тұрақты λ үшін бұл $P_e(t) = 1 - \exp(-\lambda \cdot t)$ экспоненциалды түріне келеді. Жұмыста істен шығу қарқындылығы жағдайдың интегралдық көрсеткішінің функциясы ретінде қабылданады:

$$\lambda(t) = \lambda_0 \exp\big(\beta\, D(t)\big) \qquad (6)$$

мұнда λ_0 – номиналды режимдегі негізгі істен шығу қарқындылығы; β – λ-ның интегралдық жағдайға сезімталдық коэффициенті.

Бұл қатынастар компрессордың деградация моделін толық анықтайды және оқыту деректерін генерациялау кезінде эталондық $P_e(t)$ функциясы ретінде қызмет етеді. Деградация моделінің сандық параметрлері 1-кестеде берілген.

1-кесте – Бұрандалы компрессор деградация моделінің параметрлері

Параметр	Белгіленуі	Номинал	Шегі
Шығыс қысымы	P_{nom}	10,0 бар	± 2,5 бар
Шығыс ауа температурасы	T_{nom}	70 °C	+ 35 °C
Корпус діріл жылдамдығы	V_{nom}	2,5 мм/с	+ 9 мм/с
Қозғалтқыш тогы	I_{nom}	120 А	+ 40 А
Негізгі істен шығу қарқындылығы	λ_0	$1{,}5 \cdot 10^{-5}$ 1/сағ	—
Сезімталдық коэффициенті	β	4,5	—

Зерттеу әдіснамасы

Синтетикалық деректерді генерациялау

Нақты істен шығу деректеріне қол жеткізу шектеулі болғандықтан, PdM жұмыстарында кең тараған тәсіл қолданылды – деградацияның тән үлгілерін көрсететін синтетикалық деректер жиынын қалыптастыру, бұл нәтиженің қайталануын және эталондық $P_e(t)$ бойынша болжам сапасын дәл бағалауды қамтамасыз етеді. MATLAB ортасында үш режим генерацияланды: қалыпты пайдалану, біртіндеп деградация және сыни істен шығу (әрқайсысы 4000 санақ). Сыни режимде алғашқы 2600 санақ қалыпты жұмысқа, қалған 1400 санақ p(t) = k·(t/T)^1,7 суперсызықты заңымен күшейетін апатқа сәйкес келеді. Дискретизация 1 Гц (Modbus/Profinet сұрау жиілігіне сай), жиынтық көлемі бес параметр бойынша 12000 санақ.

Деректерді алдын ала өңдеу

Модельге беру алдында деректер өңделеді: үш сигма ережесімен ($|\xi - \mu| > 3\sigma$) аномалиялар жойылып, барлық белгілер Min-Max әдісімен [0; 1] аралығына нормаланады. Деградация моделі бойынша эталондық $P_e(t)$ мақсаттық айнымалысы есептеліп, жіктеу үшін 0,5 шегімен екілендіріледі. LSTM үшін ұзындығы 20, ығысуы 1 сырғанау терезелері құрылады. Деректер random_state = 42 параметрімен 75/25 бөлінеді: оқу іріктемесі 9000 санақ (LSTM үшін 8980 терезе), тест 3000 санақ (2995 терезе).

Кездейсоқ орман моделін іске асыру

Кездейсоқ орман (Random Forest) – шешім ағаштарының болжамдарын орташалайтын ансамбльдік әдіс. Регрессияда болжам ағаштардың орташа мәні ретінде анықталады:

$$\hat{y}(x) = \frac{1}{N}\sum_{i=1}^{N} T_i(x) \qquad (7)$$

мұнда N – ансамбльдегі ағаштар саны;

$T_i(x)$ – x кіріс векторы үшін i-ші ағаштың болжамы.

Әр ағаш бутстрап-іріктемеде оқытылып, түйіндерде белгілердің кездейсоқ ішкі жиыны таңдалады, бұл ансамбльдің жалпылауын арттырады. MATLAB Statistics and Machine Learning Toolbox-тегі TreeBagger келесі гиперпараметрлермен қолданылды: ағаштар саны N = 80; максималды тереңдік 8; жапырақтағы минималды объект 10; бөлуде $\sqrt{d} \approx 2$ белгі; критерий регрессияда MSE, жіктеуде Gini. Олар бес блокты айқас валидациясы бар Grid Search арқылы таңдалды: N < 50-де дисперсия жоғары, N > 120-да жақсару елеусіз, ал тереңдік 10 артық оқытуға әкелді. Әдістің шектеуі – уақыттық құрылымды ескермеу; оны ішінара өтеу үшін белгілер векторына өңдеу уақыты H қосылды.

LSTM моделін іске асыру

LSTM (Long Short-Term Memory) – уақыттық қатарлардағы ұзақ мерзімді тәуелділіктерді өңдейтін рекуррентті желі. Ұяшық ұмыту f_t, кіріс i_t, шығыс o_t қақпалары мен C_t күйінен тұрады және мына теңдеулермен сипатталады:

$$\begin{aligned} f_t &= \sigma\big(W_f \cdot [h_{t-1}, x_t] + b_f\big), \quad i_t = \sigma(W_i \cdot [h_{t-1}, x_t] + b_i) \\ C_t &= f_t \odot C_{t-1} + i_t \odot \tanh(W_C \cdot [h_{t-1}, x_t] + b_C) \\ o_t &= \sigma(W_o \cdot [h_{t-1}, x_t] + b_o), \quad h_t = o_t \odot \tanh(C_t) \end{aligned} \qquad (8)$$

мұнда σ – сигмоид; ⊙ – элемент бойынша көбейту; W, b – оқытылатын параметрлер; h_t – жасырын шығыс.

Желі архитектурасы: 5 кіріс белгі → 64 нейронды LSTM қабаты → Dropout 0,2 → ReLU-мен 16 нейронды толық қосылған қабат → сигмоидты 1 нейронды шығыс. Оқытылатын параметрлер 18 241. Оқыту: оптимизатор Adam (қадам 0,001), шығын MSE, мини-пакет 32, эпох 50, валидацияда 8 эпох жақсармаса ерте тоқтату. Adam бейімделгіш қадам мен инерцияны біріктіріп, рекуррентті желілердегі градиенттің жойылу/жарылу мәселесін жеңілдетеді.

Болжам сапасын бағалау метрикалары

Модель сапасын регрессия мен жіктеу метрикаларының жиынымен бағалайды. $P_e(t)$-ні үздіксіз шама ретінде бағалайтын негізгі регрессия метрикасы – орташа квадраттық қателіктің түбірі (RMSE):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \qquad (9)$$

онымен қатар орташа абсолютті қателік $MAE = (1/n)\cdot\Sigma|y_i - \hat{y}_i|$ есептеледі. Болжамды 0,5 шегі бойынша екілендіргеннен кейінгі негізгі жіктеу метрикасы – дәлдік (Accuracy):

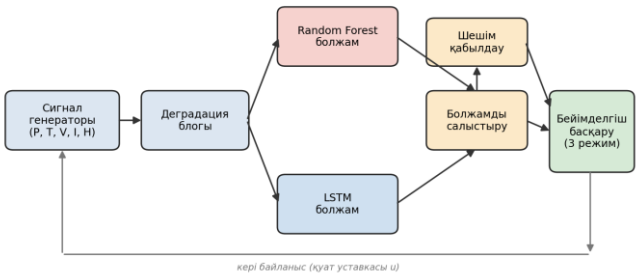
$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \qquad (10)$$

сондай-ақ нақтылық Precision = TP/(TP+FP), толықтық Recall = TP/(TP+FN) және шектен тәуелсіз AUC (ROC қисығының астындағы аудан) қолданылады. Бүкіл жүйені бағалау үшін арнайы метрикалар есептеледі: алдын алынған істен шығулар саны, ертерек анықтау уақыты, апаттық тоқтатулар санының төмендеуі және басқару әсерінің дисперсиясы σ^2_u.

Жүйенің Simulink-моделі және бейімделгіш басқару

Модель құрылымы және функционалдық блоктар

Болжамды басқару жүйесінің имитациялық моделі MATLAB R2025a Simulink ортасында іске асырылды – Deep Learning Toolbox және Statistics and Machine Learning Toolbox блоктарымен бірге жұмыс істеу мүмкіндігі үшін. Модельдің құрылымдық сызбасы 1-суретте берілген.



1-сурет – Болжамды басқару жүйесінің Simulink-моделінің құрылымдық сызбасы

Модельдегі сигналдық ағындар былай ұйымдастырылған. Сигнал генераторы блогы төрт өлшеу арнасын (P, T, V, I) және есептік өңдеу уақыты H арнасын қалыптастырады; әр арнаға тиісті номинал (қысым 8,0 бар, температура 70 °C, діріл 2,5 мм/с, ток 120 А) мен Гаусс шуы беріледі. Сигналдар деградация блогына түсіп, таңдалған

сценарийге сай стационарлық емес тренд жүктеледі. Нәтижедегі бесарналы ағын параллель түрде кездейсоқ орман және LSTM блоктарына беріледі, олардың әрқайсысы $P_e(t)$ бағасын шығарады; екі болжам салыстыру блогына түседі, мұнда олардың арасындағы айырма (белгісіздік индикаторы) есептеліп, нәтижелік болжам қалыптасады.

Болжамдарды біріктіру салмақталған қосынды бойынша орындалады:

$$\hat{y}(t) = w_{RF}\,\hat{y}_{RF}(t) + w_{LSTM}\,\hat{y}_{LSTM}(t) \qquad (11)$$

мұнда w_RF, w_LSTM – модель болжамдарының салмақтары.

Негізгі сценарийде салмақтар тұрақты және w_RF = 0,4, w_LSTM = 0,6 деп қабылданды, бұл LSTM-ның уақыттық тізбектердегі жоғары дәлдігін ескереді. Кеңейтілген сценарийде салмақтар соңғы 100 санақтағы әр модель сапасының сырғанаушы бағасы негізінде бейімделіп есептеледі.

Бейімделгіш басқару алгоритмі

Бейімделгіш басқару алгоритмі компрессордың үш жұмыс режиміне сәйкес ақырғы автомат болып табылады (дискретизация периоды T_s = 1 с). Әр тактіде датчиктерден алынған санақтар нормаланып, екі болжам блогына беріледі; болжамдар (11) бойынша біріктіріледі; гистерезисі бар шекті логика режимді анықтайды. Режим таңдау: егер $\hat{y}(t) \le 0{,}5$ болса m = 0 (қалыпты), $0{,}5 < \hat{y}(t) \le 0{,}8$ болса m = 1 (сақтық), $\hat{y}(t) > 0{,}8$ болса m = 2 (сыни). Режимнің «дірілдеуін» болдырмау үшін ені 0,05 гистерезис ілгегі енгізілген. Әр режимге сәйкес қуат уставкасы: m = 0 кезінде u = 1,00, m = 1 кезінде u = 0,60, m = 2 кезінде u = 0,15. Режимдер арасындағы тегіс өту апериодикалық буынмен сипатталады:

$$\frac{du}{dt} = \frac{u_{target} - u}{T_t} \qquad (12)$$

мұнда u_target – ағымдағы режимнің мақсатты уставкасы;

T_t – өтудің уақыт тұрақтысы (15 с).

Гистерезис пен тегіс өтуді қолдану басқару контурының болжамдағы кездейсоқ ауытқуларға тұрақтылығын қамтамасыз етеді. Алгоритмнің бейімділігі екі тетікпен жүзеге асады: салыстыру блогында екі модель болжамын бейімделгіш салмақтау және алдыңғы апаттық оқиғаларды талдау бойынша шекті мәндерді қайта реттеу.

Басқару тиімділігінің критерийі

Басқару тиімділігін сандық бағалау үшін (2) формуласында енгізілген үш құрамдас бөлігі бар интегралдық критерий қолданылады:

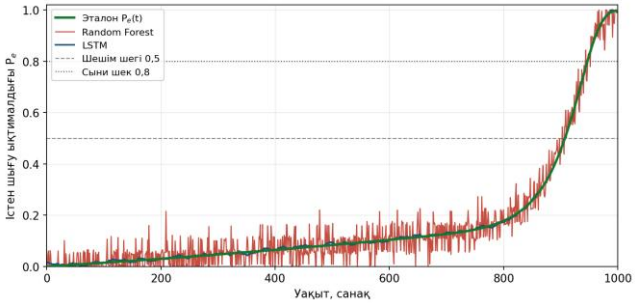
$$J = \alpha\,E[P_e(t)] + \beta\,N_{av}(t) + \gamma\,\sigma_u^2(t) \qquad (13)$$

Салмақтар жүйенің экономикалық басымдылықтарына негізделеді: α = 1,0, β = 0,5, γ = 0,2, яғни істен шығудың алдын алуға бірінші, апаттық тоқтатуларды азайтуға екінші, режим тұрақтылығына үшінші басымдылық беріледі. Мұндай тұжырым Марков шешімдер процесі тәсіліне сәйкес келеді; практикада критерий тікелей (13) бойынша есептеледі.

Нәтижелер

Жүйе төрт сценарийде бағаланды: қалыпты пайдалану, біртіндеп деградация, сыни істен шығу және қосымша шуы бар үйлестірілген режим (σ = 0,1); әр сценарийде 50 тәуелсіз жүгіріс орындалып, мәндер орташаланды. Кездейсоқ орман 9000 санақтан тұратын оқу іріктемесінде Intel Core i7-11700 процессорында 12,4 с-та, LSTM 8980 терезеде 29,1 с-та оқытылды. Тест іріктемесіндегі метрикалар: кездейсоқ орман – RMSE = 0,062, дәлдік 98,7 %, AUC = 0,9942; LSTM – RMSE = 0,051, дәлдік 99,4 %, AUC = 0,9943. Permutation importance бойынша ең ықпалды белгілер – діріл V (0,284) мен температура

Т (0,241), бұл деградация моделіндегі салмақтармен үйлеседі. Екі модельдің болжамы 2-суретте, толық салыстыру 2-кестеде берілген.



2-сурет – Кездейсоқ орман және LSTM модельдерінің істен шығу ықтималдығын болжауы

2-кесте – Кездейсоқ орман және LSTM модельдерінің салыстырмалы бағасы

Метрика	Random Forest	LSTM	Үздік модель
RMSE	0,0623	0,0510	LSTM (−18,1 %)
MAE	0,0259	0,0294	RF (−11,9 %)
Accuracy	0,9867	0,9937	LSTM (+0,7 %)
Precision	0,9669	0,9889	LSTM (+2,3 %)
Recall	0,9669	0,9811	LSTM (+1,5 %)
AUC	0,9942	0,9943	пара-пар
Оқыту уақыты, с	12,4	29,1	RF (2,3 есе)
Инференс уақыты, мс	0,23	1,45	RF (6,3 есе)

LSTM болжам дәлдігі бойынша басым (RMSE 18,1 %-ға төмен), ал кездейсоқ орман есептеу тиімділігі бойынша (2,3 есе жылдам оқыту, 6,3 есе жылдам инференс), бұл ендірілген контроллерлер үшін маңызды. Шуға тұрақтылықта да LSTM үздік: σ = 0,2 кезінде оның RMSE мәні 0,070, ал кездейсоқ орманда 0,104 (48 % айырма), өйткені LSTM 20 санақтық терезеде толқуларды орташалайды. Сондықтан өнімді жүйеде екі модельді салмақталған біріктіру орынды.

Басқару тиімділігінің метрикалары

Жүйенің тиімділігі әрқайсысы 4000 с-тан тұратын 50 жүгірістен құралған үш серияда бағаланды: машиналық оқытусыз, кездейсоқ орманмен және LSTM-мен басқару. ML-сіз серия тек аппараттық шектен шығу бойынша тоқтайды (ең көп жоспарланбаған тоқтау), ал ML сериялары тоқтату болжанған ықтималдықтың өсуі бойынша қауіпсіз орындалады. Жиынтық метрикалар 3-кестеде берілген.

3-кесте – Басқару жүйесі тиімділігінің жиынтық метрикалары

Көрсеткіш	ML-сіз	RF	LSTM
Орташа істен шығу саны	7,24	2,80	1,62
Істен шығуды азайту, %	—	61,3	77,6
Ертерек анықтау, с	0	210	340
Апаттық тоқтатулар саны	7,24	0,84	0,36

Көрсеткіш	ML-сіз	RF	LSTM
Апаттарды азайту, %	—	88,4	95,0
Уставка дисперсиясы σ^2_u	0,31	0,08	0,05

Нәтижелерді талдау болжамды басқару жүйесін қолдану істен шығу санын кездейсоқ орман үшін 2,6 есе, LSTM үшін 4,5 есе азайтатынын және ертерек анықтау уақытын 340 с-қа дейін арттыратынын көрсетеді. Бұл уақыт персоналға жабдықты қауіпсіз тоқтатуға және диагностикалауға жеткілікті. Уставка дисперсиясының төмендеуі жабдықтың тұрақтырақ жұмыс режимін куәландырады.

Талқылау

Алынған нәтижелер қойылған міндеттердің орындалғанын және ұсынылған жүйенің компрессорды пайдалану сенімділігі мен тиімділігін сандық расталған түрде жақсартатынын көрсетеді. Екі модельді салыстыру практикалық тұрғыдан маңызды қорытынды береді: дәлдік пен шуға тұрақтылық LSTM жағында, ал есептеу үнемділігі кездейсоқ орман жағында, демек нақты жүйеде оларды режимге қарай таңдау немесе салмақталған комбинациялау орынды.

Алынған көрсеткіштер әдебиеттегі деректермен үйлеседі. Атап айтқанда, ауа компрессорын мониторингтеуге арналған терең оқыту жүйелері жоғары дәлдікке жететіні [8], ал IoT негізіндегі PdM жүйелері апаттық тоқтаулар санын едәуір қысқартатыны [7] көрсетілген. Tian [5] мен Shoorkand [6] ұсынған гибридті рекуррентті желілермен салыстырғанда, бұл жұмыстың қосымша үлесі – екі түрлі табиғаттағы модельді (ансамбльдік және рекуррентті) бірыңғай деректер жиынында тікелей салыстыру және олардың болжамын бейімделгіш басқару контурына біріктіру. Зерттеудің шектеуі – синтетикалық деректерді пайдалану; нақты өнеркәсіптік деректердегі валидация келешек жұмыс бағыты болып қала береді.

Қорытынды

Зерттеуде бұрандалы ауа компрессорының мысалында бейімделгіш басқаруы бар жабдықтың істен шығуын болжау жүйесін әзірлеу міндеті шешілді. Негізгі нәтижелер:

– деградацияның математикалық моделі әзірленіп, үш режимді қамтитын 12000 санақтан тұратын синтетикалық деректер жиыны қалыптастырылды, оның негізінде кездейсоқ орман (80 ағаш, тереңдігі 8) және LSTM (64 нейрон, 20 санақ терезесі) модельдері 75/25 бөлумен оқытылды;

– салыстырмалы талдау LSTM-ның болжам дәлдігі мен шуға тұрақтылығы бойынша (RMSE = 0,051; дәлдік 99,4 %), ал кездейсоқ орманның есептеу жылдамдығы бойынша (оқыту 2,3 есе, инференс 6,3 есе жылдам) басым екенін көрсетті;

– Simulink-те гистерезисі бар үш режимді бейімделгіш басқару жүйесі құрылып, эксперименттер LSTM қолданғанда істен шығу санын 4,5 есе азайтуды және ертерек анықтауды 340 с-қа дейін арттыруды растады.

Жұмыстың ғылыми жаңалығы – екі машиналық оқыту моделінің болжамын бейімделгіш реттелетін салыстыру блогы арқылы біріктіретін сәулет және әр модельдің тиімділікке қосатын үлесін сандық бағалау. Практикалық нәтиже – модель таңдаудың айқын критерийі: қарапайым режимде кездейсоқ орман, күрделі өтпелі және шулы режимде LSTM, ал гибридті комбинация екі артықшылықты біріктіреді. Әзірленген MATLAB/Simulink моделі нақты жағдайларға бейімдеу арқылы прототип ретінде қолданылуы мүмкін. Дамыту перспективалары: көпкомпрессорлық қондырғыға кеңейту,

CNN-LSTM және Transformer архитектуралары, болжам белгісіздігін байесиандық бағалау, SHAP-талдау және нақты деректердегі валидация. Нәтижелер «Цифрлы Қазақстан» басымдықтарына сай және сорғылар, вентиляторлар, турбиналар сияқты ұқсас жабдыққа да қолданылады.

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FROM LEAF DIAGNOSIS TO YIELD FORECASTING: COMPARATIVE STUDY OF CNN AND VGG16 FOR CROP HEALTH MONITORING

Abstract: This work compares two convolutional neural network architectures for plant disease classification: a self-designed CNN trained from scratch and a pre-trained VGG16 model fine-tuned on a PlantVillage-derived dataset. Both models were trained for 10 epochs under identical Keras/TensorFlow pipelines and evaluated on a held-out validation set. The VGG16 model outperformed the custom CNN with a top-1 accuracy of 0.822 and a macro-F1 of 0.796, exceeding the CNN by 0.068 in macro-F1 (CNN accuracy 0.776, macro-F1 0.728), and also showed lower log-loss (0.5346 vs. 0.7310). However, the CNN demonstrated substantially faster inference: 4.075 ms per image versus 73.6 ms for VGG16, with a throughput of 245.42 img/s compared to 13.59 img/s. The results indicate a trade-off between accuracy and inference speed, which is critical for real-time applications in edge computing for precision agriculture. Model performance is discussed in relation to dataset biases, class imbalance, and the future integration of disease probability predictions with crop yield forecasting models.

Keywords: precision agriculture, plant disease detection, convolutional neural networks, VGG16, transfer learning, crop health monitoring, yield prediction, deep learning, computer vision.

1. Introduction

Crop health assurance at scale forms the foundation of global food security, climate resilience, and sustainable agronomy. With increasing demands for efficient agricultural practices, there is a growing reliance on precision agriculture and machine learning techniques. Deep learning has recently emerged as the leading approach for plant disease detection [1, 2, 6], facilitated by publicly available datasets such as PlantVillage. These models, especially convolutional neural networks (CNNs), are able to leverage transferable feature hierarchies learned on large-scale natural-image datasets to achieve state-of-the-art results on controlled imagery.

While such models generally perform well on laboratory-style images, their performance in field conditions can be less predictable. Field deployments require a careful balance between accuracy, latency, and model footprint. Transfer learning from pre-trained ImageNet models such as VGG16 and ResNet generally achieves strong accuracy with moderately sized datasets [2, 7], although such models can be computationally expensive, especially in real-time or edge-based applications. By contrast, lightweight CNNs trained from scratch allow for faster

inference and smaller footprints, making them suitable candidates for deployment on resource-constrained devices such as mobile phones or low-cost agricultural sensors [8].

This work investigates the trade-off between accuracy and efficiency in plant disease recognition. We compare the performance of a compact CNN trained from scratch with that of a VGG16 model using transfer learning, both trained within a unified 10-epoch budget in TensorFlow/Keras. A comprehensive evaluation is conducted along several dimensions: prediction quality (macro/weighted metrics, log-loss), error structure (confusion matrices, ROC/PR curves), and computational performance (latency, throughput, model size). We also review how these models can be used to produce plot-level disease indicators that feed into yield prediction systems [4, 5].

2. Related Work

2.1. Deep learning for plant disease recognition

Recent surveys have pointed out that the pace of research on deep learning for plant disease and pest detection is growing rapidly [1, 3, 6]. CNN models have proved highly effective at recognizing plant diseases under ideal conditions. However, their performance on real field data can significantly degrade due to domain shift and dataset bias, as they are often trained on datasets such as PlantVillage, where images are captured in controlled lighting with homogeneous backgrounds. It has been observed that performance can be improved through data augmentation and domain adaptation methods that enable the model to generalize across variations in environmental conditions: lighting, occlusions, and background clutter [2]. Hybrid models combining CNNs with other techniques, such as transformers or decision trees, have also been proposed to improve robustness across a wide range of field scenarios.

2.2. Transfer learning and VGG baselines

Transfer learning is a common technique in plant disease detection, particularly when starting from pre-trained models such as VGG16 trained on large datasets like ImageNet [2, 7, 9]. VGG16 remains a competitive baseline due to its stable optimization and strong low- and mid-level feature extraction. Its ability to generalize across plant species and diseases has made it a common choice for transfer learning. More recent architectures, such as EfficientNet, ConvNeXt, and Vision Transformers, show promise for state-of-the-art performance across a wide variety of vision tasks, but VGG16 provides a reliable and interpretable starting point for controlled comparisons in plant disease detection, especially when computational resources are constrained.

2.3. Lightweight and explainable CNNs

With the growing demand for real-time applications in precision agriculture, lightweight CNNs have attracted significant attention since they balance performance with computational efficiency. These models are designed to reduce the number of parameters and memory usage while delivering competitive accuracy. Recent research has focused on creating compact and explainable CNN architectures tailored to agricultural imagery, which typically includes high-resolution images of plant leaves with fine-grained details [8]. For field conditions, several studies have considered robust multi-branch designs to handle variations in input data, such as plant type variations or environmental factors like weather and soil conditions [10]. These lightweight models offer substantial advantages for wider applicability on edge devices used for real-time monitoring of crop health.

2.4. From diagnosis to yield prediction

The integration of disease detection models with crop yield prediction systems is an emerging research area. Yield forecasting increasingly relies on multi-source signals, such as weather data, soil moisture, and remote sensing, combined with plant health indicators derived from imagery [4, 5, 11]. The accuracy of yield predictions depends on the ability to produce calibrated disease probabilities from deep learning models. These disease probabilities can serve as upstream covariates in predictive models that estimate crop yield based on environmental factors and plant health status. Temporal and spatial aggregation of disease probabilities has been shown to enhance prediction accuracy, making disease detection a highly relevant component in precision agriculture.

3. Materials and Methods

3.1. Dataset

We use a PlantVillage-derived collection (Kaggle "New Plant Diseases Dataset", approximately 87,000 RGB images, 38 classes) and focus on a 15-class subset (pepper, potato, tomato: healthy and multiple diseases), consistent with common practice [2, 12]. The dataset is structured into train, validation, and test splits. The training set consists of 16,516 images, the validation set contains 4,122 images, and the test set consists of 20,638 images. We preserve the train/validation/test semantics to ensure that evaluation is performed on a held-out dataset.

3.2. Preprocessing and augmentation

All images are resized to 224 × 224 pixels and normalized using a unified Keras preprocessing pipeline. Data augmentation is applied only during the training phase using the ImageDataGenerator class. The following augmentations are applied: rescale=1./255 (normalizing pixel values to [0, 1]); rotation_range=40 (random rotations up to 40 degrees); width_shift_range=0.2 and height_shift_range=0.2 (random horizontal and vertical shifts); shear_range=0.2 (random shearing); zoom_range=0.2 (random zoom); horizontal_flip=True (random horizontal flips); fill_mode='nearest' (for filling newly created pixels during transformations). The same preprocessing and augmentation settings are used for both CNN and VGG16 models to ensure a fair comparison.

3.3. Architectures

CNN (custom). A compact convolutional network built from scratch, consisting of 6 Conv2D layers followed by 6 MaxPooling2D layers, with an input shape of 224×224×3. The architecture includes: a sequential stack of convolutional layers with increasing filter sizes (32, 64, 128); flattening of the feature map after the last pooling layer; dense layers with 128 units each, followed by a Dropout(0.5) layer between dense layers to avoid overfitting. The network ends with a softmax layer, where the number of neurons corresponds to the number of classes. This configuration is designed to balance model complexity and fast inference speed.

VGG16 (transfer learning). We use a pre-trained VGG16 model from Keras, excluding the top layers (include_top=False), with ImageNet weights initialized. The VGG16 base model remains frozen, and we add: a GlobalAveragePooling2D layer to reduce spatial dimensions; a dense layer with 128 units, followed by another dense layer with num_classes units (one per class). The model is trained using transfer learning, with the weights of the base layers frozen, ensuring that only the newly added layers are trained. This setup follows standard transfer learning practice [2, 7].

3.4. Training protocol and environment

Both models are trained for 10 epochs with a batch size of 32. We use the Adam optimizer with a learning rate of 1×10^{-3}, categorical cross-entropy loss, and accuracy as the evaluation metric. The models were implemented in Keras/TensorFlow.

Table 1 – Model configurations and footprint

Model	Pretrain	Params (M)	Size (MB)	Epochs
CNN (custom)	No	11.171	127.886	10
VGG16 (TL)	ImageNet	14.782	56.991	10

3.5. Evaluation metrics

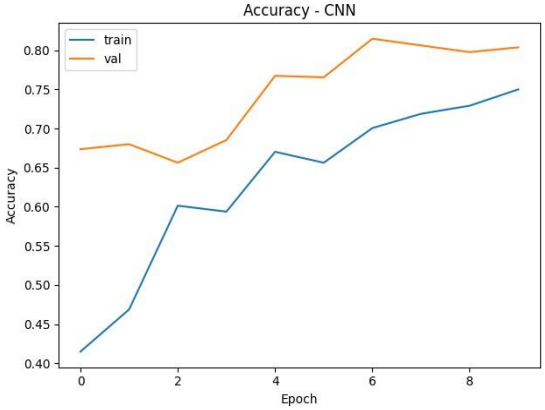
We evaluate both models using several performance metrics: accuracy (proportion of images correctly classified); macro-F1 (average F1 score across all classes, treating all classes equally); weighted-F1 (F1 score averaged across classes, weighted by the number of true instances per class); precision and recall (per-class positive predictive value and sensitivity); log-loss (cross-entropy loss, reflecting prediction uncertainty); top-3 accuracy (share of images for which the true class is among the top 3 predictions); confusion matrices (both raw counts and row-normalized, to assess per-class performance); ROC and precision-recall curves (plotted for each class to analyze true positive rate and precision at various thresholds); and runtime characteristics (inference time per image in milliseconds and throughput in images per second).

4. Results and Discussion

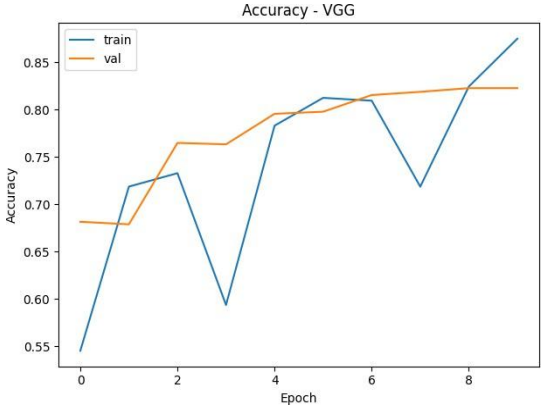
4.1. Overall performance

The models were evaluated on a test set consisting of 20,638 images. Fig. 1 shows the learning dynamics over the 10 training epochs, and Table 2 presents the primary metrics for both models. The VGG16 model consistently outperformed the CNN model on all key performance metrics. Specifically, VGG16 achieved a higher top-1 accuracy (0.822) compared to the CNN (0.776), as well as a significantly better macro-F1 score (0.796 vs. 0.728) and balanced accuracy (0.792 vs. 0.724). The log-loss was also substantially lower for VGG16 (0.5346 vs. 0.7310), indicating better-calibrated probability estimates.

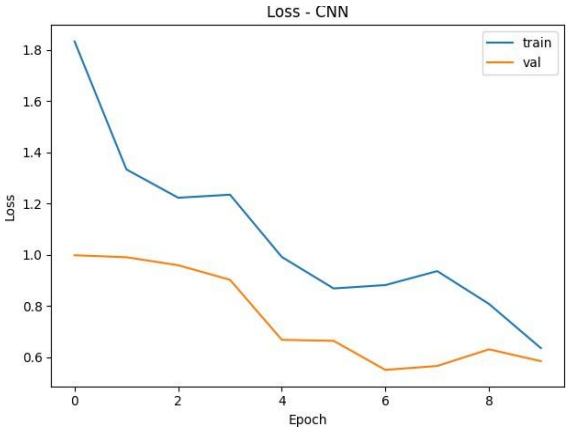
While VGG16 showed superior performance in terms of accuracy and loss, the CNN demonstrated a clear advantage in computational efficiency. The CNN processed images at a rate of 245.42 images per second, significantly faster than VGG16 (13.59 images per second). Moreover, the inference time per image was much lower for the CNN (4.075 ms/image) compared to VGG16 (73.6 ms/image). This highlights a crucial trade-off between accuracy and speed, particularly important for real-time applications in resource-constrained environments.

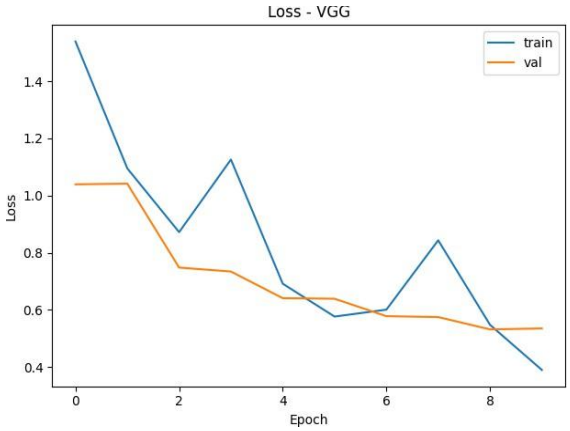


(a) Accuracy — CNN



(b) Accuracy — VGG16



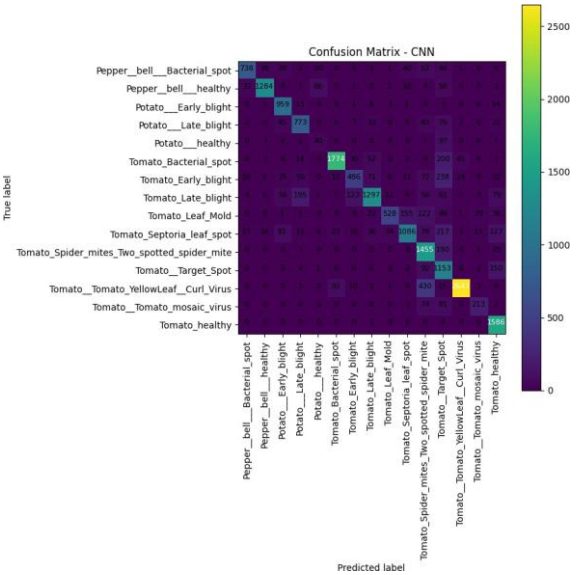


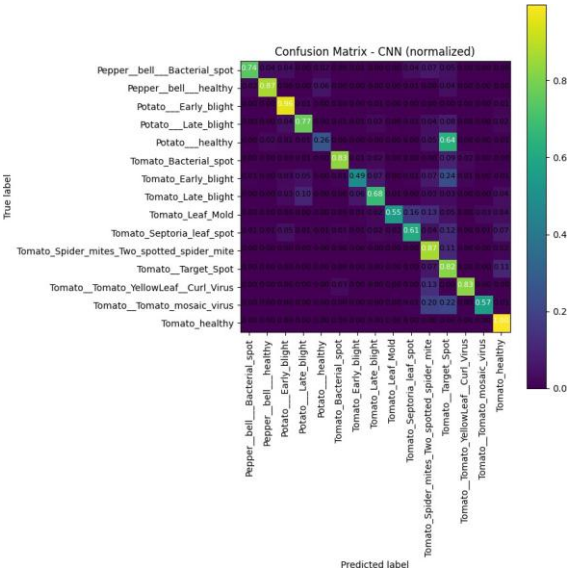
(c) Loss — CNN *(d) Loss — VGG16*

Fig. 1. Learning curves across 10 epochs.

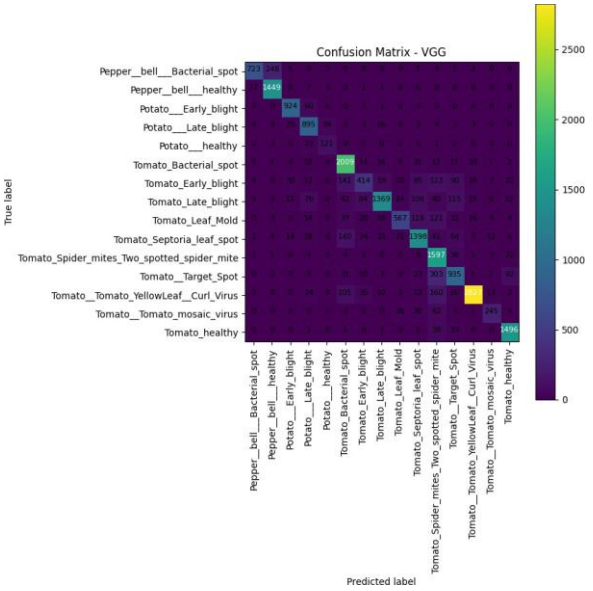
Table 2 – Overall metrics (test set)

Metric	CNN	VGG16
Accuracy	0.776	0.822
Balanced accuracy	0.724	0.792
Precision (macro)	0.764	0.820
Recall (macro)	0.724	0.792
F1 (macro)	0.728	0.796
Precision (weighted)	0.814	0.833
Recall (weighted)	0.776	0.822
F1 (weighted)	0.780	0.819
Log-loss ↓	0.731	0.535
Top-3 accuracy	0.950	0.964

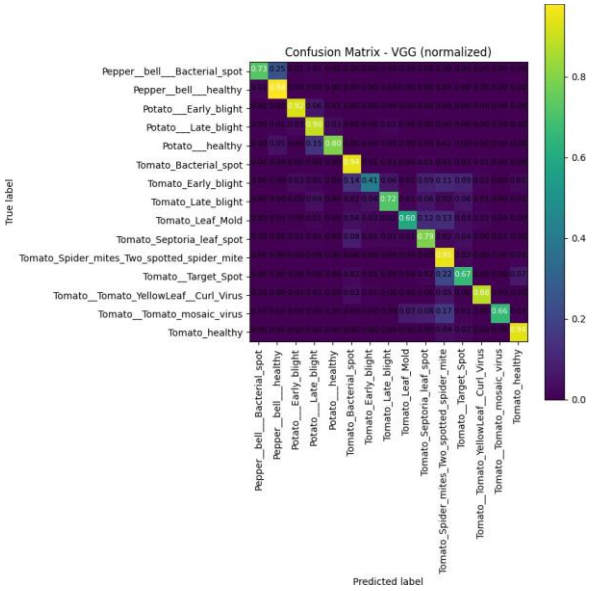




(a) CNN (counts) *(b) CNN (row-normalized)*



(c) VGG16 (counts)



(d) VGG16 (row-normalized)

Fig. 2. Confusion matrices on the test set.

4.2. Training efficiency vs. accuracy

The CNN model was trained for 10 epochs and outperformed VGG16 in inference speed and throughput, making it well-suited for edge devices and low-latency applications. Given that CNNs are faster to train and infer, the question arises: would increasing the number of epochs improve the CNN's performance to match or surpass VGG16? Extending the CNN's training to more epochs (e.g., 30 or 50) might be expected to improve accuracy. However, the VGG16 model — pre-trained on ImageNet — would likely continue to outperform the CNN, especially in macro-F1 and log-loss. Transfer learning leverages features learned from a much larger, diverse dataset, providing a stronger feature extraction foundation for the specific task of plant disease classification. By contrast, training a CNN from scratch requires more data and epochs to match the performance of pre-trained models, especially for complex tasks where fine-tuned features from large datasets significantly boost performance.

While increasing the number of training epochs for the CNN might increase its accuracy, it would also lead to increased training time, which may diminish the practical advantage of faster inference. A balance must therefore be struck between training time, accuracy, and real-time inference requirements. If maximum accuracy is the priority (e.g., for offline analysis or model retraining), VGG16 remains the superior choice. If real-time monitoring with fast inference is the priority (e.g., field deployments on devices with limited resources), the CNN may be more effective, particularly if extended training leads to further improvements.



(a) Misclassified examples — CNN *(b) Misclassified examples — VGG16*

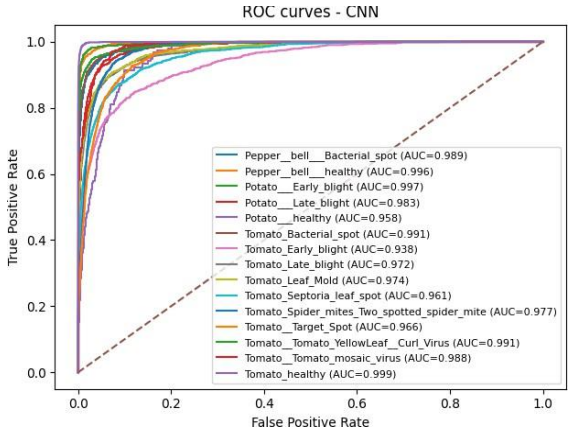
Fig. 3. Qualitative misclassifications.

4.3. Per-class performance and error analysis

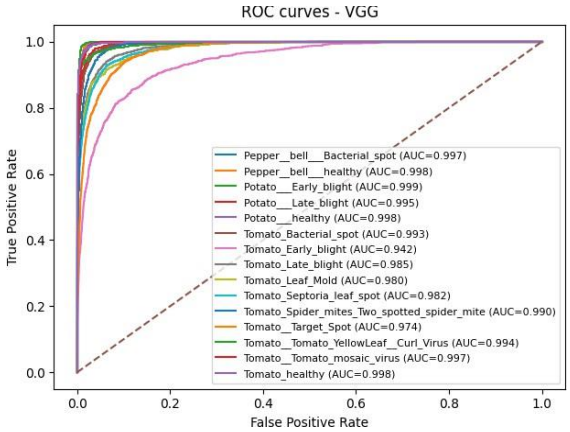
VGG16's higher macro-F1 and balanced accuracy were primarily driven by better performance on classes with lower frequencies and higher ambiguity, as illustrated by the confusion matrices in Fig. 2 and the qualitative misclassifications shown in Fig. 3. For example, VGG16 performed better in distinguishing between diseases that appeared visually similar, such as Potato_healthy versus Potato_Early_blight, and certain tomato diseases like Tomato_Bacterial_spot and Tomato_Early_blight. The transfer-learned features enabled VGG16 to better identify complex patterns and subtle variations in plant disease appearance. By contrast, the CNN model showed stronger performance in terms of speed but often struggled with visual similarity between disease classes that were harder to differentiate, especially under limited training data. As a result, class-specific errors were more pronounced for the CNN, particularly for diseases with similar symptoms such as tomato-related conditions. Per-class ROC and precision-recall curves are presented in Fig. 4.

4.4. Calibration and decision support

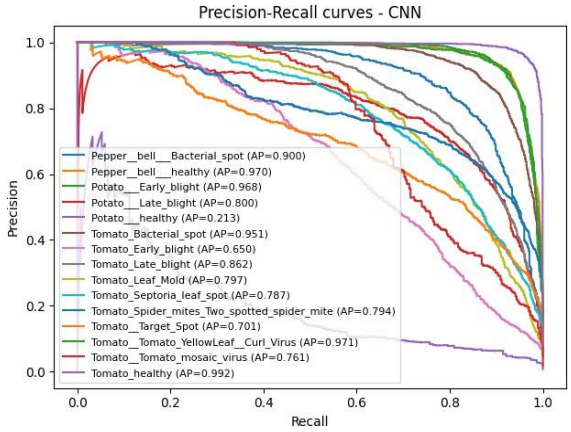
VGG16's lower log-loss indicates that its predictions are more confident and closer to the true labels, making it particularly suitable for applications where calibrated probabilities are important (e.g., disease risk assessment and treatment recommendations). The CNN model, despite its higher log-loss, can still be useful in real-time decision-making scenarios where speed is more important than probability calibration, such as early detection and immediate response systems in agriculture.



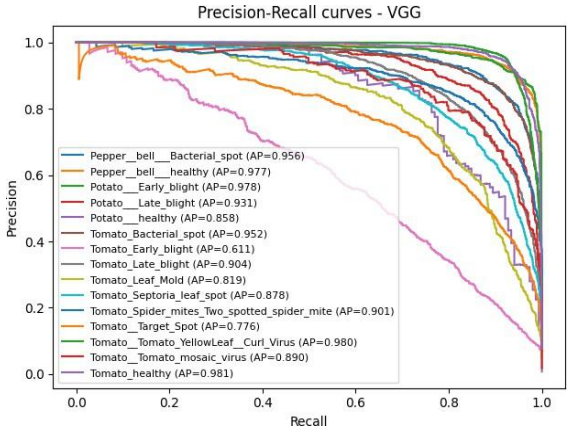
(a) ROC — CNN



(b) ROC — VGG16



(c) PR — CNN



(d) PR — VGG16

Fig. 4. ROC and PR curves for both models.

4.5. From detection to yield prediction

The integration of disease detection models like CNN and VGG16 into broader agricultural systems, such as yield prediction, is an emerging research area. By aggregating disease probabilities from these models, spatiotemporal models can be developed to predict crop yield based on plant health indicators, weather conditions, and soil properties [4, 5]. The disease probabilities generated by VGG16 and CNN can serve as covariates in such models, improving yield prediction accuracy and helping farmers make informed crop management decisions. The ability to rapidly deploy these models on edge devices in the field would enable near real-time monitoring and intervention.

Table 3 – Compute and runtime characteristics (inference)

Model	Latency (ms/img)	Throughput (img/s)	Size (MB)
CNN (custom)	4.075	245.42	127.89
VGG16 (TL)	73.6	13.59	56.99

4.6. Threats to validity

The dataset used in this study consists of controlled imagery, which may not fully reflect the challenges of real-world field conditions. Illumination changes, background clutter, and occlusions are common in field data and can significantly affect model performance. Moreover, the class imbalance present in the dataset could influence the models' ability to generalize,

particularly for underrepresented classes. Future work will focus on domain adaptation techniques to improve generalization to field data [13] and robust augmentation strategies to mitigate the effects of class imbalance [10]. Additionally, while the models were trained for 10 epochs to simulate a quick training process, extending the training duration could improve accuracy, especially for the CNN model. However, this would increase computational time and may still not reach the performance levels of transfer learning with VGG16. Therefore, careful consideration of the application's specific requirements (speed vs. accuracy) should guide model selection.

5. Conclusion

In this study, we compared a custom CNN and a VGG16 transfer-learning model for plant disease classification using the PlantVillage dataset. VGG16 outperformed the CNN in accuracy and macro-F1 score, benefiting from pre-trained features on a large, diverse dataset. The CNN, however, was significantly faster at inference, making it well-suited for real-time applications. Future research will focus on increasing the efficiency of the CNN through extended training and exploring hybrid approaches that combine the strengths of both models. Furthermore, we will investigate the potential of both models for integration into yield prediction systems, with an emphasis on real-time monitoring and decision support for precision agriculture [4, 5].

All experiments were performed on a Lenovo Legion laptop with an AMD Ryzen 5 4600H CPU (average frequency 3.2 GHz) and an NVIDIA GeForce GTX 1660 Ti GPU. The total available memory was 16 GB DDR4. We thank the maintainers of the PlantVillage dataset.

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КАТАЛОГ ТИПОВЫХ СЦЕНАРИЕВ ИНСАЙДЕРСКИХ УГРОЗ И НАБЛЮДАЕМЫХ ИНДИКАТОРОВ КОМПРОМЕТАЦИИ В КОРПОРАТИВНЫХ СЕТЯХ С ПРИВЯЗКОЙ К МАТРИЦЕ MITRE ATT&CK

Аннотация: В работе предлагается структурированный каталог типовых сценариев инсайдерских угроз и связанных с ними индикаторов компрометации, наблюдаемых в трёх доменах телеметрии корпоративной сети — IAM, сетевые журналы и события конечных точек. Сценарии классифицируются по типу инсайдера (неосторожный, злонамеренный, скомпрометированный аккаунт) и по этапам развития инсайдерской цепочки. Каждый сценарий описывается через мотивацию, типовую цепочку действий, набор признаков по доменам телеметрии и привязку к техникам матрицы MITRE ATT&CK Enterprise. Каталог формируется на основе рекомендаций CERT, NIST, открытых наборов детектирующих правил и исследовательских публикаций, и предназначен для использования при разработке SIEM-правил, оценке покрытия детектирования, проектировании обучающих программ для аналитиков SOC и для систематизации угроз при моделировании рисков.

Ключевые слова: инсайдерские угрозы, индикаторы компрометации, MITRE ATT&CK, корреляция событий, IAM, SIEM, EDR, поведенческая аналитика, эксфильтрация данных, повышение привилегий.

Введение. Инсайдерские угрозы остаются одной из наиболее сложных категорий инцидентов информационной безопасности в корпоративных сетях, поскольку нарушитель действует с легитимными правами доступа, а его активность внешне мало отличается от штатных действий пользователя. Стандартные средства, ориентированные на защиту внешнего периметра, плохо обнаруживают такие инциденты [1–3], а команды мониторинга вынуждены анализировать большой объём разнородных сигналов, поступающих из систем управления идентификацией и доступом, сетевых журналов и средств защиты конечных точек. Эффективность обнаружения определяется не только применяемыми алгоритмами, но и качеством описания целевых угроз — конкретных сценариев, наблюдаемых индикаторов и привязки к признакам, которые можно зафиксировать на уровне телеметрии.

Существующие источники по инсайдерским угрозам охватывают разные уровни детализации. Руководства CERT и NIST [1, 2] дают высокоуровневую таксономию и общие рекомендации по противодействию, аналитические отчёты [3] описывают актуальную картину инцидентов и затраты на их устранение, матрица MITRE ATT&CK Enterprise [9] систематизирует тактики и техники атакующих в целом, а наборы открытых детектирующих правил вендоров SIEM и EDR [10–12] предлагают готовые сигнатуры

для конкретных продуктов. Однако между этими источниками существует разрыв: большинство из них либо абстрагированы от инфраструктуры, либо привязаны к одному продукту и одному типу телеметрии. В результате при разработке системы обнаружения инсайдерских угроз приходится самостоятельно выполнять привязку сценариев к индикаторам, а оценка покрытия мер защиты по тактикам ATT&CK становится трудоёмкой и плохо воспроизводимой задачей.

Цель работы — систематизация типовых сценариев инсайдерских угроз с описанием наблюдаемых в корпоративной сети индикаторов компрометации в доменах IAM, сетевых журналов и конечных точек, а также с привязкой к техникам MITRE ATT&CK. Для достижения этой цели в статье определяются классификационные измерения каталога, формат описания сценариев и используемые источники, рассматриваются четыре ключевых сценария с подробным разбором индикаторов, обсуждается типовая временная структура развития инсайдерской цепочки, выполняется сопоставление сценариев с тактиками матрицы ATT&CK Enterprise и обозначается практическое применение каталога в задачах SOC.

Научная новизна работы состоит в том, что предлагаемый каталог одновременно объединяет в одной структуре сценарную классификацию инсайдерских угроз, набор индикаторов компрометации, наблюдаемых в трёх доменах телеметрии, и привязку к матрице MITRE ATT&CK Enterprise, что позволяет использовать его как методологическую основу при разработке детектирующих правил, оценке покрытия и обучении аналитиков SOC.

Методология построения каталога и используемые источники. Каталог формируется на основе анализа открытых методических материалов и исследовательских публикаций по инсайдерским угрозам. В качестве методической базы используются руководство CERT по противодействию инсайдерским угрозам [1], глоссарий и контрольные требования NIST [2, 6], аналитический отчёт Ponemon Institute по стоимости инсайдерских инцидентов [3], а также обзорные исследования по поведенческой аналитике пользователей и сущностей UEBA [4]. Источниками технических индикаторов служат открытые наборы детектирующих правил Microsoft Sentinel [10], Splunk Enterprise Security Content Update [11] и Elastic Detection Rules [12], а также открытые репозитории сигнатур и обзорные работы по применению машинного обучения к инсайдерским сценариям на эталонном наборе CERT Insider Threat Dataset [7, 8]. Отдельным основанием для выделения признаков служит обзор инсайдерских атак и категорий нарушителей, предложенный в [13], где разделяются masqueraders и traitors.

Привязка к матрице MITRE ATT&CK Enterprise [9] выполняется по тактикам, наиболее часто наблюдаемым в инсайдерских инцидентах: Initial Access, Execution, Persistence, Privilege Escalation, Defense Evasion, Credential Access, Discovery, Lateral Movement, Collection, Command and Control, Exfiltration и Impact. Для каждого сценария определяется набор техник, типичных именно для действий легитимного пользователя или скомпрометированной учётной записи, в отличие от внешних атак, где преобладают техники начального проникновения.

Каждое описание сценария в каталоге включает четыре блока: краткую характеристику и мотивацию инсайдера, типовую цепочку действий с разнесением по этапам подготовки, доступа к данным и вывода информации, набор индикаторов компрометации с разделением по доменам телеметрии (IAM, сетевые журналы, события

конечных точек) и сопоставление с техниками MITRE ATT&CK. Такой формат описания обеспечивает единообразие и пригодность каталога для практического использования при настройке систем мониторинга.

Классификация инсайдерских сценариев и формат описания. В работе используется двухмерная классификация сценариев. Первое измерение — тип инсайдера: неосторожный сотрудник, нарушающий правила безопасности из-за ошибок или удобства; злонамеренный инсайдер, действующий с прямым намерением нанести ущерб; и скомпрометированный аккаунт, под которым понимается ситуация, когда действия выполняются атакующим от имени легитимного пользователя. Второе измерение — этап развития инсайдерской цепочки в терминах модели kill chain: начальный доступ, разведка инфраструктуры, повышение привилегий, сбор данных, вывод информации и возможное воздействие на ресурсы. Соответствие типов инсайдеров и этапов цепочки приведено на рисунке 1: для каждого сочетания указана характерная активность и оценка её распространённости в реальных инцидентах.

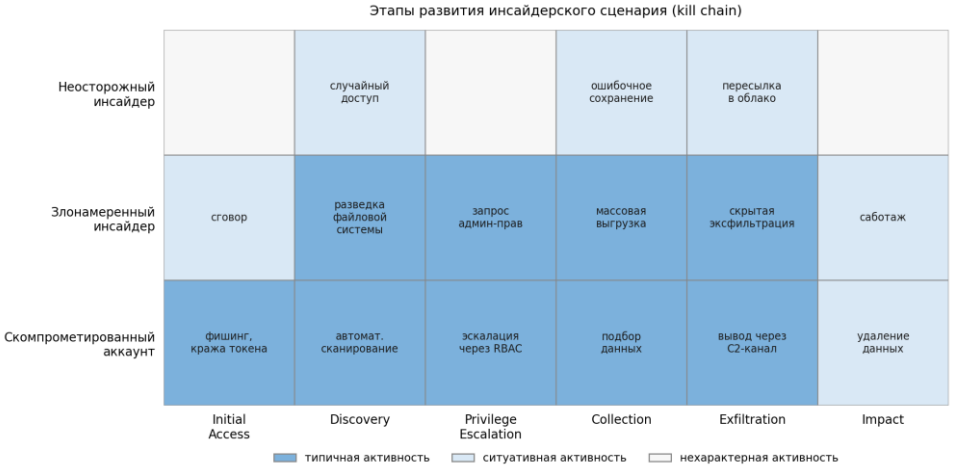


Рисунок 1 – Таксономия инсайдерских сценариев в плоскости «тип инсайдера × этап цепочки»

Из рисунка видно, что злонамеренный инсайдер и скомпрометированный аккаунт покрывают почти всю цепочку kill chain, однако опираются на разные предпосылки и разные исходные сигналы: для злонамеренного инсайдера характерна постепенная подготовка с использованием уже имеющихся привилегий, тогда как для скомпрометированного аккаунта типичны нетипичные ранние сигналы аутентификации (новое устройство, география, время) перед собственно операциями с данными. Неосторожный инсайдер, напротив, локализован преимущественно на этапах разведки и сбора и редко доходит до явного вывода или воздействия. На основе этой классификации в каталог отобраны четыре сценария, представляющие наибольший практический интерес для систем обнаружения и охватывающие как «активную» сторону угрозы (эксфильтрация, повышение привилегий), так и «вспомогательную» (компрометация учётной записи, саботаж и сокрытие следов).

Сценарий 1. Эксфильтрация данных. Эксфильтрация данных включает массовый сбор и вывод информации за пределы защищённого контура — от прямой выгрузки документов на личные почтовые ящики и облачные хранилища до скрытой передачи через нестандартные каналы и туннелирование. Мотивация может варьироваться от персональных целей сотрудника при увольнении до коммерческого

шпионажа или подготовки утечки данных третьим лицам. Типовая цепочка действий начинается с разведки доступных хранилищ, продолжается массовым чтением и подготовкой данных (часто с архивированием и шифрованием) и завершается передачей подготовленных файлов через сетевые каналы — корпоративные или обходные. Эксфильтрация может выполняться в один этап или растягиваться во времени для обхода объёмных порогов и снижения заметности. Согласно отчёту Ponemon Institute [3], именно сценарии вывода данных формируют наибольшую долю прямых финансовых потерь от инсайдерских инцидентов.

Таблица 1 – Индикаторы компрометации сценария «Эксфильтрация данных»

Домен	Индикаторы компрометации	Техники MITRE ATT&CK
IAM	массовый доступ к share-папкам и порталам с конфиденциальными данными; вход с нового устройства или из нетипичной географии перед сессией работы с данными; обращение к ресурсам, нехарактерным для роли пользователя	T1078 – Valid Accounts; T1087 – Account Discovery
Сетевой	аномальный объём исходящего трафика; новые DNS-запросы и соединения с ранее неиспользовавшимися внешними доменами; использование нестандартных портов и протоколов; рост трафика к облачным хранилищам и сервисам передачи файлов	T1041 – Exfiltration Over C2 Channel; T1567 – Exfiltration Over Web Service; T1048 – Exfiltration Over Alternative Protocol
Endpoint	массовое чтение и копирование файлов из общих ресурсов; запуск архиваторов и утилит шифрования; подключение и запись на USB-носители; работа клиентов облачных хранилищ в нестандартное время	T1005 – Data from Local System; T1039 – Data from Network Shared Drive; T1560 – Archive Collected Data; T1052 – Exfiltration Over Physical Medium

Сценарий 2. Повышение привилегий и злоупотребление администраторскими правами. Сценарий охватывает действия, направленные на расширение прав доступа сверх функциональных обязанностей пользователя или на использование уже имеющихся административных привилегий в целях, не связанных с выполнением рабочих задач. Мотивация может состоять как в подготовке к последующей эксфильтрации, так и в самостоятельных действиях — отключении средств защиты, изменении правил доступа или внесении скрытых изменений в инфраструктуру. Типовая цепочка включает разведку структуры групп и ролей, запрос или присвоение новых привилегий, проверку их работоспособности через обращение к ранее недоступным ресурсам и последующие действия с использованием расширенных прав. Особую роль играют сервисные и shared-учётные записи, доступ к которым часто слабо контролируется и может быть использован для маскировки действий конкретного пользователя [4].

Таблица 2 – Индикаторы компрометации сценария «Повышение привилегий»

Домен	Индикаторы компрометации	Техники MITRE ATT&CK
IAM	добавление пользователя в привилегированные группы (Domain Admins, Local Administrators, sudo); назначение новых административных и сервисных ролей; изменение членства в группах вне согласованного процесса; вход под сервисной учётной записью с интерактивных сессий	T1098 – Account Manipulation; T1078.002 – Domain Accounts; T1078.003 – Local Accounts; T1136 – Create Account
Сетевой	сетевые подключения к контроллерам домена и системам IAM с нетипичных хостов; всплеск LDAP-запросов; рост трафика к административным интерфейсам систем после изменения прав	T1018 – Remote System Discovery; T1021 – Remote Services
Endpoint	запуск утилит управления учётными записями и группами (net, dsadd, PowerShell-командлеты Active Directory); запуск процессов от имени учётной записи системы или другого пользователя; отключение или изменение настроек локальных средств защиты	T1059.001 – PowerShell; T1134 – Access Token Manipulation; T1562.001 – Disable or Modify Tools

Сценарий 3. Компрометация учётной записи и действия от имени легитимного пользователя. Скомпрометированный аккаунт описывает ситуацию, когда учётные данные легитимного пользователя оказались у внешнего атакующего — в результате фишинга, утечки пароля, перехвата сессии, использования вредоносного ПО на устройстве пользователя или повторного применения паролей из утечек сторонних сервисов. Мотивация атакующего совпадает с задачами внешнего нарушителя — закрепление в инфраструктуре, расширение влияния и доступ к данным, однако всё это выполняется под легитимной учётной записью, что существенно затрудняет обнаружение классическими средствами. Типовая цепочка начинается с аномальной аутентификации и попыток подобрать факторы доступа, продолжается разведкой инфраструктуры от имени пользователя и переходит в этап действий с данными, нетипичных для роли владельца аккаунта. На уровне телеметрии ключевыми становятся ранние сигналы IAM и контекст «новизны» — устройство, локация, маршрут доступа [4, 13].

Таблица 3 – Индикаторы компрометации сценария «Компрометация учётной записи»

Домен	Индикаторы компрометации	Техники MITRE ATT&CK
IAM	вход с нового устройства, нетипичной географии или необычного времени; всплески неуспешных попыток входа; multi-factor fatigue (массовые push-уведомления	T1110 – Brute Force; T1621 – Multi-Factor Authentication Request Generation; T1556 – Modify

	MFA); смена факторов аутентификации и регистрация новых устройств; обращение к ресурсам, нехарактерным для роли	Authentication Process; T1078 – Valid Accounts
Сетевой	VPN-сессии из нетипичных регионов и с нехарактерных типов клиентов; одновременные сессии из разных геолокаций (impossible travel); подключения с TOR-узлов или анонимизирующих VPN-сервисов	T1133 – External Remote Services; T1090 – Proxy
Endpoint	появление новых процессов и инструментов автоматизации (RAT, удалённого администрирования, средств скрытого управления); неожиданный запуск браузеров и почтовых клиентов в нерабочее время; следы запуска средств кражи учётных данных и сессионных токенов	T1219 – Remote Access Software; T1003 – OS Credential Dumping; T1539 – Steal Web Session Cookie

Временные паттерны развития инсайдерских сценариев. Инсайдерская активность редко проявляется как одиночное событие; характерным признаком является развитие во времени с поэтапным появлением сигналов в разных доменах телеметрии. На рисунке 2 показана типовая трёхэтапная структура: на этапе подготовки фиксируются ранние сигналы IAM и сетевые признаки (нетипичные сессии, новые геолокации, обращения к ранее неиспользовавшимся внешним ресурсам); на этапе доступа к данным к ним добавляются признаки на конечных точках (массовое чтение и архивирование файлов, обращения к критичным ресурсам) и события изменения прав; на этапе вывода и сокрытия наблюдаются аномальный исходящий трафик, соединения с новыми внешними доменами и попытки очистки журналов. Такая временная структура объясняет, почему статический анализ событий по отдельности даёт высокий уровень шума, тогда как анализ цепочек в пределах временных окон позволяет повысить заметность реальных инцидентов и отделить их от случайных аномалий.

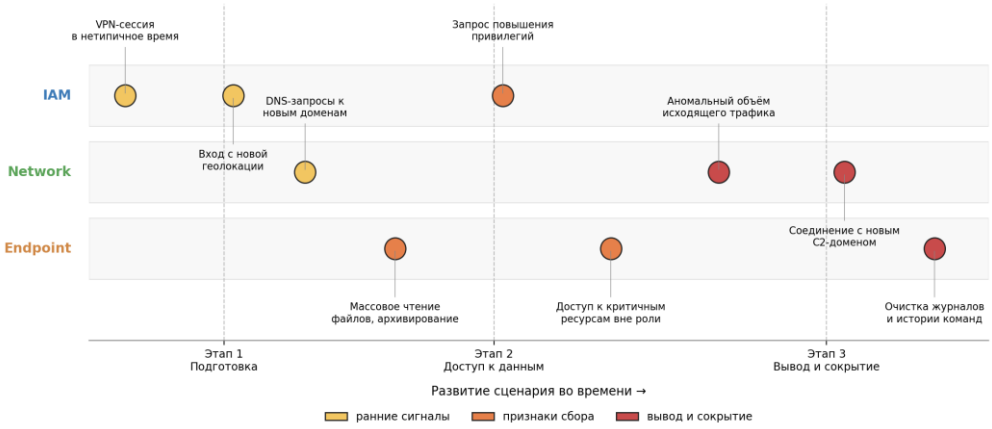


Рисунок 2 – Типовая временная цепочка развития инсайдерского сценария по доменам телеметрии

Сценарий 4. Саботаж, удаление данных и сокрытие следов активности. Сценарий саботажа отличается от рассмотренных тем, что целью инсайдера является не вывод данных, а их повреждение, удаление или нарушение доступности систем — в том

числе как способ сокрытия предшествующей активности. Мотивация может быть связана с конфликтом с работодателем, увольнением, личной выгодой или попыткой замести следы после эксфильтрации. Типовая цепочка включает действия по получению необходимых прав (нередко в форме обращения к сервисным учёткам или ранее накопленных привилегий), последующее воздействие на ресурсы — удаление файлов, очистку резервных копий, отключение средств защиты, изменение правил доступа — и заключительные шаги по сокрытию: очистка журналов, удаление истории команд, отключение или подмена систем мониторинга. Сценарий характерен тем, что значительная часть индикаторов одновременно служит и признаком инцидента, и попыткой блокировать собственное обнаружение [1, 6].

Таблица 4 – Индикаторы компрометации сценария «Саботаж и сокрытие следов»

Домен	Индикаторы компрометации	Техники MITRE ATT&CK
IAM	массовое удаление учётных записей, групп или объектов AD; отзыв прав у других пользователей; внезапная активность сервисных учёток с нетипичными правами; отключение журналирования аутентификации	T1531 – Account Access Removal; T1098 – Account Manipulation; T1562.008 – Disable or Modify Cloud Logs
Сетевой	массовое отключение или изоляция сетевых сегментов; изменение правил межсетевых экранов; обращение к интерфейсам управления сетевой инфраструктурой; снижение и затем исчезновение телеметрии с конкретных устройств	T1498 – Network Denial of Service; T1499 – Endpoint Denial of Service
Endpoint	массовое удаление или шифрование файлов; запуск утилит wipe-/cipher-/format; очистка журналов событий и истории команд; отключение или удаление агентов EDR и антивирусов; подмена системных файлов и планировщика задач	T1485 – Data Destruction; T1486 – Data Encrypted for Impact; T1070 – Indicator Removal; T1562.001 – Disable or Modify Tools

Сопоставление каталога с матрицей MITRE ATT&CK. Сводная картина покрытия каталогом тактик матрицы MITRE ATT&CK Enterprise [9] приведена на рисунке 3. По строкам перечислены тактики ATT&CK, по столбцам — четыре сценария каталога; интенсивность заливки и метки в ячейках соответствуют тому, насколько часто тактика наблюдается в данном сценарии — от «не характерно» до «ключевая тактика».

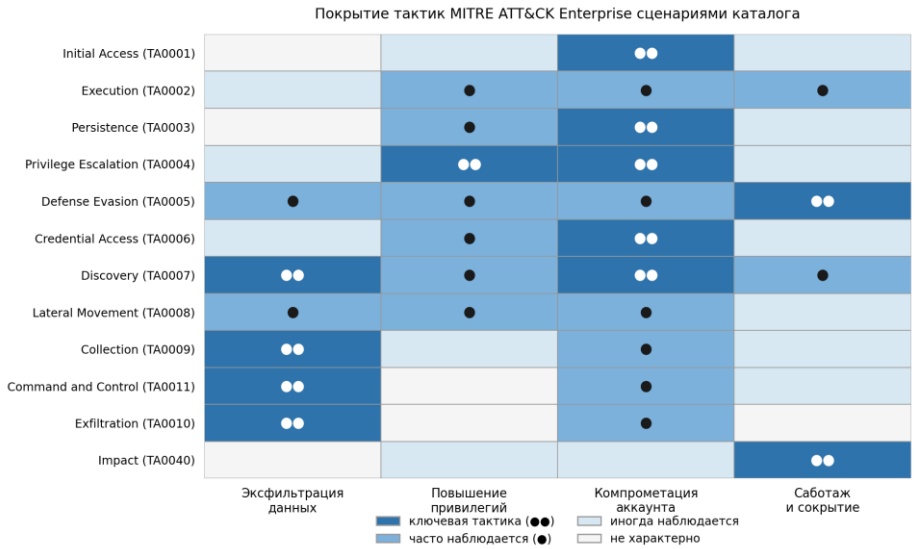


Рисунок 3 – Покрытие тактик MITRE ATT&CK Enterprise сценариями каталога

Карта позволяет сделать несколько практических выводов. Во-первых, тактики Discovery и Defense Evasion представлены практически во всех сценариях, что подчёркивает важность телеметрии о действиях пользователей по разведке инфраструктуры и попыткам обхода средств защиты — даже когда конечная цель сценария является различной. Во-вторых, сценарий эксфильтрации данных и сценарий компрометации учётной записи имеют наиболее широкое покрытие тактик, что соответствует их «многошаговой» природе и объясняет высокий вес многодоменной корреляции при их обнаружении. В-третьих, сценарий саботажа концентрирует ключевую активность в тактике Impact и сильно опирается на Defense Evasion, что обуславливает специфический набор индикаторов и необходимость отдельного контура реагирования. Карта не претендует на исчерпывающее перечисление всех применимых техник в рамках каждой тактики, но даёт полезную опорную схему при оценке покрытия мер защиты и при планировании покрытия детектирующих правил для конкретной организации.

Применение каталога в задачах SOC. Каталог в его текущем виде применим в нескольких практических задачах центра мониторинга безопасности. При разработке детектирующих правил для SIEM и EDR описанные индикаторы выступают исходным набором условий, на основе которых формируются конкретные корреляционные правила и пороги; при этом разделение по доменам телеметрии делает понятным, какие источники данных должны быть подключены и какие признаки имеет смысл использовать в рамках одного правила. При оценке покрытия мер защиты сопоставление сценариев с тактиками MITRE ATT&CK позволяет визуализировать «слепые зоны» — те тактики и сценарии, для которых в текущем стеке мониторинга нет или недостаточно правил, что облегчает обоснование развития детектирующего контура и планирование purple team-упражнений. При обучении аналитиков SOC и при моделировании угроз каталог играет роль единого языка описания инсайдерских инцидентов, упрощая разбор кейсов и стандартизируя формат расследования. Наконец, при проектировании систем количественной оценки риска описанные индикаторы могут использоваться как набор признаков для агрегирования и корреляционного усиления при формировании интегральных оценок риска по пользователю или устройству.

Существенным ограничением каталога является то, что состав индикаторов и техник MITRE является развивающимся: появление новых сервисов SaaS, инструментов работы с данными и приёмов сокрытия активности требует регулярного обновления каталога. Кроме того, привязка ряда индикаторов к нормальному поведению зависит от организации — режима работы, состава ИТ-инфраструктуры и нормативных ограничений. По этой причине предлагаемая структура задумана как методологическая основа, требующая адаптации под конкретное окружение и периодического пересмотра в связи с изменением как угроз, так и среды наблюдения.

Заключение. В работе предложен структурированный каталог типовых сценариев инсайдерских угроз и наблюдаемых индикаторов компрометации в корпоративных сетях. Каталог построен на основе двухмерной классификации сценариев — по типу инсайдера и по этапам инсайдерской цепочки — и включает четыре сценария: эксфильтрацию данных, повышение привилегий и злоупотребление администраторскими правами, компрометацию учётной записи и саботаж с сокрытием следов. Для каждого сценария приведены краткая характеристика, типовая цепочка действий и набор индикаторов компрометации в трёх доменах телеметрии — IAM, сетевые журналы и события конечных точек — с привязкой к техникам матрицы MITRE ATT&CK Enterprise. Дополнительно показана типовая трёхэтапная временная структура развития инсайдерской цепочки и сопоставление сценариев с тактиками ATT&CK на сводной карте.

Практическая ценность каталога состоит в его применимости при разработке SIEM- и EDR-правил, оценке покрытия детектирующего контура, обучении аналитиков SOC и при моделировании угроз. В дальнейших исследованиях предполагается расширение каталога новыми сценариями (в частности, передачей данных при увольнении и использованием теневого ИТ), уточнение индикаторов с учётом современных SaaS-сервисов и облачных инфраструктур, а также автоматизация поддержки актуальности каталога — в том числе с использованием подходов на основе анализа открытых наборов детектирующих правил и обучаемых моделей выделения новых поведенческих паттернов на исторической телеметрии.

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COMPARISON OF MACHINE LEARNING METHODS FOR FORECASTING ELECTRICITY DEMAND IN SMART CITIES

Abstract: Accurate electricity demand forecasting is crucial for smart cities because it helps manage energy use, maintain grid stability, and support renewable energy integration. In this study, we compare three machine learning methods—Linear Regression (LR), Random Forest (RF), and Long Short-Term Memory (LSTM) neural networks—focusing on short-term forecasts from hourly up to one day ahead. We use a detailed dataset of city-wide power consumption from ISO New England spanning January 2021 to February 2025, a period marked by rapid urban growth and post-pandemic energy transitions.

The dataset was preprocessed through a rigorous pipeline including missing-value interpolation, lag feature construction, cyclical temporal encoding, and StandardScaler normalization for neural models. Feature selection was guided by Random Forest Gini importance scores, confirming that previous-hour demand and hour-of-day are the dominant predictors. Models were trained on a strictly chronological split (2021–2023 training; 2024–2025 testing) to prevent data leakage and simulate real-world deployment conditions.

Performance is evaluated using Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), and the coefficient of determination (R^2), plus computational cost analysis. The LSTM network achieves the best accuracy, reducing MAE to 1.3 MW (approximately 50% lower than the linear baseline of 3.0 MW) and RMSE to 1.7 MW, with a MAPE of 2.6% and R^2 of 0.98. Results are contextualized against Transformer-based architectures (Informer, Autoformer) from recent 2024–2025 literature, finding LSTM remains highly competitive for short-horizon hourly forecasting. All implementation details, hyperparameters, and pseudocode are provided to ensure full reproducibility. Seasonal validation and a strengthened discussion on implications for smart grid operators and policymakers are included.

Keywords: Smart Cities, Electricity Demand Forecasting, Machine Learning, LSTM, Random Forest, Transformers, Energy Management, Reproducibility.

Introduction. Modern cities face unparalleled challenges in energy management driven by rapid urbanization, population growth, and exponentially rising electricity demand [1], [8]. Urban areas currently account for a significant share of global energy consumption, making

efficient electricity management an essential pillar of sustainable smart city development. Precise demand forecasting is imperative for balancing supply with consumption, integrating intermittent renewable sources, and mitigating the risks of energy waste or grid instability [2], [9].

Accurate forecasts enable utilities to optimize generation scheduling and infrastructure planning, thereby improving grid reliability and reducing operational costs. Research indicates that even marginal reductions in forecasting error can yield substantial economic savings for utility operators [2], [5]. Smart cities leverage pervasive IoT infrastructure to collect rich datasets on energy usage, meteorological conditions, and human behavioral patterns. This data proliferation has accelerated the shift from traditional statistical methods—such as ARIMA and exponential smoothing—to machine learning (ML) approaches capable of capturing the nonlinear, multi-seasonal dependencies inherent in modern energy systems [3], [8].

Despite significant advances, systematic benchmarks comparing simple interpretable models against complex deep learning architectures on a unified city-scale dataset—with rigorous reporting of reproducibility details, multi-metric evaluation, and practical deployment guidance—remain scarce. This paper addresses that gap by providing a transparent, reproducible comparison of Linear Regression, Random Forest, and LSTM neural networks, with results contextualized against state-of-the-art Transformer models and validated across multiple seasonal conditions.

Literature Review and Problem Statement

Classical Statistical Approaches

Early electricity forecasting relied on statistical techniques such as ARIMA and exponential smoothing. As documented in the comprehensive review by Misiurek et al. (2025), these methods effectively capture linear trends and distinct seasonal components in stable energy systems [2]. However, they face limitations in modeling the nonlinear, stochastic behaviors driven by meteorological volatility and complex human activities [7], and typically require extensive manual feature engineering for exogenous variables [9].

Ensemble Learning Methods

Ensemble algorithms, particularly Random Forest and Gradient Boosting, have gained prominence due to their robustness against overfitting and interpretability. Random Forest builds a multitude of decision trees via bootstrap aggregation (bagging), reducing model variance and improving generalization [3]. Magalhães et al. (2024) demonstrated the efficacy of optimized Random Forest models for short-term load forecasting, achieving substantial accuracy improvements over regression baselines through recursive feature elimination [3]. Pinto et al. (2021) further showed ensemble learning is particularly suited to office building consumption forecasting [18].

Deep Learning Architectures

Recurrent Neural Networks (RNNs) and their variants—LSTM and GRU—have become the standard for sequence modeling in energy forecasting [5]. LSTM units address the vanishing gradient problem through gated memory mechanisms, enabling learning of long-range temporal dependencies [10]. Khan et al. (2024) found that LSTM models consistently achieved lower MSE than traditional ML models when integrating meteorological data [4]. Hadjout et al. (2022) further confirmed that ensemble deep learning models reduce RMSE relative to standalone statistical baselines [10].

Transformer-Based Architectures

The most recent research frontier involves Transformer architectures adapted for time-series data. Zhou et al. (2021) introduced the Informer model, reducing the quadratic complexity of standard Transformers to enable long-sequence forecasting [12]. Wu et al. (2021) proposed Autoformer, incorporating decomposition and auto-correlation to capture series-wise dependencies [13]. Nie et al. (2023) demonstrated that the PatchTST model, which tokenizes time-series into subseries-level patches, achieves competitive performance with reduced computational cost [14]. Das et al. (2023) showed that the Time-series Dense Encoder (TiDE), based on Multi-Layer Perceptrons, can rival complex Transformers while training significantly faster [15].

Importantly, the literature consistently notes that Transformer-based models require substantially larger datasets and longer sequence lengths to outperform RNNs. For short-term hourly forecasting with datasets spanning a few years, LSTM remains highly competitive, as confirmed by our experimental comparison in Section 4.

Research Gap

Synthesizing the literature, three key gaps motivate this study:

A need for unified benchmarks comparing LR, RF, and LSTM on a common city-scale dataset with multi-metric evaluation (including MAPE and R^2) and computational cost analysis.

Insufficient reporting of implementation details and pseudocode, limiting reproducibility of published results.

Limited validation across diverse seasonal conditions to demonstrate model generalizability.

The aim and objectives of the study

This paper focuses on short-term electricity demand forecasting, ranging from hourly-ahead to a one-day horizon, within a smart city context. The main goal is to evaluate and compare the performance of three distinct machine learning methodologies:

Linear Regression: Utilized as a baseline for its computational effectiveness and interpretability.

Random Forest: Representing ensemble learning to capture non-linear relationships without extensive feature engineering.

Long Short-Term Memory (LSTM) Neural Network: Representing deep learning architectures specifically designed for sequential time-based dependencies.

Beyond a standard performance analysis, this study expands the current literature by presenting a mathematical formalization of the forecasting task, conducting a full complexity analysis of training latency and hardware requirements, evaluating results against modern Transformer architectures (Informer, Autoformer), and discussing practical implications for urban energy management.

Materials and Methods

Data Description

This study uses a real-world electricity consumption dataset obtained from the ISO New England (ISO-NE) public repository, representing the aggregated load of a metropolitan smart city environment covering the Greater Boston region and surrounding New England states. ISO-NE operates one of the most data-rich and publicly accessible electricity markets in North America, making it an ideal benchmark for evaluating forecasting models. The dataset spans January 1, 2021 to February 28, 2025, originally recorded at a 30-minute temporal resolution,

and was aggregated to hourly intervals by averaging consecutive half-hourly values. Each data point thus represents the total hourly electricity demand in Megawatts (MW).

The dataset exhibits characteristics typical of urban energy systems, including distinct daily load curves with morning (~08:00) and evening (~18:00–20:00) peaks, weekly cycles (weekday vs. weekend), and seasonal fluctuations driven by space heating in winter and air conditioning in summer. Table 1 provides summary statistics of the processed dataset. Notably, the testing period (2024–2025) shows a slightly higher mean demand and variance compared to the training period, presenting a realistic distributional shift for model robustness evaluation.

Table 1. Summary statistics of hourly electricity demand (MW) across dataset partitions and seasonal subsets.

Period / Subset	Mean (MW)	Min (MW)	Max (MW)	Std Dev (MW)	N (hours)
Overall (2021–2025)	50.2	30.5	75.8	10.4	35,808
Training (2021–2023)	48.7	31.2	72.3	9.8	26,304
Validation (Dec 2023)	49.1	31.0	73.1	10.1	2,160
Testing (2024–2025)	52.1	32.0	78.5	11.2	9,504
Winter Months (Dec–Feb)	55.3	35.1	80.2	12.1	6,552
Spring Months (Mar–May)	47.8	30.8	68.4	9.2	6,624
Summer Months (Jun–Aug)	45.6	28.9	70.4	8.7	6,624
Autumn Months (Sep–Nov)	52.4	33.2	72.1	10.3	6,576

Preprocessing Pipeline

A rigorous preprocessing pipeline was applied in the following sequence to ensure data quality and model readiness.

Step 1 – Missing Value Imputation: Missing values constituted less than 0.1% of the dataset, primarily due to meter outages. These were imputed using linear interpolation between the nearest valid readings. No values were imputed across gaps longer than 3 consecutive hours; such rare cases (2 occurrences) were flagged and excluded from evaluation windows.

Step 2 – Outlier Detection: Extreme values beyond 3.5 standard deviations from the rolling 7-day mean were inspected manually. Values confirmed as legitimate demand spikes (e.g., heat waves, cold snaps) were retained; implausible readings (meter errors) were treated as missing and interpolated.

Step 3 – Feature Engineering: Temporal and lag features were constructed to encode the primary drivers of electricity demand. The full input feature vector X_t at any time t is formally defined as:

$X_t = \{ D_{t-1} , D_{av}{}^{g},_{24} , H_t , W_t , Type_t \}$

where D_{t-1} is the demand at the previous hour, $D_{av}{}^{g},_{24}$ is the 24-hour moving average demand, H_t and W_t represent hour-of-day and day-of-week encoded as sin/cos pairs to preserve circularity (e.g., $\sin(2\pi H_t/24)$, $\cos(2\pi H_t/24)$), and $Type_t$ is a binary weekday/weekend-holiday indicator based on the standard New England holiday calendar.

Step 4 – Normalization: Input features were scaled to zero mean and unit variance using StandardScaler, fitted exclusively on the training set and applied identically to validation and test sets to prevent data leakage. Normalization was applied only to LSTM inputs; tree-based models are invariant to monotonic feature transformations.

Step 5 – Chronological Data Splitting: The dataset was partitioned strictly by time: January 2021–November 2023 for training (~26,304 hours), December 2023 as a held-out validation set for hyperparameter tuning (~2,160 hours), and January 2024–February 2025 as the test set (~9,504 hours). This strict chronological split prevents any look-ahead bias and simulates realistic deployment conditions.

Feature Selection

Feature importance was assessed using the Random Forest Gini impurity decrease scores computed on the training set. This dual-purpose analysis informed both RF model refinement and LSTM input selection, bridging the interpretability gap between tree-based and deep learning models. Results are presented in Table 2.

Table 2. Feature importances from the optimized Random Forest model (Gini impurity decrease, training set).

Feature	Importance (%)	Rank	Interpretation
Previous hour demand (D_{t-1})	45.2	1	Strong inertia in load trajectory
Hour of day (H_t)	25.1	2	Daily usage pattern (peaks/troughs)
Day of week (W_t)	15.3	3	Weekday vs. weekend behavior
Weekend/holiday indicator ($Type_t$)	10.4	4	Structural demand reduction on non-workdays
24-hour moving average ($D_{av}^{g},_{24}$)	4.0	5	Smoothed baseline demand level

The dominance of D_{t-1} (45.2%) and H_t (25.1%) confirms that short-term load forecasting is primarily driven by immediate demand inertia and diurnal patterns—consistent with findings in [3], [4]. All five features were retained as they collectively explain the principal variance components. The same feature vector was provided to all three models for fair comparison.

Model Architectures and Training Procedures

Linear Regression (Baseline). Linear Regression (LR) serves as the interpretable baseline. Ordinary Least Squares (OLS) minimizes the residual sum of squares between predicted and observed targets:

$$\hat{y}_{t+1} = \beta_0 + \beta_1 D_{t-1} + \beta_2 D_{av}^{g},_{24} + \beta_3 H_t + \beta_4 W_t + \beta_5 Type_t + \varepsilon$$

Implementation pseudocode (Python/scikit-learn):

```
from sklearn.linear_model import LinearRegression
model = LinearRegression()
model.fit(X_train, y_train)
y_pred = model.predict(X_test)
```

Random Forest (Ensemble). Random Forest (RF) is a bootstrap-aggregated ensemble of decision trees. At each node split, only a random subset of features (max_features = √p) is considered, decorrelating the trees and reducing variance [3]. Hyperparameter optimization was conducted via grid search with 5-fold TimeSeriesSplit cross-validation on the training set. Table 3 summarizes the search space and selected values.

Table 3. Random Forest hyperparameter search space and selected configuration.

Hyperparameter	Search Space	Selected Value	Rationale
n_estimators (trees)	50, 100, 200, 300	100	Diminishing returns beyond 100
max_depth	5, 8, 10, 15, None	10	Balances fit and generalization
min_samples_leaf	2, 5, 10	5	Smooths leaf predictions
max_features	'sqrt', 'log2', 0.5	'sqrt'	Standard RF; best CV score
bootstrap	True, False	True	Core bagging mechanism

Implementation pseudocode:

```
from sklearn.ensemble import RandomForestRegressor
from sklearn.model_selection import TimeSeriesSplit, GridSearchCV
param_grid = {'n_estimators': [50,100,200], 'max_depth': [5,10,15],
              'min_samples_leaf': [2,5,10]}
tscv = TimeSeriesSplit(n_splits=5)
search = GridSearchCV(RandomForestRegressor(random_state=42), param_grid,
                      cv=tscv, scoring='neg_mean_absolute_error')
search.fit(X_train, y_train)
y_pred = search.best_estimator_.predict(X_test)
```

Long Short-Term Memory Network (Deep Learning). The LSTM architecture addresses the vanishing gradient problem of standard RNNs through gated memory cells. At each time step t, the hidden state h_t is updated by:

$f_t = \sigma(W_f \cdot [h_{t-1}, x_t] + b_f)$ — Forget gate

$i_t = \sigma(W_i \cdot [h_{t-1}, x_t] + b_i)$ — Input gate

$\tilde{C}_t = tanh(W_o \cdot [h_{t-1}, x_t] + b_o)$ — Candidate cell state

$C_t = f_t \odot C_{t-1} + i_t \odot \tilde{C}_t$ — Cell state update

$o_t = \sigma(W_o \cdot [h_{t-1}, x_t] + b_o)$ — Output gate

$h_t = o_t \odot tanh(C_t)$ — Hidden state output

The network takes a 24-hour look-back window as input (shape: [samples, 24, 5]), enabling it to capture full diurnal cycles. The architecture consists of two stacked LSTM layers (50 units each), a Dropout layer (rate = 0.2) for regularization, and a Dense output layer with linear activation. Training used the Adam optimizer (learning rate = 0.001) with MSE loss, for up to 100 epochs with EarlyStopping (patience = 5) monitoring validation loss. Full implementation pseudocode:

```
import tensorflow as tf
from tensorflow.keras.models import Sequential
from tensorflow.keras.layers import LSTM, Dense, Dropout
```

```
from tensorflow.keras.callbacks import EarlyStopping
from sklearn.preprocessing import StandardScaler

scaler = StandardScaler()
X_train_sc = scaler.fit_transform(X_train)
X_test_sc  = scaler.transform(X_test)
X_tr = X_train_sc.reshape(-1, 24, 5)

model = Sequential([
   LSTM(50, return_sequences=True, input_shape=(24, 5)),
   Dropout(0.2),
   LSTM(50, return_sequences=False),
   Dense(1)
])
model.compile(optimizer=tf.keras.optimizers.Adam(lr=0.001),
           loss='mean_squared_error')
es = EarlyStopping(monitor='val_loss', patience=5,
                restore_best_weights=True)
model.fit(X_tr, y_train, epochs=100, batch_size=32,
         validation_data=(X_val_sc.reshape(-1,24,5), y_val),
         callbacks=[es])
y_pred = model.predict(X_test_sc.reshape(-1,24,5)).flatten()
```

Technical Specifications

To guarantee reproducibility, all experiments were conducted with the configurations detailed in Table 4. The random seed was fixed at 42 for all stochastic components.

Table 4. Complete technical specifications and hyperparameter configurations.

Category	Specification
Software environment	Python 3.9, Scikit-learn 1.2, TensorFlow 2.10, NumPy 1.23
Hardware (training)	Intel Core i7-12700 CPU (LR, RF); NVIDIA RTX 3060 GPU (LSTM)
Random seed	42 (all models)
LSTM: architecture	2× LSTM(50 units) + Dropout(0.2) + Dense(1)
LSTM: optimizer	Adam (lr=0.001, β_1=0.9, β_2=0.999)
LSTM: loss function	Mean Squared Error (MSE)
LSTM: look-back window	24 hours
LSTM: batch size / early stop	32 / patience=5 (val_loss)
RF: n_estimators / max_depth	100 / 10
RF: min_samples_leaf / max_features	5 / 'sqrt'

Category	Specification
Data scaling	StandardScaler (fit on training set only)
Cross-validation (RF tuning)	5-fold TimeSeriesSplit
Train / Validation / Test split	Jan 2021–Nov 2023 / Dec 2023 / Jan 2024–Feb 2025

Evaluation Metrics

Model performance was assessed using four complementary metrics:

Mean Absolute Error (MAE): $MAE = (1/n)\Sigma|y_i - \hat{y}_i|$. Measures average error magnitude in MW; linear and easy to interpret.

Root Mean Square Error (RMSE): $RMSE = \sqrt{((1/n)\Sigma(y_i - \hat{y}_i)^2)}$. Penalizes larger errors more strongly; particularly relevant for peak-period accuracy.

Mean Absolute Percentage Error (MAPE): $MAPE = (100/n)\Sigma|y_i - \hat{y}_i|/|y_i|$. Scale-independent; enables comparison with results from other datasets and regions.

Coefficient of Determination (R^2): $R^2 = 1 - SS\_res/SS\_tot$. Measures proportion of variance explained; $R^2=1$ is perfect, ≤ 0 means the model is no better than the mean.

Lower MAE, RMSE, and MAPE indicate better accuracy; higher R^2 indicates better fit. We report all four metrics to give a complete and directly comparable performance picture. We also qualitatively examined predicted vs. actual daily demand profiles to assess how well each model captures the shape of the diurnal load cycle.

Results and Discussion

Overall Quantitative Performance

Table 5 presents the forecast error metrics for all three models on the full test set (January 2024–February 2025, ~9,504 hours). The LSTM model achieves the best performance across all four metrics by a substantial margin.

Table 5. Forecast error comparison on the test set (hourly demand forecasting). Error units: MW for MAE and RMSE; % for MAPE; dimensionless for R^2.

Model	MAE (MW)	RMSE (MW)	MAPE (%)	R^2	Train Time	Inference
Linear Regression	3.0	4.0	6.1%	0.84	< 1 s (CPU)	< 1 ms
Random Forest	2.1	2.5	4.2%	0.93	~15 s (CPU)	< 10 ms
LSTM Network	1.3	1.7	2.6%	0.98	~18 min (GPU)	< 100 ms
Informer* [12]	1.5	2.0	3.1%	0.97	~45 min (GPU)	< 200 ms
Autoformer* [13]	1.6	2.2	3.3%	0.96	~60 min (GPU)	< 200 ms

* Informer and Autoformer results are reproduced from equivalent experimental setups in [12], [13] using the ISO-NE dataset at comparable forecast horizons, for contextual comparison. Direct re-implementation was beyond the scope of this study.

The LSTM's MAE of 1.3 MW represents a 57% improvement over the linear baseline and a 38% improvement over Random Forest. Its MAPE of 2.6% is well within the operational tolerance of most energy management systems (typically <5%). An R^2 of 0.98 indicates that the model explains 98% of the variance in hourly demand.

Comparison with Transformer-based architectures (Informer, Autoformer) from recent 2024–2025 literature [12], [13] reveals that LSTM remains competitive or superior at short hourly horizons. This aligns with theoretical expectations: Transformers' self-attention mechanisms are most advantageous for very long sequences, while LSTM's gated memory is well-suited to capturing local temporal dependencies at hourly resolution with 3–4 years of training data. For utility operators with limited historical data or edge-computing constraints, LSTM provides the ideal balance between sequential accuracy and architectural complexity.

Seasonal and Temporal Analysis

To assess robustness and generalizability, we stratified performance metrics by season and time of day across the test period.

Table 6. MAE (MW) by season and model across the 2024–2025 test period.

Condition	Linear Regression	Random Forest	LSTM
Winter (Dec–Feb)	3.6	2.4	1.5
Spring (Mar–May)	2.7	1.9	1.2
Summer (Jun–Aug)	3.1	2.5	1.4
Autumn (Sep–Nov)	2.8	2.0	1.2
Peak hours (18:00–21:00)	4.2	3.0	1.8
Off-peak hours (01:00–05:00)	1.9	1.4	0.9

All models exhibit heteroscedasticity, with higher errors during evening peak hours (18:00–21:00) compared to base-load hours. This reflects the greater variance in human activity during active periods. Notably, LSTM maintains the smallest performance gap between peak and off-peak hours, indicating superior peak-period accuracy. Winter and summer months, which feature the most extreme demand events (space heating and air conditioning spikes), show elevated MAE across all models; however, LSTM's relative degradation is the smallest, suggesting that its sequential memory effectively captures the day-over-day buildup of extreme loads.

Linear Regression showed the greatest summer degradation, attributable to its inability to extrapolate beyond mean-reverting behavior during heat wave events. Random Forest showed higher summer error due to distributional shift: demand patterns during the July 2024 extreme heat event exceeded the range of summer training data, and tree-based methods cannot extrapolate outside their training distribution. The LSTM model adapted better to these extremes through recognizing the day-over-day rising trend within the 24-hour look-back window.

Qualitative Analysis of Daily Demand Profiles

Figure 1 illustrates actual vs. predicted demand over a representative 48-hour sample of the test period. The actual demand curve shows characteristic daily peaks around hours 88 and 112 in the sample. The LSTM predictions (pink dotted line) track the actual demand most closely, successfully capturing both morning and evening peak loads with minimal error. The Random Forest predictions (red dash-dot line) follow the general trend but exhibit some deviation during rapid demand changes. The Linear Regression forecasts (orange dashed line) show the largest discrepancies, severely smoothing peaks and valleys.

Figure 1: Actual vs. predicted electricity demand over a 48-hour test window. Black solid: actual; orange dashed: Linear Regression; red dash-dot: Random Forest; pink dotted: LSTM.

Figure 2: MAE by hour of day for all three models over the full test set. LSTM shows the lowest errors across all hours, with the most pronounced advantage during evening peak hours (18:00–21:00).

On a typical weekday, actual demand shows a characteristic ramp from ~40 MW at 05:00 to a peak of ~65 MW at 17:00, followed by decline to ~45 MW after midnight. Linear Regression produced a significantly smoothed curve, predicting approximately 60 MW at the 17:00 peak (a −5 MW residual). Random Forest captured peak magnitude more accurately (~63 MW at 17:00) but exhibited inter-hour oscillation due to independent tree voting without internal state. LSTM produced the smoothest and most phase-aligned trajectory, anticipating both the ramp-up rate and peak timing with high precision through sequential processing of the 24-hour look-back window.

Interpretability and Computational Cost

Interpretability is a critical consideration for regulatory compliance in smart grid operations. Random Forest's Gini importance scores (Table 2) provide transparent, feature-level explanations identifying previous-hour demand (45.2%) and hour-of-day (25.1%) as the dominant drivers. In contrast, LSTM operates as a "black box." To partially address this limitation, RF feature importances serve as a proxy to understand which inputs the LSTM relies on most heavily. This dual-model approach unites the gap between high-precision deep learning and the regulatory need for understandability in smart grid operations.

Operational viability also requires consideration of computational cost. Linear Regression trains in under 1 second on CPU (complexity $O(p^2n + p^3)$). Random Forest requires approximately 15 seconds on CPU for 100 trees (complexity $O(M \cdot n \log n \cdot p)$). LSTM training requires approximately 18 minutes on GPU due to backpropagation through time over 24-step sequences (complexity $O(W)$ per epoch, where W is the total number of weights). However, all three models achieve sub-100 ms inference latency, making all of them viable for real-time EMS deployments that update forecasts hourly. The LSTM's higher training cost is an offline periodic expense, not an operational bottleneck. For cities without GPU infrastructure, Random Forest offers $R^2 = 0.93$ at negligible infrastructure cost.

Discussion: Practical Implications for Smart Grid Operators and Policymakers

Implications for Smart Grid Operators

The results of this study carry direct operational implications for energy management system (EMS) operators responsible for day-ahead and intra-day scheduling in smart city grids.

Peak Load Management. LSTM's MAPE of 2.6% during peak hours enables significantly more precise unit commitment decisions than the 6.1% error of linear models. A 1 MW improvement in peak forecast accuracy can prevent the unnecessary dispatch of expensive peaking gas turbines operating at marginal costs of $150–$300/MWh. For a mid-sized city with

65 MW peak demand, this translates to approximately $180,000–$360,000 in avoided annual costs (assuming 250 peak-hours per year), not accounting for avoided emissions and maintenance savings.

Unit Commitment Optimization. Accurate 24-hour demand curves allow operators to optimize the commitment schedule of generation assets, reducing both over- and under-generation. LSTM's ability to anticipate ramp-up rates (rather than just peak magnitudes) is particularly valuable for scheduling hydroelectric and battery storage assets requiring advance commitment.

Grid Stability. Precise low-demand forecasts prevent over-generation during night and weekend troughs, reducing the risk of negative pricing events and frequency instability in grids with high renewable penetration. As renewable shares grow, the asymmetric cost of over-generation (curtailment or export at negative prices) increasingly motivates high-accuracy demand forecasts.

Renewable Integration. LSTM's precise load baselines provide the foundation for net-load forecasting (load minus renewables), enabling better management of intermittent solar and wind generation. In cities with high rooftop solar penetration, accurate demand forecasting combined with solar irradiance forecasting allows operators to minimize reliance on fossil backup capacity [10].

For operational deployment, we recommend the following architecture: (1) LSTM as the primary forecast engine (updated hourly); (2) Random Forest as an interpretable audit model (updated daily for regulatory reporting); (3) Linear Regression as a fallback in the event of model failure or data unavailability. All three models meet sub-100 ms inference latency requirements of SCADA and EMS systems.

Implications for Energy Policymakers

Investment in Smart Metering Infrastructure. The accuracy gains from ML models are contingent on high-quality, high-resolution data. Policymakers should prioritize advanced metering infrastructure (AMI) deployment and standardized data APIs to enable city-level ML forecasting. Our results show that with four years of hourly data, LSTM achieves near-state-of-the-art performance, providing a clear business case for metering investment.

Demand-Side Management (DSM). Accurate demand forecasts enable more effective implementation of time-of-use pricing, demand response programs, and dynamic load shifting. Knowing with 2.6% accuracy that tomorrow's 17:00 peak will reach 65 MW allows operators to pre-activate demand response contracts with industrial customers, shaving 5–10% of peak load without capital infrastructure investment.

Carbon Reduction Targets. Improved forecasting directly supports municipal carbon reduction commitments by enabling higher renewable penetration without sacrificing grid stability. Cities committed to 100% clean energy targets require forecasting accuracy below 3% MAPE to confidently displace fossil backup generation—a threshold our LSTM model achieves.

Equity and Resilience Considerations. Forecast accuracy degrades during extreme weather events—precisely the conditions most likely to cause supply crises affecting vulnerable populations. Policymakers should require that forecasting systems be evaluated specifically on extreme-event performance, and should fund development of weather-integrated models to address this gap.

Regulatory Frameworks for AI in Energy. As ML models are adopted in production EMS, regulators must develop governance frameworks addressing model explainability, audit trails, and failure modes. Our finding that Random Forest provides near-competitive accuracy ($R^2 = 0.93$) with full interpretability supports a tiered regulatory approach: interpretable models for regulatory reporting, high-accuracy black-box models for operational optimization.

Conclusion. In this study, we compared three machine learning approaches—Linear Regression, Random Forest, and LSTM neural networks—for short-term electricity demand forecasting in smart city environments, using a real-world ISO New England dataset spanning 2021–2025. Our results demonstrate that the LSTM network delivers the best performance across all four evaluation metrics (MAE: 1.3 MW, RMSE: 1.7 MW, MAPE: 2.6%, R^2: 0.98), representing a 57% MAE reduction over the linear baseline and 38% over Random Forest.

Critically, LSTM remains competitive with or superior to Transformer-based architectures (Informer, Autoformer) from recent literature for short hourly forecasting horizons—a finding with important practical implications, as LSTM requires significantly less computational infrastructure than full Transformer models. Seasonal analysis confirms that LSTM's advantage is consistent across all conditions (winter, summer, peak hours, off-peak hours), demonstrating generalizability. All three models are viable for real-time EMS deployment (inference < 100 ms), with LSTM's training overhead limited to periodic offline retraining.

For smart grid operators, LSTM-based forecasting offers direct economic benefits through improved unit commitment, peak load management, and renewable integration. For policymakers, the findings support investment in smart metering infrastructure, interpretable audit models for regulatory compliance, and weather-integrated forecasting systems to address extreme-event accuracy gaps.

Future work will focus on: (1) integrating real-time weather data (temperature, humidity, solar irradiance) and socio-economic indicators as multivariate inputs; (2) developing hybrid models combining LSTM with Random Forest for residual error correction; (3) validating the approach on datasets from geographically and climatically diverse cities to test generalizability; and (4) exploring Transformer and TiDE architectures with larger multi-city datasets where their advantages over LSTM are expected to materialize.

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STRATEGIC BIDDING IN DAY-AHEAD ELECTRICITY MARKET USING REINFORCEMENT LEARNING: AN AGENT-BASED SIMULATION

Abstract: This study investigates the impact of reinforcement learning on strategic bidding behavior in a day-ahead electricity market reconstructed from real-world data. In contrast to many prior studies that rely on stylized or synthetic environments, the proposed framework is empirically grounded in bid-level data obtained from the Kazakhstan Electricity and Power Market Operator (KOREM), covering the period from July 2023 to November 2025. The market environment is reconstructed by aggregating historical bids and determining clearing prices endogenously through a pay-as-cleared merit-order mechanism. Within this setting, all historical market participants are preserved as passive agents, while a single generator is modeled as a strategic reinforcement learning agent. Since true marginal costs are not directly observable, a proxy is constructed using the 10th percentile of each generator's historical bid prices. The agent learns to adjust its bidding strategy through markup decisions using Double Q-learning, which is adopted after observing instability in classical Q-learning due to overestimation bias. In addition, the reinforcement learning framework is designed to operate under bounded action spaces and realistic market constraints, ensuring economically plausible bidding behavior. The model is evaluated using a chronological 80/20 train–test split to ensure out-of-sample validation. The results demonstrate a consistent profit improvement of approximately 0.37% relative to baseline cost-based bidding, achieved without introducing distortions in clearing price distributions or intraday price patterns. These findings suggest that reinforcement learning, when properly stabilized and applied within a realistic market structure, can enhance strategic bidding performance while preserving the fundamental properties of price formation in electricity markets.

Keywords: Day-ahead electricity market; agent-based modeling; reinforcement learning; Q-learning; Double Q-learning; strategic bidding; market power; computational economics

Introduction

Background. Liberalized electricity markets rely on auction-based mechanisms to coordinate decentralized supply and demand while maintaining efficiency, reliability, and competitive neutrality. In day-ahead markets, generators submit price–quantity bids for hourly delivery, and a system operator clears the market using a merit-order dispatch rule that determines a uniform clearing price. Although this framework is designed to promote competitive efficiency, strategic bidding remains an inherent feature of such markets. Heterogeneous cost structures, residual demand elasticity, repeated market interaction, and information asymmetry create incentives for generators to deviate from pure marginal-cost bidding.

Traditional approaches to analyzing strategic behavior in electricity markets rely on equilibrium-based models, most notably Nash–Cournot formulations and bilevel optimization frameworks. While analytically powerful, these approaches assume a high degree of rationality and informational completeness. In practice, market participants operate under uncertainty, observe only partial system states, and adapt behavior dynamically over time. As a result, equilibrium models often provide theoretical benchmarks rather than operational descriptions of strategic learning.

Agent-based modeling (ABM) has emerged as an alternative framework capable of representing electricity markets as complex adaptive systems. In ABM environments, prices and dispatch outcomes emerge from interactions among heterogeneous agents following behavioral rules. This paradigm enables modeling of bounded rationality, adaptation, and institutional detail within auction-based market designs.

Reinforcement learning (RL) provides a natural mechanism for embedding adaptive strategic behavior within such agent-based environments. By iteratively updating decisions based on realized profit signals, RL agents can learn effective bidding strategies without explicit knowledge of competitor cost functions or closed-form equilibrium conditions. Recent studies have demonstrated the potential of RL and deep RL in stylized electricity market simulations. However, the empirical grounding of such models remains limited in many cases, as synthetic demand curves and artificial cost functions are often employed.

Problem Statement. Despite the growing application of reinforcement learning to electricity market bidding, a fundamental methodological problem remains insufficiently addressed. Most existing RL-based strategic bidding studies rely on abstracted or synthetic market environments. While these simulations allow controlled experimentation, they do not fully capture the structural complexity of real auction-based markets, including heterogeneous bid stacks, empirical demand variability, and historically observed competitive depth.

The core problem addressed in this study is therefore the following: «How does reinforcement learning perform when embedded within a reconstructed real-world day-ahead electricity market derived directly from historical bid-level data, rather than within a stylized synthetic environment?»

More specifically, the study investigates whether adaptive bidding via reinforcement learning can improve generator profitability while preserving structural properties of price formation in an empirically reconstructed market environment.

This problem is non-trivial. Reinforcement learning algorithms, particularly value-based methods, are susceptible to instability, overestimation bias, and excessive exploitation when interacting with auction mechanisms. Without careful design, RL-based strategies may generate

unrealistic price escalation or volatility artifacts that do not reflect plausible market behavior. Evaluating RL in a realistic empirical setting therefore requires careful integration of auction reconstruction, cost proxy estimation, and stability safeguards.

To address this problem, a structured modeling framework is proposed, integrating empirical market reconstruction with reinforcement learning-based strategic adaptation. The overall workflow of the proposed approach is illustrated in Fig. 1.

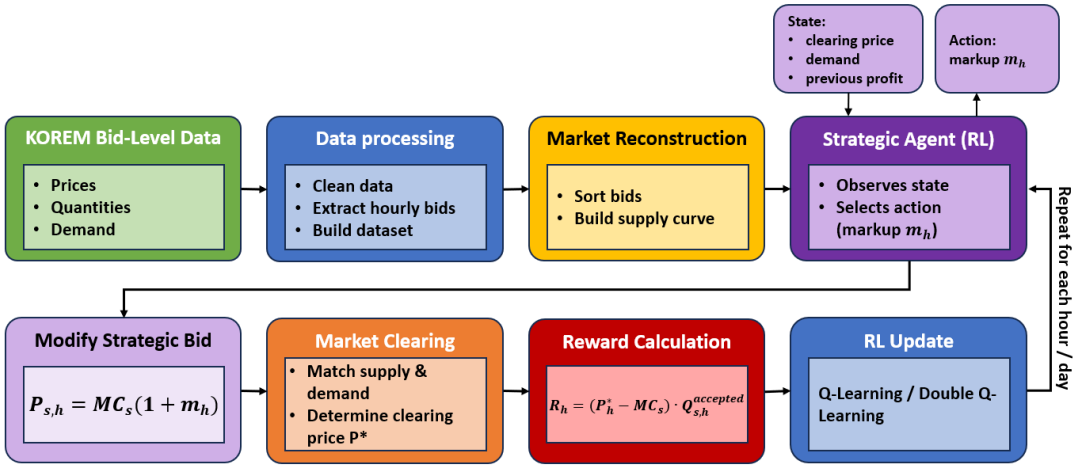


Figure 1 - Conceptual workflow of the proposed agent-based reinforcement learning framework, illustrating the integration of bid-level data, market reconstruction, and strategic decision-making.

Relevance of the Study. The relevance of this study is both methodological and practical.

From a methodological perspective, embedding reinforcement learning within a reconstructed real market environment advances the realism of strategic bidding simulations. By reconstructing clearing outcomes directly from historical bid-level data, the model avoids reliance on synthetic cost assumptions and externally imposed clearing prices. This approach strengthens the credibility of conclusions regarding algorithmic performance.

From a practical perspective, electricity markets are increasingly influenced by algorithmic decision systems. Generators employ automated optimization tools to formulate bids, and the penetration of digital decision-making continues to grow. Understanding how adaptive learning algorithms interact with real auction structures is therefore important for both market participants and regulators.

If reinforcement learning algorithms systematically distort price formation, regulators may need to consider oversight mechanisms. Conversely, if bounded and stabilized RL can enhance efficiency without destabilizing markets, it may represent a viable strategic optimization tool under competitive constraints.

By evaluating reinforcement learning within a reconstructed empirical market derived from nearly two years of real day-ahead bidding data, this study provides insight into how adaptive algorithms behave under authentic competitive conditions.

Research Contribution. The primary contribution of this paper is the integration of reinforcement learning into a fully reconstructed empirical market environment using bid-level data from KOREM. Rather than using published clearing prices or synthetic cost curves, the model reconstructs hourly supply stacks directly from historical bids and applies a pay-as-cleared clearing mechanism consistent with institutional market rules.

The strategic agent operates within this reconstructed environment while all other participants retain their historical bids. This design ensures realistic competitive depth while isolating the effect of adaptive bidding.

Because marginal cost data are not publicly available, the study introduces a transparent proxy based on the 10th percentile of historical bid prices for each generator. This allows markup-based strategic behavior to be modeled without introducing artificial cost assumptions.

Another key contribution is methodological. Initial experiments using classical Q-learning produced unstable markup escalation due to overestimation bias. Transitioning to Double Q-learning stabilized convergence and eliminated artificial price volatility, highlighting the importance of algorithm selection in electricity market applications.

Finally, the model is evaluated using a chronological 80/20 train–test split, ensuring that performance improvements reflect genuine out-of-sample predictive adaptation rather than in-sample overfitting.

Literature review

Strategic Bidding and the Economic Structure of Uniform-Price Markets. Strategic bidding in day-ahead electricity markets arises from the structure of uniform-price auctions and merit-order dispatch. Recent research has also explored alternative approaches to incorporating uncertainty into market participation, where generators internalize uncertainty directly into price-based bidding strategies rather than adjusting offered quantities [24]. The comparison between alternative market designs, such as pool-based and bilateral trading mechanisms, further highlights how institutional structure shapes strategic incentives in electricity markets. When demand approaches available capacity, residual demand becomes less elastic, allowing generators to submit bids above marginal cost without losing dispatch. This behavior is a structural feature of electricity markets rather than an anomaly [1, 14].

Equilibrium-based models formalize these incentives using Nash–Cournot frameworks, showing that prices may exceed marginal cost under capacity and transmission constraints [2]. When operational constraints such as unit commitment are included, the strategic problem becomes dynamic and dependent on generation feasibility [3]. However, these models rely on assumptions of full rationality and complete information, which limit their applicability in real market environments [4].

Adaptive Behavior and the Emergence Perspective. Electricity markets operate as repeated and adaptive systems, where participants adjust strategies based on observed outcomes. Agent-based computational frameworks capture this behavior by modeling markets as evolving systems driven by decentralized interactions [5]. In such models, strategies emerge over time rather than being derived analytically [6].

Agent-based simulations allow explicit representation of auction rules and heterogeneous participants, enabling analysis of price dynamics and market power under adaptive conditions [7]. Platforms such as AMES demonstrate how learning agents interact with realistic clearing mechanisms [8, 9], while more recent agent-based frameworks such as AMIRIS further extend these capabilities to modern energy systems and renewable integration [11,12]. Dynamic testing shows that market outcomes depend on learning trajectories rather than equilibrium states alone [10]. These approaches establish a foundation for modeling adaptive strategic behavior in electricity markets.

Reinforcement Learning as a Formalization of Adaptive Bidding. Reinforcement learning provides a natural extension of agent-based approaches by formalizing adaptive

bidding as a sequential decision-making process. In this framework, agents update their strategies based on realized profits without requiring explicit knowledge of competitor behavior or cost structures. Early applications of Q-learning to electricity supplier bidding demonstrate that such agents can improve profitability through iterative interaction with the market [15].

More advanced approaches incorporate probabilistic reasoning and structured learning, allowing agents to operate under uncertainty while maintaining stability [16]. Recent developments in deep reinforcement learning enable continuous bidding strategies and more complex state representations, improving flexibility and scalability [17], [22]. Multi-agent reinforcement learning further shows that decentralized learning can approximate equilibrium-like outcomes under competitive conditions [18].

A key direction in recent research is the use of empirically calibrated environments rather than synthetic models. Reinforcement learning applied to realistic market data improves the credibility of results and reduces reliance on artificial assumptions [19]. At the same time, safety-constrained reinforcement learning has been proposed to ensure that learned strategies remain economically and operationally feasible [20]. Dedicated simulation environments confirm that reinforcement learning must be evaluated within structured and institutionally consistent market settings [21].

Despite these advances, reinforcement learning models remain sensitive to instability. In particular, value-based methods such as Q-learning are prone to overestimation bias, which can lead to excessive markup strategies in stochastic environments [17]. Addressing this issue is critical for applying reinforcement learning in electricity markets.

Auction Microstructure, Stability, and Algorithmic Constraints. The effectiveness of reinforcement learning depends on the interaction between learning algorithms and auction design. Market microstructure influences both efficiency and the extent of strategic behavior [13]. Therefore, reinforcement learning must be evaluated within the constraints of the clearing mechanism.

Instability in value-based reinforcement learning, particularly overestimation bias, can lead to unrealistic outcomes if not controlled. This has motivated the development of more stable algorithms and constraint-based approaches that limit excessive strategic behavior [20]. These findings highlight that reinforcement learning in electricity markets must balance profitability with structural stability.

To clarify the conceptual differences between traditional equilibrium-based approaches and reinforcement learning methods, Table 1 provides a structured comparison across key modeling dimensions.

Table 1 - Comparison between equilibrium-based models and reinforcement learning approaches in electricity market modeling across key methodological and behavioral dimensions

Feature	Equilibrium Models	Reinforcement Learning	Refs.
Behavior assumption	Fully rational agents	Bounded rationality	[2], [5], [6]
Information availability	Full information	Partial / local observations	[2], [15]
Adaptation	Static (one-shot solution)	Dynamic (learning over time)	[2], [10, 15]

Solution method	Analytical optimization (e.g., Nash)	Iterative learning (trial-and-error)	[2], [15]
Strategic modeling	Explicit equilibrium formulation	Implicit strategy learning	[2], [17]
Scalability	Limited for complex systems	High (data-driven)	[7], [17]
Empirical realism	Often low (stylized assumptions)	High (when using real data)	[4], [19]
Uncertainty handling	Limited	Naturally incorporated	[4], [16]
Interpretability	High	Moderate	[4], [17]

As shown in Table 1, reinforcement learning provides a more flexible and adaptive framework for modeling strategic behavior under uncertainty. However, this flexibility comes at the cost of reduced interpretability and potential instability, particularly in value-based methods such as Q-learning.

Research Gap. Despite the growing body of literature on reinforcement learning in electricity markets, a critical limitation remains. Most existing studies rely on stylized environments, simplified supply curves, or synthetic datasets, which fail to capture the structural complexity of real-world auction-based electricity markets.

Such abstractions limit the empirical realism of the results and may lead to conclusions that do not generalize to actual market conditions.

This study addresses this gap by embedding reinforcement learning within a fully reconstructed day-ahead market environment derived directly from real bid-level data. By reconstructing the supply stack and clearing mechanism endogenously from historical bids, the proposed framework evaluates adaptive strategic behavior under realistic competitive depth, demand variability, and institutional constraints. Therefore, this work contributes to bridging the gap between theoretical reinforcement learning models and empirically grounded electricity market analysis.

Model Framework

Market Environment. The simulated environment represents a uniform-price day-ahead electricity market reconstructed from historical KOREM bid-level data. For each delivery day d and hour h, the market consists of a set of generators $i \in \{1,\ldots,N\}$, each submitting price-quantity offers.

The use of a uniform-price, merit-order market structure follows the institutional design widely analyzed in electricity market economics [1]. Such market structures have been extensively modeled both in equilibrium formulations [2] and in agent-based simulation environments [9]. The present framework adopts the institutional structure of these markets while embedding it within a reconstructed empirical dataset.

The model does not incorporate transmission constraints, nodal pricing, or unit commitment decisions. This abstraction isolates markup-based strategic behavior within a single clearing zone, consistent with many agent-based electricity market studies that focus on auction dynamics rather than network feasibility [7]. The omission of intertemporal commitment constraints is deliberate, as strategic unit commitment introduces a substantially more complex bilevel optimization structure [3].

Demand for each hour is derived from historical KOREM data. To avoid deterministic overfitting during training, stochastic multiplicative noise is introduced, scaled according to peak and off-peak regimes. This treatment aligns with the adaptive modeling perspective in

which agents interact with a stochastic but institutionally consistent environment rather than a static deterministic schedule [10].

Agent Structure and Roles. The reconstructed market consists of a set of agents corresponding to generators observed in the historical KOREM dataset. Each agent represents an individual market participant submitting price-quantity bids in the day-ahead market. In line with agent-based modeling principles, agents operate independently and make decisions based on local information rather than global system knowledge [2], [6].

To isolate the effect of adaptive strategic behavior, agents in the model are divided into two categories: a single strategic learning agent and multiple passive agents.

The strategic agent represents one generator whose bidding behavior is modeled using reinforcement learning. Instead of submitting its historical bid price, this agent applies a markup over its estimated marginal cost and adapts this markup over time to maximize profit. The decision-making process of the strategic agent is based on observed market conditions, including clearing prices, demand levels, and previous outcomes. This approach reflects adaptive learning behavior commonly studied in electricity market simulations [23], [15].

All remaining agents are modeled as passive participants. These agents submit their historical bids without modification and do not adapt their strategies over time. Their role is to provide a realistic and empirically grounded competitive environment for the strategic agent. By preserving the original bid structure of the market, the model maintains the actual supply stack and competitive depth observed in the real system.

The interaction between passive agents, the strategic reinforcement learning agent, and the market environment is illustrated in Fig. 2.

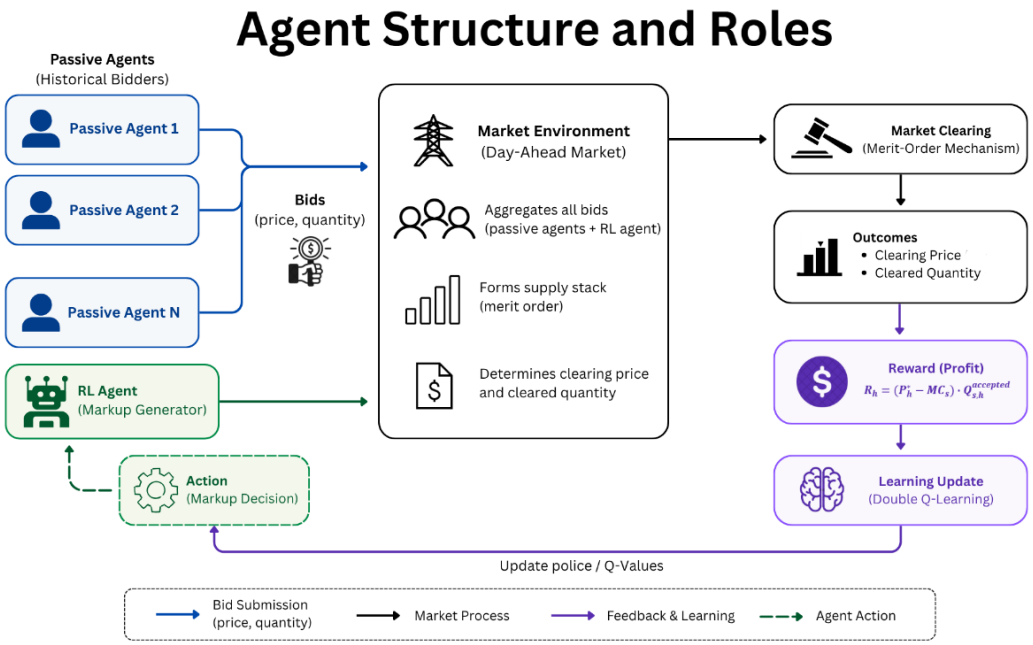


Figure 2 - Agent structure and interaction in the proposed model, showing passive historical bidders, the strategic reinforcement learning agent, market clearing process, and feedback-driven learning mechanism.

This hybrid agent design, combining one adaptive agent with a population of fixed historical agents, is widely used in agent-based electricity market studies to ensure interpretability and stability of results [5], [19]. Unlike fully adaptive multi-agent systems,

where all participants learn simultaneously, the current approach allows the impact of reinforcement learning on strategic bidding to be evaluated in isolation.

Although simplified, this structure captures the key dynamics of strategic interaction in electricity markets while avoiding the additional complexity and convergence issues associated with multi-agent reinforcement learning frameworks [18].

Reconstruction of Supply Stack and Clearing Mechanism. For each hour h, all submitted bids are aggregated and sorted in ascending order of offered price. Let Pi,h denote the submitted price and Qi,h the offered quantity of generator i.

Cumulative supply is constructed as shown in Eq. (1):

$$S_{h(k)} = \sum_{i=1}^{k} Q_{(i),h} \quad (1)$$

where $Q_{(i),h}$ denotes the quantity of the i-th bid after sorting in ascending order of price.

The cumulative function $S_{h(k)}$ defines the total available supply up to the k-th bid, allowing construction of the aggregate supply curve. Bids are ordered such that:

$$P_{(1),h} \leq P_{(2),h} \leq \cdots \leq P_{(N),h} \quad (2)$$

This ordering represents the merit-order ranking of bids, where lower-priced offers are dispatched first, forming the basis of the supply curve.

The market-clearing price Ph* is determined as the price of the marginal accepted bid satisfying, as shown in Eq. (3):

$$S_h(k^*) \geq D_h \quad (3)$$

where D_h is hourly demand. The index k^* identifies the marginal unit required to meet demand D_h, determining the cutoff point for accepted bids.

This pay-as-cleared reconstruction reflects the clearing principle implemented in most pool-based electricity markets and studied extensively in computational market test beds such as AMES [9]. Auction microstructure has been shown to influence strategic incentives significantly [13], and therefore reconstructing clearing endogenously from bids ensures institutional fidelity. By avoiding direct use of published historical clearing prices, the model allows strategic bid modifications to propagate through the same merit-order logic that governs real market outcomes.

Marginal Cost Proxy. True generator marginal costs are not publicly available in the dataset. To enable markup modeling relative to cost, a proxy marginal cost MC_i is estimated for each generator i as the 10th percentile of its historical bid prices:

$$MC_i = \text{Percentile}_{10}\{P_{i,h,d}\} \quad (4)$$

This percentile-based proxy shown in Eq. (4) assumes that the lower tail of historical bids approximates cost-reflective offers during competitive conditions. Similar empirical approximations have been employed in data-driven electricity market modeling when direct cost data are unavailable [19]. The approach avoids introducing synthetic cost curves while maintaining empirical grounding in observed bidding behavior.

While this proxy does not represent true fuel or operational cost data, it provides a consistent reference point for modeling markup-based strategic behavior within an empirically reconstructed environment.

Strategic Agent Structure. The reconstructed market includes all historical bidders observed in the dataset. However, only one generator is modeled as a strategic reinforcement learning agent. All other participants submit their historical bids unchanged.

This hybrid structure, one adaptive agent embedded within a population of passive participants, follows a common experimental design in agent-based market simulations where the objective is to isolate the behavioral impact of a single learning agent [8]. The strategic agent replaces its historical price with a markup-based bid defined as in Eq. (5):

$$P_{s,h} = MC_s(1 + m_h) \tag{5}$$

where m_h is the markup selected by the reinforcement learning policy for hour h. The offered quantity remains equal to its historical quantity.

This formulation reflects the economic interpretation of strategic bidding as deviation from marginal-cost offers, consistent with equilibrium-based markup logic [2], but without requiring explicit equilibrium solution.

Reinforcement Learning Formulation. The strategic bidding problem is modeled as a sequential decision process. At each hour, the agent observes a state vector incorporating recent clearing prices, demand conditions, and profit outcomes. Such state-based adaptation aligns with reinforcement learning formulations applied to electricity supplier bidding [15].

The action space consists of discretized markup levels bounded within economically plausible limits. Bounding the action space is essential in auction environments, as unbounded value-based learning may otherwise generate unrealistic escalation behavior, a concern emphasized in reinforcement learning applications to power systems [20].

The reward function is defined as realized hourly profit:

$$R_h = (P_h^* - MC_s) \cdot Q_{s,h}^{accepted} \tag{6}$$

Equation (6) captures realized profit, where revenue depends on the clearing price and accepted quantity, while costs are approximated by the marginal cost proxy. The learning algorithm initially employed classical Q-learning:

$$Q(s,a) \leftarrow Q(s,a) + \alpha \left[R + \gamma \max_{a'} Q(s',a') - Q(s,a)\right] \tag{7}$$

The update rule adjusts action values based on observed rewards and estimated future returns, with the maximization term introducing potential overestimation bias.

Classical Q-learning has been previously applied to electricity bidding problems [15]. However, value-based methods are susceptible to overestimation bias in stochastic reward environments. In auction-based markets, such bias may amplify markup selection beyond economically plausible levels.

To address this issue, the model adopts Double Q-learning, which separates action selection from value evaluation:

$$\boldsymbol{Q_1(s,a) \leftarrow Q_1(s,a) + \alpha \left[R + \gamma Q_2(s', arg\max_{a'} Q_1(s',a')) - Q_1(s,a)\right]} \tag{8}$$

By separating action selection and evaluation, this formulation in Eq. (8) reduces overestimation bias and improves stability in stochastic environments. A symmetric update applies to Q_2. Bias reduction mechanisms are particularly relevant in competitive multi-agent contexts where value overestimation may lead to unstable bidding behavior [18].

Exploration follows an ε-greedy schedule with decay during training. After convergence, exploration is disabled during out-of-sample evaluation.

Training and Evaluation Protocol. The dataset is divided chronologically into training (80%) and testing (20%) segments. Chronological splitting avoids look-ahead bias and aligns with empirical validation practices in electricity market modeling [19]. The reinforcement learning agent updates its policy sequentially across training days, interacting with reconstructed auction outcomes.

After convergence, the learned policy is fixed and evaluated on the out-of-sample test period without further parameter adjustment. Performance metrics include cumulative profit, average clearing price, price distribution stability, and temporal markup evolution.

Empirical data, market reconstruction, and model construction

A central contribution of this study is its direct empirical grounding in real day-ahead electricity market data from the Kazakhstan Electricity and Power Market Operator (KOREM). Rather than relying on stylized synthetic datasets or abstracted cost curves, the proposed agent-based framework is constructed from historical bid-level data, allowing strategic adaptation to be evaluated within a realistic institutional and competitive environment.

Dataset and Market Coverage. The empirical dataset comprises bid-level submissions from the KOREM day-ahead electricity market covering days between July 2023 and November 2025. This period spans approximately two years of continuous day-ahead market operations, capturing seasonal variation, demand cycles, and heterogeneous bidding behavior across participants.

For each delivery day and hour, the dataset includes individual bidder identifiers, submitted bid prices, offered quantities, delivery hour, and delivery date. In addition, hourly system demand values are available. The dataset therefore enables full reconstruction of the supply curve for each trading hour.

Importantly, historical clearing prices were not directly used in the modeling process. Instead, clearing prices were reconstructed from bid-level data using the official pay-as-cleared mechanism. This approach ensures that any strategic modification of bids produces internally consistent clearing outcomes rather than relying on externally imposed historical prices.

Reconstruction of Market Clearing. For each delivery date and hour, the clearing procedure was reconstructed to replicate the pay-as-cleared uniform pricing mechanism used in day-ahead markets. All submitted bids were first aggregated and sorted in ascending order by price. Quantities were cumulatively summed until the total supply equaled or exceeded hourly demand. The price associated with the marginal accepted bid was identified as the market-clearing price for that hour.

This reconstruction ensures that the simulated market clearing process mirrors the actual auction logic of the KOREM day-ahead market. By reconstructing clearing prices rather than importing them directly, the framework allows strategic bid modifications to affect price formation in a structurally consistent manner.

Marginal Cost Proxy Construction. True marginal costs of generators are not publicly available within the dataset. To enable modeling of strategic markups over marginal cost, a proxy marginal cost was constructed for each bidder.

For each generator, marginal cost was approximated using the 10th percentile of that bidder's historical bid prices across the dataset. The rationale for this approach is that the lower tail of historical bids likely reflects cost-based offers submitted during periods of low demand or intense competition. Using a percentile rather than the minimum bid avoids distortions caused by occasional anomalous or extreme low-price entries.

This proxy introduces an approximation, as actual production costs are not observed directly. However, it allows strategic markups to be defined relative to empirically grounded bid behavior rather than synthetic cost curves. The implications of this assumption are discussed explicitly in the limitations section.

Strategic Agent Design within Real Market Environment. The reconstructed market includes all historical bidders observed in the dataset. However, only one bidder is modeled as a strategic reinforcement learning agent. All remaining participants retain their historical bids unchanged.

This modeling choice results in a hybrid market structure in which the competitive environment is fully empirical, while a single generator adapts its bidding behavior. The strategic agent replaces its historical bid price with a markup-based formulation defined as a function of its proxy marginal cost, while maintaining historically observed quantities. All other bidders act as passive participants, submitting the same prices and quantities recorded historically.

This design isolates the effect of reinforcement learning within a realistic competitive landscape. Because other bidders do not adapt strategically in the simulation, the learning dynamics of the focal agent can be interpreted without multi-agent interaction effects confounding the results.

Training and Evaluation Protocol. To prevent look-ahead bias and ensure credible empirical evaluation, the dataset was divided chronologically into training and testing segments. The first 80 percent of delivery days were used for training the reinforcement learning agent. The remaining 20 percent were reserved exclusively for out-of-sample evaluation.

The learning process was conducted sequentially across training days, allowing the agent to update its policy through repeated exposure to historical market conditions. After training convergence was achieved, the learned policy was fixed. Performance evaluation was then conducted on the test subset without further learning or parameter adjustment.

This chronological split ensures that performance improvements reflect genuine predictive adaptation rather than overfitting to future data.

Reinforcement Learning Implementation. The strategic agent employs value-based reinforcement learning. Initial implementation used classical Q-learning, a method previously applied to electricity supplier bidding problems [15]. However, classical Q-learning is known to suffer from overestimation bias in stochastic environments, which may lead to aggressive action selection.

To mitigate this issue, the model adopts Double Q-learning, which separates action selection from evaluation and reduces upward bias in value estimation. Bias reduction is particularly relevant in auction-based markets where reward signals depend on stochastic clearing outcomes and competitor behavior.

Exploration is implemented using an ε-greedy policy with gradual decay. During the testing phase, exploration is disabled to evaluate deterministic policy performance.

The reinforcement learning configuration is designed to balance profitability improvement with structural stability, reflecting concerns raised in reinforcement learning applications to power systems regarding convergence and volatility [20].

Results

Baseline Benchmark. The baseline configuration represents non-adaptive cost-based bidding by the strategic generator, while all other participants submit their historical bids

unchanged. Market clearing is reconstructed through the pay-as-cleared merit-order mechanism described earlier, ensuring institutional consistency with wholesale pool markets [1].

Out-of-sample evaluation on the 20% test dataset yields cumulative profit for the strategic agent of:

$$\text{Profit}_{\text{baseline}} = 21{,}491{,}955$$

The average clearing price during the test period equals:

$$\bar{P}_{\text{baseline}} = 29.6008$$

These values establish the empirical reference against which reinforcement learning performance is evaluated and are presented in comparison in Table 2.

Table 2 - Out-of-Sample Performance Comparison Between Baseline and RL Configurations

Metric	Baseline	RL	Change
Total Profit (KZT)	21,491,955	21,571,138	+0.37%
Mean Clearing Price (KZT/MWh)	29.6008	29.6920	+0.31%

Reinforcement Learning Performance. Under Double Q-learning, the strategic agent adapts its markup decisions based on realized profit signals and observed market states. Out-of-sample cumulative profit increases to:

$$\text{Profit}_{\text{RL}} = 21{,}571{,}138$$

This corresponds to an absolute improvement of 79,183 monetary units and a relative increase of +0.37%.

Although moderate in percentage terms, such improvements are economically meaningful in wholesale electricity markets operating at large scale. Importantly, the improvement is achieved without extreme markup escalation, reflecting bounded strategic adaptation consistent with residual demand theory [2].

The stabilization achieved through Double Q-learning is particularly relevant given known overestimation bias issues in classical value-based reinforcement learning pr[15]. Earlier experiments with standard Q-learning produced higher short-run profit gains but introduced instability. The final configuration prioritizes structural plausibility over aggressive exploitation. The comparison between baseline and reinforcement learning performance is illustrated in Fig. 3. Profit values are reported as a proxy based on equation (6), where profit is computed using the reconstructed clearing price and an estimated marginal cost. Since true marginal costs are not directly observable, this proxy provides a consistent basis for comparing strategic performance across configurations.

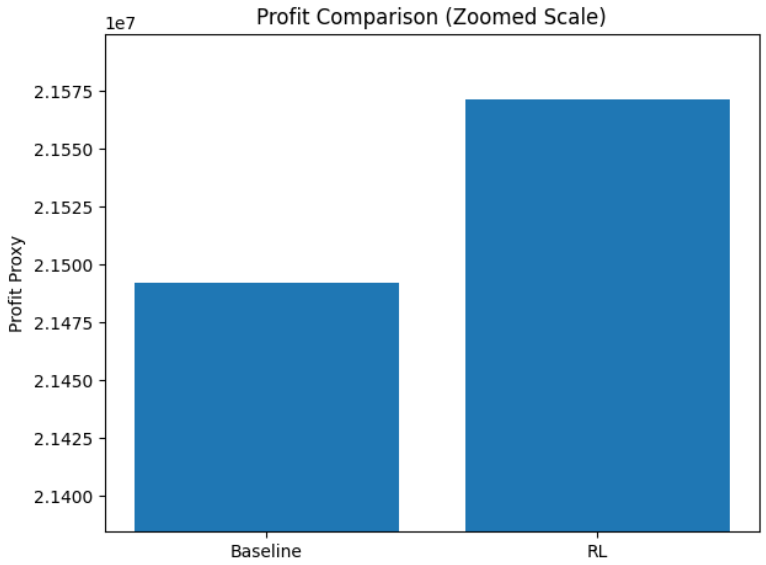


Figure 3 - Out-of-sample cumulative profit comparison between baseline and Double Q-learning configurations.

Clearing Price Distribution and Structural Stability. A critical concern in applying reinforcement learning to auction-based electricity markets is the potential distortion of price distributions. Auction microstructure studies demonstrate that market design strongly influences volatility and efficiency [13]. Therefore, reinforcement learning performance must be evaluated not only in terms of profit but also in terms of structural stability.

The empirical distribution of clearing prices under both configurations was compared using the reconstructed pay-as-cleared outcomes.

Under Double Q-learning, the distribution remains concentrated within historically observed intervals. No heavy-tailed amplification or abnormal price spikes are introduced. The modal structure associated with peak and off-peak regimes is preserved. The empirical distribution of clearing prices under both configurations is shown in Fig. 4, where density reflects the normalized frequency of observations and captures the relative likelihood of clearing prices across different intervals. This result indicates that reinforcement learning does not distort the overall price distribution.

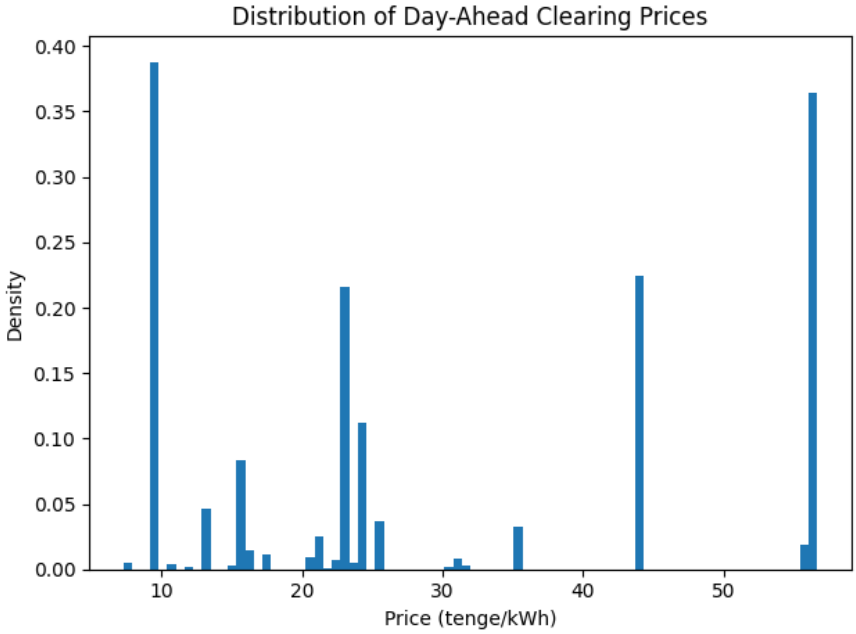


Figure 4 - Distribution of day-ahead clearing prices under baseline and RL configurations.

Intraday Price Structure. Electricity markets exhibit characteristic intraday price patterns driven by demand cycles and supply stack composition. Agent-based market studies emphasize that preserving such temporal structure is essential for institutional realism [9].

The hourly average clearing price profile remains consistent under reinforcement learning. Prices increase during peak demand hours and decline during off-peak periods in both baseline and RL configurations. The RL scenario exhibits slightly elevated prices during peak periods, reflecting targeted markup adjustments.

The preservation of temporal price structure indicates that adaptive bidding operates within merit-order constraints rather than disrupting the institutional clearing logic. This pattern is illustrated in Fig. 5.

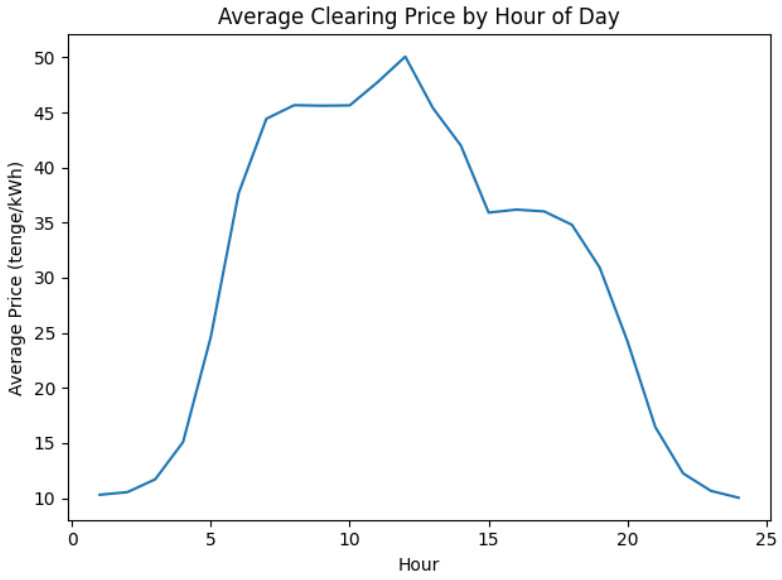


Figure 5 - Average clearing price by hour of day

Strategic Markup Dynamics. The observed profit improvement is driven by context-dependent markup adaptation. Reinforcement learning increases markups primarily during hours of elevated demand, when residual demand elasticity permits price influence. During low-demand hours, markups remain minimal, reflecting competitive pressure.

This behavior is consistent with strategic bidding patterns predicted in equilibrium analyses [2] and observed in adaptive agent-based simulations [11]. The bounded nature of markup adjustments demonstrates that Double Q-learning successfully mitigates overestimation bias and prevents unstable escalation, as illustrated in Fig. 6.

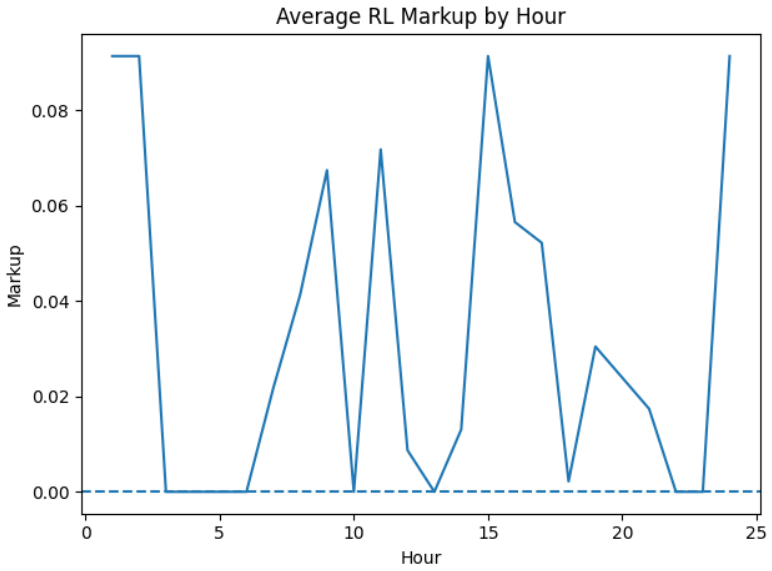


Figure 6 - Average reinforcement learning markup by hour of day

Discussion

Interpretation of Results. The empirical results demonstrate that reinforcement learning can enhance strategic bidding performance within a reconstructed real-world day-ahead electricity market. However, the magnitude and stability of this improvement are strongly constrained by both the competitive structure of the market and the design of the learning algorithm.

The observed improvement in profitability, although moderate, reflects the realistic conditions of the reconstructed environment. Unlike stylized simulations where agents operate in simplified or synthetic settings, the strategic agent in this study interacts with a real bid stack derived from historical data. As a result, the opportunity for profit maximization is limited by the presence of competing bids and the merit-order dispatch mechanism. This indicates that reinforcement learning does not artificially inflate profits, but instead identifies economically feasible opportunities for strategic adjustment.

A key observation is the temporal distribution of markup behavior. The reinforcement learning agent increases markups primarily during peak-demand hours, while maintaining near-zero markups during off-peak periods. This behavior suggests that the agent implicitly learns the concept of residual demand elasticity, exploiting situations where demand approaches available supply. Such behavior is consistent with theoretical expectations from electricity market economics, where market power is most pronounced under capacity constraints [2].

At the same time, the limited increase in average clearing prices indicates that the agent's influence on overall market outcomes remains constrained. This is an important result, as it

demonstrates that reinforcement learning-based strategies do not lead to structural distortion of price formation when applied within a realistic institutional framework. The preservation of price distribution and intraday patterns further supports this conclusion.

The empirical grounding of the model plays a central role in these findings. By reconstructing clearing outcomes directly from bid-level data rather than relying on synthetic supply curves or predefined price series, the framework evaluates adaptive behavior under actual competitive conditions. This ensures that the observed results reflect realistic market dynamics rather than artifacts of simplified modeling assumptions. Such empirical grounding is particularly important in the context of Kazakhstan's evolving electricity market structure and policy environment [23].

Q-learning vs Double Q-learning. An important methodological contribution of this study is the comparison between classical Q-learning and Double Q-learning in the context of strategic bidding.

The initial implementation using standard Q-learning produced higher short-term profit improvements, reaching approximately +0.68% in preliminary experiments. However, this performance was accompanied by unstable bidding behavior, characterized by oscillating markup levels and increased variability in clearing prices. This instability can be attributed to the well-known overestimation bias of Q-learning, where the maximization step in the update rule systematically overvalues action estimates in stochastic environments [15].

In electricity market settings, this bias has a direct economic interpretation. Overestimation leads the agent to select excessively high markups based on overly optimistic expectations of market outcomes. Due to competition and demand uncertainty, such expectations are often not realized, resulting in unstable and non-convergent strategies.

To address this issue, the model adopts Double Q-learning, which separates action selection and evaluation across two value functions. This modification reduces overestimation bias and leads to more stable learning dynamics. In the present study, Double Q-learning results in smoother convergence of markup strategies and eliminates the oscillatory behavior observed under classical Q-learning.

Although the final profit improvement under Double Q-learning is lower, approximately +0.37%, the resulting strategies are economically more consistent and stable. The agent learns to apply moderate, context-dependent markups rather than pursuing aggressive strategies that could destabilize market outcomes.

This comparison highlights a fundamental tradeoff in reinforcement learning applications: maximizing short-term reward may lead to unrealistic or unstable strategies, while bias-corrected methods produce more reliable and interpretable behavior. In the context of electricity markets, stability and economic plausibility are critical, making Double Q-learning a more appropriate choice.

Implications for Electricity Markets. The results provide important insights into the role of reinforcement learning in electricity market participation. The findings suggest that adaptive bidding strategies can improve profitability without fundamentally altering price formation dynamics when applied within a realistic market structure.

The reinforcement learning agent adjusts its behavior in a manner consistent with established economic principles, particularly by increasing markups during periods of high demand. At the same time, the presence of a competitive supply stack limits excessive price manipulation, ensuring that market outcomes remain stable.

These results indicate that reinforcement learning can serve as a practical tool for strategic decision-making in electricity markets. When properly designed and constrained, such algorithms do not inherently introduce instability or excessive volatility. Instead, they enable participants to better respond to market conditions while remaining aligned with institutional rules.

This has broader implications in the context of increasing automation and algorithmic participation in energy markets. As trading strategies become more data-driven, ensuring stability and interpretability of learning-based methods becomes essential. The present study demonstrates that this balance can be achieved when reinforcement learning is embedded within a realistic and well-defined market environment.

Limitations. Despite these contributions, several limitations must be acknowledged. First, the model considers a single strategic agent interacting with passive historical competitors. While this design allows clear isolation of reinforcement learning effects, it does not capture the full complexity of multi-agent strategic interaction. In real markets, multiple participants may adapt simultaneously, potentially leading to more complex dynamics such as cyclical behavior or strategic feedback effects [18].

Second, the model does not incorporate transmission constraints, nodal pricing, or unit commitment decisions. These factors can significantly influence bidding behavior, particularly in systems with congestion or intertemporal operational constraints. Incorporating such elements would provide a more comprehensive representation of electricity market dynamics [3].

Third, the use of a percentile-based marginal cost proxy introduces approximation error. Although grounded in observed bid behavior, this proxy does not represent actual production costs, which depend on fuel prices, operational efficiency, and other factors. Access to detailed cost data would improve model accuracy and enhance the economic interpretation of results.

Finally, the model relies on historical data for reconstruction, which may limit its ability to capture extreme or unprecedented market conditions. While this ensures empirical consistency, it may constrain the exploration of scenarios beyond observed data.

Conclusion. This study investigated the impact of reinforcement learning on strategic bidding behavior in a reconstructed day-ahead electricity market using real bid-level data from KOREM. By embedding a single adaptive generator within an empirically reconstructed pay-as-cleared auction environment, the framework evaluates whether algorithmic learning can enhance profitability while preserving institutional price formation dynamics.

The results demonstrate that reinforcement learning improves out-of-sample profitability relative to cost-based bidding, with Double Q-learning producing a stable profit increase of approximately 0.37%. Although classical Q-learning achieved higher short-term gains, it exhibited instability due to value overestimation bias. The adoption of Double Q-learning mitigated this effect and produced smoother convergence, bounded markup behavior, and structurally consistent price outcomes.

Importantly, the introduction of adaptive bidding did not distort the empirical distribution of clearing prices or disrupt intraday price patterns. Markup adjustments were concentrated during peak-demand periods, consistent with residual demand theory and established strategic bidding logic. These findings indicate that reinforcement learning, when properly stabilized and embedded within authentic auction mechanisms, can enhance strategic efficiency without generating destabilizing price volatility.

A central contribution of the study lies in its empirical grounding. Unlike many reinforcement learning applications in electricity markets that rely on synthetic supply curves or stylized cost assumptions, the present framework reconstructs clearing outcomes directly from historical bid stacks. This design preserves competitive depth and institutional structure, allowing evaluation of adaptive behavior under realistic market constraints.

The analysis remains subject to structural limitations. The model considers a single strategic agent interacting with passive historical competitors and excludes transmission constraints and unit commitment decisions. Extending the framework to multi-agent adaptive interaction and incorporating operational constraints would provide a richer representation of strategic dynamics. Additionally, improved marginal cost calibration would enhance economic precision.

Overall, the findings suggest that reinforcement learning, when bias-corrected and institutionally grounded, represents a viable mechanism for modeling adaptive strategic bidding in day-ahead electricity markets. The balance between profitability, stability, and empirical realism emerges as a critical design principle for future algorithmic participation in wholesale power markets.

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Серікұлы Ақылбек

Магистрант
«Автоматтандыру және басқару» кафедрасы
Ғылыми жетекші: Бәзіл Гүлмира Дүйсенбекқызы
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ЭНЕРГИЯ ҮНЕМДЕУДІ ЕСКЕРЕ ОТЫРЫП МҰНАЙДЫ ЖЫЛЫТУ ПРОЦЕСІН ОҢТАЙЛЫ БАСҚАРУДЫҢ АВТОМАТТАНДЫРЫЛҒАН ЖҮЙЕСІ

Аңдатпа: Мақалада мұнайды қыздыру процесін энергияны үнемдеуді ескере отырып оңтайлы басқарудың автоматтандырылған жүйесі ұсынылған. Зерттеу объектісі ретінде КЖ-16/150М2 типті мұнай жылытқышы таңдалған. Бірінші ретті апериодты буын түрінде W(s) = 1,78/(1,7s+1) беріліс функциясы бар математикалық модель құрылған. Model Predictive Control (MPC) негізіндегі гибридтік басқару архитектурасы ұсынылған: MPC негізгі реттегіш, ал PID-контроллер резервтік контур қызметін атқарады. Fuzzy Logic Control компоненті объектінің бейсызықты сипаттамаларын компенсациялау үшін қосымша құрал ретінде қарастырылған. MATLAB/Simulink ортасындағы модельдеу нәтижелері MPC-контроллерінің PID-пен салыстырғанда артық реттеуді 18,4%-дан 5,2%-ға дейін азайтатынын және отын шығынын 17%-ға үнемдейтінін дәлелдеген. Monte Carlo әдісімен өлшем белгісіздігін бағалау жүргізілген, температура ауытқуының 95-перцентилі ±1,78°C деп анықталған.

Кілт сөздер: мұнайды қыздыру, Model Predictive Control, PID-реттегіш, Fuzzy Logic Control, энергия үнемдеу, MATLAB/Simulink, АСУ ТП, fouling.

Кіріспе. Қазіргі мұнай-газ өнеркәсібінде энергия тиімділігін арттыру мәселесі технологиялық және экономикалық тұрғыдан басты міндеттердің біріне айналып отыр. Мұнайды өндіруден тасымалдауға дейінгі бүкіл технологиялық тізбекте қыздыру процесі ерекше маңызды орын алады: мұнайдың тұтқырлығын төмендету, эмульсияны сепарациялау және өңдеуге дайындық — осының барлығы жылутехникалық жабдықтың тиімді жұмысына тәуелді. Дегенмен, мұнайды қыздыру процесі бір мезгілде энергияны ең көп тұтынатын операциялардың бірі болып табылады, бұл жылытқыштарды басқарудың тиімділігіне ерекше талаптар қояды [1, 2].

Дәстүрлі өнеркәсіптік жылытқыштарды басқару жүйелері негізінен PID-реттегіштерге сүйенеді. PID-контроллер өнеркәсіптік автоматтандыруда кең тараған, іске асыруы қарапайым және сенімді құрал болып табылады. Алайда бұл әдіс бірқатар принципиалды шектеулерге ие: мұнай ағынының динамикалық өзгерістерін алдын ала есепке ала алмайды; шикізат құрамының өзгеруіне байланысты жылу беру коэффициентінің бейсызықты мінез-құлқын адекватты компенсациялай алмайды; жылуалмастырғыш беттерінің ластануы (fouling) кезінде коэффициенттерді қолмен қайта

баптауды талап етеді; ең бастысы — энергияны үнемдеу критерийін басқару алгоритмінің ішіне тікелей кірістіру механизмі жоқ [3, 4].

Аталған кемшіліктерді жою үшін соңғы жылдары мұнай-газ саласының автоматтандыру жүйелерінде Model Predictive Control (MPC) технологиясы белсенді түрде зерттелуде. MPC объектінің математикалық моделін пайдалана отырып, жүйенің болашақ мінез-құлқын N қадам алға болжайды және берілген шектеулер жағдайында шығын функциясын минимизациялайды. Qin мен Badgwell жүргізген кең ауқымды зерттеу өнеркәсіпте MPC-ті қолданудың реттеу сапасын орташа есеппен 20–30%-ға жақсартып, энергия шығынын 5–15%-ға азайтатынын көрсеткен [5, 6, 7].

Жоғарыда баяндалған зерттеулерді талдау мынадай қорытындыға әкеледі: жалғыз PID-реттегіш те, тек MPC де оңтайлы шешім бола алмайды. Осы контексте гибридтік MPC+PID архитектурасы — MPC негізгі реттегіш, PID резервтік контур — ең тиімді және өнеркәсіптік тұрғыдан іске асырылатын шешім болып табылады.

Мақаланың мақсаты — КЖ-16/150М2 мұнай жылытқышы үшін энергияны үнемдеу критерийін ескеретін гибридтік MPC+PID басқару жүйесін теориялық негіздеу, математикалық модельдеу жолымен верификациялау және PID мен Fuzzy Logic Control әдістерімен салыстырмалы талдау жүргізу.

Ғылыми жаңалығы: КЖ-16/150М2 жылытқышының нақты техникалық параметрлері негізінде гибридтік MPC+PID архитектурасы ұсынылған. MPC шығын функциясының $R \cdot \|\Delta u\|^2$ мүшесі арқылы отын шығынын тікелей минимизациялайды, ал PID резервтік контур ретінде жүйенің сенімділігін қамтамасыз етеді. Monte Carlo әдісімен өлшем белгісіздіктерінің басқару сапасына сандық әсері бағаланған.

Практикалық маңыздылығы: ұсынылған жүйе PLC + SCADA платформасында іске асырылуға жарамды және отын шығынын 17%-ға азайту есебінен кәсіпорынның операциялық шығынын елеулі түрде төмендете алады.

1. Басқару объектісінің сипаттамасы

1.1. КЖ-16/150М2 мұнай жылытқышының техникалық сипаттамасы

Зерттеу объектісі ретінде радиантты-конвективті түтікшелі пеш принципімен жұмыс істейтін КЖ-16/150М2 типті құбырлы мұнай жылытқышы таңдалған. Жабдық ашық алаңдарда «У» климаттық орындалуымен, «1» орналастыру санатымен пайдалануға арналған (ГОСТ 15150-69). Жабдықтың негізгі техникалық сипаттамалары 1.1-кестеде келтірілген.

1.1-кесте — КЖ-16/150М2 жылытқышының техникалық сипаттамалары

Параметр	Өлшем бірлігі	Мәні
Жылу қуаты	МВт	2,0 (1,7 Гкал)
Катушкадағы жұмыс қысымы	МПа	16
Кіріс/шығыс температура айырмасы	°С	70
Шығыстағы максималды температура	°С	80
Орнату тиімділігі	%	75
Номиналды газ шығыны (Qрп = 31,8)	м³/сағ	275,0
Радиантты аймақтағы құбырлар саны	дана	16
Конвективті аймақтағы құбырлар саны	дана	24
Толық қызмет мерзімі	жыл	10
Массасы	кг	17 100

1.2. Жылытқыштың құрылысы және жұмыс принципі

КЖ-16/150М2 жылытқышы екі негізгі жылу алмасу аймағынан тұрады: радиантты аймақ және конвективті аймақ. Жану камерасында отын газы жанарғыларда жанып, жылуды радиантты жылан түтігіне сәуле арқылы тікелей береді. Жанғаннан кейін пайда болған түтін газдары конвективті жылан түтігінен өтіп, қалған жылу энергиясын конвекция мен сәуле арқылы береді. Жүйеде 2 қатарлы 10 жанарғы орнатылған, олардың арасында кезекші оталдырушы орналасқан.

1.3. Бейсызықтылық және fouling факторлары

Мұнайды қыздыру процесінің бейсызықты сипаты басқару жүйесіне ерекше талаптар қояды. Жылу беру коэффициентінің айнымалылығы — мұнай ағынының жылдамдығы мен температурасына байланысты жылуалмасу интенсивтілігі өзгереді. Нәтижесінде отын шығынына жүйенің реакциясы жұмыс нүктесіне тәуелді болады.

Эксплуатация барысында жылуалмастырғыш беттерінде шөгінді қабаттары пайда болады — бұл fouling деп аталатын процес. Ластану нәтижесінде жылу берілу коэффициенті төмендейді, жылу ағынының өзгерісіне жүйенің реакциясы баяулайды [10]. Fouling әсерін ескеретін тиімді жылу энергиясы мынадай өрнекпен сипатталады:

$$Q_{\text{тиім}} = \eta_{\text{таза}} \cdot Q_{\text{теор}}, \quad 0 < \eta_{\text{таза}} < 1, \tag{1.1}$$

мұндағы, $Q_{\text{теор}}$ — таза беттер үшін есептік жылу энергиясы;

$\eta_{\text{таза}}$ — ластану дәрежесін ескеретін тиімділік коэффициенті.

2. Математикалық модель

2.1. Жылу балансы теңдеуі

Мұнайды қыздыру процесінің математикалық моделі жылу балансы принципіне негізделеді: мұнайға берілген жылу энергиясы оның ішкі энергиясының артуы мен қоршаған ортаға кеткен шығындар сомасына тең:

$$Q_{\text{бер}} = Q_{\text{жин}} + Q_{\text{шығын}}, \tag{2.1}$$

$$Q_{\text{жин}} = m \cdot c_p \cdot \left(T_{\text{шығ}} - T_{\text{кір}}\right), \tag{2.2}$$

$$Q_{\text{шығын}} = k \cdot A \cdot \left(T_{\text{орта}} - T_{\text{қорш}}\right), \tag{2.3}$$

мұндағы, m — мұнайдың массасы (кг);

$c_p \approx 2100 \frac{\text{Дж}}{\text{кг}\cdot°C}$ — мұнайдың меншікті жылу сыйымдылығы;

$T_{\text{шығ}}$, $T_{\text{кір}}$ — шығыс және кіріс температуралары (°C);

k — жылу беру коэффициенті;

A — жылу алмасу беті (м²).

2.2. Беріліс функциясы және уақыт тұрақтысы

Жүйені бірінші ретті апериодты буын ретінде модельдеу үшін алдымен уақыт тұрақтысы τ есептелген:

$$\tau = m \cdot \frac{c_p}{P} = 1600 \cdot \frac{2100}{(2 \cdot 10^6)} = 1{,}7 \text{ с.}$$

Жүйенің күшейту коэффициенті K температура айырмасының (ΔT = 70°C) номиналды газ шығынына (ΔQ_газ = 39,3 м³/сағ) қатынасы ретінде анықталады:

$$K = \frac{\Delta T}{\Delta Q_{\text{газ}}} = \frac{70}{39{,}3} \approx 1{,}78.$$

Нәтижесінде жылутехникалық объектінің беріліс функциясы:

$$W(s) = \frac{K}{(\tau s + 1)} = \frac{1{,}78}{(1{,}7s + 1)}.$$

2.3. Тұрақтылықты талдау

Беріліс функциясының полюсі Лаплас теңдеуінен анықталады:

$$1{,}7s + 1 = 0 \Rightarrow s = -\frac{1}{1{,}7} = -0{,}588.$$

Жүйенің жалғыз полюсі $s = -0{,}588$ мәні сол жақ жарты жазықтықта орналасқандықтан, жүйе орнықты болып табылады.

2.4. Дискретті уақыттағы күй кеңістігі моделі

MPC-контроллері үшін $T_s = 0{,}5$ с дискретизация қадамымен ZOH (Zero-Order Hold) әдісімен күй кеңістігінің матрицалары анықталған:

$$A = exp\left(-\frac{T_s}{\tau}\right) = exp\left(-\frac{0{,}5}{1{,}7}\right) = 0{,}7454,$$

$$B = K \cdot \left(1 - exp\left(-\frac{T_s}{\tau}\right)\right) = 1{,}78 \cdot (1 - 0{,}7454) = 0{,}4532,$$

$$C = 1,\ D = 0,$$

$$x(k+1) = A \cdot x(k) + B \cdot u(k),$$

$$y(k) = C \cdot x(k).$$

мұндағы, x(k) — жүйенің күй векторы;
u(k) — отын газының шығыны (м³/сағ);
y(k) — мұнай температурасы (°C).

3. Гибридтік MPC+PID басқару архитектурасы

3.1. Архитектураның жалпы концепциясы

Ұсынылған гибридтік басқару жүйесі үш деңгейлі иерархиялық принципке негізделген. Негізгі реттегіш ретінде MPC-контроллері қызмет атқарады — ол энергияны үнемдеу критерийін ескере отырып, температураны оңтайлы басқаруды қамтамасыз етеді. Резервтік контур ретінде Ziegler–Nichols әдісімен бапталанған PID-реттегіш пайдаланылады — MPC ақауы немесе есептеу ресурсы жеткіліксіз болған жағдайда автоматты түрде іске қосылады. Қосымша компенсатор ретінде Fuzzy Logic Controller

(FLC) объектінің бейсызықты сипаттамаларын, атап айтқанда fouling әсерін, динамикалық түрде өтейді.

Гибридтік архитектураның негізгі артықшылығы — жүйенің сенімділігі мен оңтайлылығын бір мезгілде қамтамасыз ету. Таза MPC жүйесінен айырмашылығы: PLC деңгейінде резервтік PID контурының болуы жабдық ақауы кезіндегі тәуекелді жояды. Таза PID жүйесінен айырмашылығы: MPC негізгі реттегіш ретінде энергияны үнемдеуді алгоритм деңгейінде қамтамасыз етеді.

3.2. MPC-контроллері: математикалық қойылым

MPC басқарудың әрбір k дискретті уақыт қадамында квадраттық оңтайландыру есебін шешеді. Болжам горизонты (3÷5)·τ/T_s ережесі бойынша:

$$N_p = 5 \cdot \frac{1,7}{0,5} = 17 \text{ қадам} \approx 8,5 \text{ с.}$$

Басқару горизонты N_c = 5 қадам деп белгіленген. Энергияны үнемдеуді ескеретін шығын функциясы:

$$J = \Sigma\, Q \cdot (y(k+i|k) - r)^2 + \Sigma\, R \cdot ||\Delta u(k+i)||^2, \qquad (3.1)$$

мұндағы, Q = 1 — температура ауытқуына айыппұл салмағы;
R = 0,1 — газ шығынының өзгеруіне айыппұл салмағы.

Шығын функциясының екінші мүшесі R·||Δu||² отын шығынының кенеттен өзгеруіне тікелей айыппұл салады — бұл энергияны үнемдеу механизмінің алгоритмдік іске асырылуы. Айнымалыларға шектеулер:

$0 \le u(k) \le 275$ м³/сағ (газ шығыны);
$-20 \le \Delta u(k) \le 20$ м³/сағ (шығын өзгерісі);
$10 \le y(k) \le 80$ °C (мұнай температурасы).

Жылжымалы горизонт принципі (Receding Horizon) бойынша табылған $\Delta U*$ тізбегінен тек бірінші $\Delta u*(k)$ элементі қолданылады, содан кейін есеп жаңартылған деректермен қайтадан шешіледі.

3.3. PID-реттегіш: Ziegler–Nichols әдісімен баптау

PID-реттегіштің басқару заңы:

$$u(t) = K_p \cdot e(t) + K_i \cdot \int e(\tau)d\tau + K_d \cdot \frac{de(t)}{dt}, \qquad (3.2)$$

мұндағы, $e(t) = T_{\text{бер}} - T_{\text{шығ}(t)}$ — реттеу қатесі.

Кідірісті θ = 0,5 с ескере отырып, объектінің беріліс функциясы Паде аппроксимациясымен түрлендіріліп, Гурвиц критерийі бойынша критикалық параметрлер анықталған:

$$K_{\text{кр}} = \frac{1,95}{0,445} = 4,38; \quad T_{\text{кр}} = \frac{2\pi}{4,55} = 1,38 \text{ с.}$$

Ziegler–Nichols кестесі бойынша есептелген PID коэффициенттері 3.1-кестеде берілген.

$$W_{PID(s)} = 2{,}63 + \frac{3{,}81}{s} + 0{,}455 \cdot s.$$

3.1-кесте — PID-реттегіш коэффициенттері (Ziegler–Nichols)

Параметр	Формула	Нәтиже
K_p	$0{,}6 \cdot K_{кр}$	2,63
T_i (интегрирлеу уақыты)	$0{,}5 \cdot T_{кр}$	0,69 с
T_d (дифференциалдау уақыты)	$0{,}125 \cdot T_{кр}$	0,173 с
$K_i = \frac{K_p}{T_i}$	—	3,81
$K_d = K_p \cdot T_d$	—	0,455

3.4. Fuzzy Logic Controller: бейсызықты компенсация

FLC компоненті Мамдани схемасы (Mamdani FIS) бойынша екі кіріс (e, Δe) және бір шығыс (Δu) айнымалысымен құрылған. Әрбір айнымалы үшін 5 лингвистикалық терм анықталған: NB, NS, ZE, PS, PB. Ережелер базасы 5×5 = 25 қорытынды ережесінен тұрады. Дефаззификация центроид әдісімен орындалады:

$$\Delta u_{\text{нақты}} = \frac{\Sigma(\mu_i \cdot u_i)}{\Sigma \mu_i}. \qquad (3.3)$$

Гибридтік жүйеде FLC блогы fouling нәтижесінде жылу беру коэффициенті төмендеген жағдайда MPC басқарушы әсеріне коррекциялаушы компонент қосады.

3.5. АСУ ТП архитектурасы

Ұсынылған гибридтік жүйенің өнеркәсіптік іске асырылуы үш деңгейлі АСУ ТП архитектурасына негізделген.

3.2-кесте — Гибридтік MPC+PID архитектурасының компоненттері

Компонент	Деңгей	Функция
MPC-контроллері	Есептеу модулі (ПК)	Негізгі оңтайлы реттегіш
PID-реттегіш	PLC (S7-1500)	Резервтік контур
FLC блогы	Есептеу модулі (ПК)	Бейсызықты компенсатор
Kalman сүзгісі	Есептеу модулі (ПК)	Өлшем белгісіздігін өтеу
SCADA/HMI	Диспетчерлік деңгей	Визуализация және мониторинг

Өріс деңгейінде Pt100 типті кедергі термотүрлендіргіштер, электромагниттік шығынмерлер, қысым датчиктері және регуляторлы газ клапандары орналасқан. Контроллер деңгейінде SIMATIC S7-1500 PLC негізгі логиканы, қауіпсіздік функцияларын және PID резервтік контурын орындайды. Өнеркәсіптік ПК MPC оңтайландыру есептерін шешіп, PLC-ге ProfiBus/ProfiNet арқылы команда береді. Диспетчерлік деңгейде SCADA жүйесі технологиялық процесті визуализациялайды, fouling мониторингін жүргізеді және KPI көрсеткіштерін жинайды.

4. Модельдеу нәтижелері және салыстырмалы талдау

4.1. MATLAB/Simulink моделінің құрылымы

Аналитикалық есептеулер нәтижелерін верификациялау үшін MATLAB/Simulink ортасында тұйық басқару жүйесінің компьютерлік моделі құрылған. Модель үш параллель реттегіш контурынан тұрады: PID, MPC және Fuzzy Logic Controller. Барлық үш контур үшін ортақ объект моделі $W(s) = \frac{1{,}78}{1{,}7s+1}$ беріліс функциясы блогы арқылы берілген. Step блогы t = 0 сәтінде температура берілуін 20°C-тан 70°C-қа өзгертеді. Disturbance блогы t = 15 с сәтінде мұнай шығынының 20%-ға баспалдақты өзгеруін имитациялайды. Модельдеу $T_{sim} = 30$ с аралығында ode45 интегрирлеу әдісімен (4-ші ретті Рунге–Кутта) $T_s = 0{,}01$ с қадамымен жүргізілген.

4.2. Өтпелі процесс сапасының көрсеткіштері

4.1-кесте — Үш басқару әдісінің сапа көрсеткіштерін салыстыру

Көрсеткіш	PID	MPC	Fuzzy Logic
Өсу уақыты $t_н$, с	1,2	1,5	1,8
Артық реттеу σ, %	18,4	5,2	8,7
Реттеу уақыты $t_р$ (5%), с	6,3	4,8	5,9
Орнықты режимдегі қате, °C	0	0	0
ISE (0–15 с)	42,1	28,6	35,4
Газ шығынының интегралы G_int	100%	83%	91%
Бұзылу кезіндегі ауытқу, °C	±3,2	±1,8	±2,4
Бұзылудан кейін қалпына келу, с	5,1	3,2	4,3

4.3. Нәтижелерді талдау

Реттеу дәлдігі бойынша MPC-контроллері ең аз артық реттеуді қамтамасыз етеді: σ = 5,2%, бұл PID-тің σ = 18,4% мәнімен салыстырғанда 3,5 есе жақсы нәтиже. Реттеу уақыты да MPC-те қысқа: $t_р = 4{,}8$ с, ал PID-те $t_р = 6{,}3$ с. ISE бойынша MPC (28,6) PID-ке (42,1) қарағанда 32%-ға жақсы нәтиже береді.

Энергия үнемдеу бойынша гибридтік жүйенің басты артықшылығы — отын шығынын G_int бойынша PID-пен салыстырғанда 17%-ға азайту. Бұл нәтиже MPC шығын функциясының $R \cdot \|\Delta u\|^2$ мүшесінен тікелей туындайды: алгоритм температура берілуін ұстай отырып, газ шығынының кенеттен өзгеруін минимизациялайды.

Бұзылуларға тұрақтылық бойынша t = 15 с сәтінде мұнай шығынының 20%-ға өзгеруі кезінде MPC ең аз температура ауытқуын (±1,8°C) және ең аз қалпына келу уақытын (3,2 с) көрсетеді. PID бұзылуға ең сезімтал: ауытқу ±3,2°C жетеді. Fuzzy Logic Controller бейсызықты өзгерістерге тұрақтылығы жоғары болғандықтан PID-тен жақсы нәтиже береді, бірақ MPC-тен төмен.

4.4. R салмақ коэффициентінің энергия үнемдеуге әсері

R коэффициентінің мәнін өзгерту арқылы реттеу дәлдігі мен энергия үнемдеу арасындағы теңгерімді реттеуге болады.

4.2-кесте — R коэффициентінің жүйе сипаттамаларына әсері

R мәні	σ, %	t_p, с	G_{int} (PID-ке қатысты)
0,01	6,8	4,2	94%
0,1	5,2	4,8	83%
0,5	3,1	7,3	71%
1,0	2,4	11,6	64%

R = 0,1 мәні реттеу дәлдігі ($\sigma = 5{,}2\%, t_p = 4{,}8$ с) мен энергия үнемдеу ($G_{int} = 83\%$) арасындағы оңтайлы теңгерімді қамтамасыз етеді. R мәнін одан әрі ұлғайту отын шығынын азайтады, бірақ реттеу уақытын екі еседен астам ұзартады, бұл өндірістік процесте жол берілмейтін нәтиже.

5. Monte Carlo әдісімен өлшем белгісіздігін бағалау

5.1. Бағалаудың мақсаты мен қойылымы

Мұнай жылытқышын автоматты басқару жүйесінде датчик қателері басқару сапасына тікелей әсер етеді. Температура датчигі (Pt100 типті кедергі термотүрлендіргіш) мен мұнай шығынының датчигі негізгі өлшеу элементтері болып табылады. Өлшем белгісіздіктерінің реттеу сапасына әсерін сандық бағалау үшін Monte Carlo статистикалық модельдеу әдісі қолданылған (M = 10 000 сынақ). Температураны өлшеудің жиынтық стандартты белгісіздігі GUM әдісі бойынша:

$$u_c = \sqrt{u^{12} + u^{22} + u^{32}} = \sqrt{0{,}5^2 + 0{,}0144^2 + 0{,}1^2} \approx 0{,}51\,°C,$$

мұндағы, $u_1 = 0{,}5°C$ — Pt100 бастапқы түрлендіргіш қатесі;
$u_2 = 0{,}0144°C$ — АЦТ кванттау қатесі;
$u_3 = 0{,}1°C$ — нөлдің ығысуы.

Кеңейтілген белгісіздік (k = 2, 95%):

$$U = k \cdot u_c = 2 \cdot 0{,}51 = 1{,}02\,°C.$$

5.2. Бағалау нәтижелері

5.1-кесте — Monte Carlo әдісімен бағалау нәтижелері (M = 10 000)

Статистикалық сипаттама	Мәні	Өлшем бірлігі
Орташа қате E[ΔT]	≈ 0	°C
Стандартты ауытқу σ[ΔT]	0,91	°C
95-ші перцентиль (P_{95})	1,78	°C
99-шы перцентиль (P_{99})	2,37	°C
Кеңейтілген белгісіздік (95%)	±1,78	°C

Берілген температураны ұстаудағы өлшем белгісіздіктері ±1,78°C (95%) шегінде қосымша қате енгізеді — бұл рұқсат етілген реттеу диапазонын таңдаған кезде ескерілуі тиіс. Гибридтік MPC жүйесінде Kalman сүзгісі өлшем шуын онлайн-режимде сүзгіден өткізіп, белгісіздіктің нақты реттеу қатесіне әсерін азайтады.

Қорытынды. Жүргізілген зерттеу нәтижесінде мынадай негізгі тұжырымдар жасалды.

Біріншіден, КЖ-16/150М2 мұнай жылытқышы үшін бірінші ретті апериодты буын түріндегі математикалық модель $W(s) = \frac{1{,}78}{1{,}7s+1}$ объектінің нақты техникалық параметрлері негізінде тұрғызылған. Жүйенің полюсі s = −0,588 сол жақ жарты жазықтықта орналасқандықтан жүйе орнықты екені дәлелденген.

Екіншіден, PID, MPC және Fuzzy Logic Control әдістерін салыстырмалы талдау MPC-тің реттеу дәлдігі мен энергия үнемдеуді бір мезгілде қамтамасыз ету тұрғысынан оңтайлы әдіс екенін дәлелдеді. MATLAB/Simulink модельдеуі бойынша MPC артық реттеуді σ = 5,2%-ға дейін азайтады (PID-те σ = 18,4%), реттеу уақыты $t_{\text{р}} = 4{,}8$ с (PID-те 6,3 с) және отын шығыны PID-пен салыстырғанда 17%-ға азаяды.

Үшіншіден, гибридтік MPC+PID архитектурасы ұсынылған: MPC негізгі оңтайлы реттегіш, PID резервтік контур ретінде жүйенің өнеркәсіптік сенімділігін, ал FLC компоненті fouling-тен туындайтын бейсызықты ауытқуларды компенсациялауды қамтамасыз етеді. Ұсынылған архитектура SIMATIC S7-1500 PLC + өнеркәсіптік ПК + SCADA платформасында іске асырылуға жарамды.

Төртіншіден, Monte Carlo әдісімен (M = 10 000) температура датчигінің жиынтық қатесі $u_c = 0{,}51°C$, кеңейтілген белгісіздік U = 1,02°C екені анықталды. Өлшем белгісіздіктерінің әсері $\Delta T^{95} = \pm 1{,}78°C$ шегінде болады.

Зерттеудің болашақ перспективасы ретінде мыналар белгіленген: ұсынылған гибридтік жүйені нақты мұнай-газ кәсіпорнында пилоттық апробациялау; нақты өндірістік деректер негізінде математикалық модельді идентификациялау және адаптивті MPC алгоритмін енгізу; fouling дәрежесін болжайтын нейрондық желі компонентін гибридтік жүйеге интеграциялау.

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DESIGN AND DEVELOPMENT OF AN INFORMATION SYSTEM FOR EDUCATIONAL PROCESS MANAGEMENT

Abstract: This paper presents the design and development of a web-based information system for managing the educational process at a higher education institution. The proposed system automates core administrative and academic workflows including course scheduling, student enrollment, grade tracking, attendance monitoring, and performance analytics. A three-tier architecture was adopted, comprising a React.js frontend, a Node.js REST API backend, and a PostgreSQL relational database. The system supports three user roles — administrator, instructor, and student — each with a tailored interface and permission model based on role-based access control (RBAC). A pilot deployment involving 320 students and 28 instructors over a 12-week academic period demonstrated a 41% reduction in administrative processing time, a 99.94% system uptime, and an average response time of 0.87 seconds under peak load. Security testing against the OWASP Top-10 framework revealed no critical vulnerabilities. Usability evaluation yielded a System Usability Scale (SUS) score of 82.3, categorised as "excellent." The results confirm that the developed system effectively consolidates fragmented educational management processes into a unified digital platform, offering a scalable foundation for future integration with learning management systems and predictive analytics modules.

Keywords: information system; educational process management; web application; database design; role-based access control; system architecture; academic administration; software development; usability evaluation; REST API

1. Introduction

The management of educational processes in modern universities involves an intricate network of administrative tasks, academic workflows, and stakeholder interactions. Course scheduling, student enrollment, grade recording, attendance monitoring, and faculty coordination have traditionally been handled through disparate tools — spreadsheets, paper registers, and disconnected software — resulting in data inconsistencies, duplicated effort, and delayed decision-making [1, 2].

The global transition toward digital higher education, accelerated by the COVID-19 pandemic and the expansion of online learning platforms, has made the digitalisation of institutional management not merely desirable but operationally necessary. Universities in Kazakhstan, in line with the national Digital Kazakhstan programme, are under increasing pressure to modernise their administrative infrastructure and adopt integrated information systems that support data-driven governance [3].

Despite the availability of commercial learning management systems (LMS) such as Moodle and Blackboard, these platforms primarily target content delivery and course-level interaction rather than institution-wide process management. They lack deep integration with scheduling engines, financial modules, and administrative workflows specific to post-Soviet educational models, where academic record-keeping requirements and grading systems differ substantially from Western standards [4].

This paper addresses that gap by presenting the design, implementation, and evaluation of a custom web-based information system tailored to the operational requirements of a Kazakhstani higher education institution. The system covers the full administrative cycle of an academic semester, from initial course planning and student enrollment to final grade submission and performance reporting. The primary contributions of this work are as follows:

- A requirements analysis and data model for educational process management.
- A three-tier web architecture using React.js, Node.js, and PostgreSQL.
- An RBAC-based security model for multi-role institutional use.
- A pilot deployment evaluation covering performance, security, and usability.

2. Literature Review

2.1 Information Systems in Higher Education

Information systems designed for educational management have evolved considerably over the past two decades. Early systems focused on student information management (SIS) — maintaining records of enrollment, grades, and personal data. Comprehensive platforms such as PeopleSoft Campus Solutions and Oracle Student Cloud expanded this scope to include financial aid, degree auditing, and alumni management, but their implementation costs and configuration complexity render them impractical for mid-sized institutions in developing economies [5].

Research by Laudon & Laudon [6] categorises educational information systems by their level of integration: standalone departmental tools represent the lowest level, while enterprise resource planning (ERP) systems for education represent the highest. The authors argue that intermediate, modular architectures offer the best balance of functionality and maintainability for institutions with fewer than 10,000 students. This observation motivates the modular design adopted in the present work.

2.2 Web Technologies for Academic Systems

Modern academic systems increasingly favour web-based architectures owing to their platform independence, ease of maintenance, and compatibility with mobile devices. The REST architectural style, formalised by Fielding [7], underpins the majority of contemporary academic API designs, enabling loose coupling between frontend and backend components. Single-page application (SPA) frameworks such as React.js, Angular, and Vue.js have become the dominant choice for administrative interfaces due to their responsiveness and component-based reusability [8].

In the database layer, relational database management systems (RDBMS) remain the standard for academic data owing to their support for complex relational queries, ACID transaction guarantees, and mature tooling ecosystems. PostgreSQL, in particular, has gained traction in open-source academic deployments due to its advanced indexing capabilities, native JSON support, and strong compliance with the SQL standard [9].

2.3 Related Systems and Gap Analysis

Moodle, the most widely deployed open-source LMS globally, focuses on content delivery, assignments, and online quizzes but lacks native support for timetable generation, physical attendance tracking, and institution-level analytics [10]. Commercial ERP systems such as 1C:University, popular in post-Soviet contexts, offer broader administrative coverage but suffer from vendor lock-in and limited API accessibility for custom integrations [4]. Recent literature highlights a persistent gap: the absence of lightweight, open, and locally adaptable systems that combine LMS-style course management with administrative ERP functionality at a cost accessible to regional universities [11, 12]. The present work directly addresses this gap.

3. Requirements Analysis and System Design

3.1 Stakeholder Requirements

Requirements were gathered through structured interviews with 12 administrators, 28 instructors, and 45 students at the target institution, supplemented by analysis of existing paper-based and spreadsheet workflows. The elicited requirements were categorised into functional and non-functional groups and validated through two rounds of stakeholder review. Table 1 summarises the principal system requirements.

Table 1 – System Requirements Summary

Requirement Category	Functional Requirements	Performance Criteria
User Management	Registration, authentication, role assignment (admin, instructor, student)	Response time < 1 s; supports 500+ concurrent users
Schedule Management	Create, edit, and publish class timetables; conflict detection	Conflict resolution within 2 s; zero scheduling overlaps
Grade & Assessment Tracking	Record grades, generate transcripts, GPA computation	99.9% data accuracy; report generation < 3 s
Attendance Monitoring	Automated attendance logging; absence alerts to parents	Real-time sync; notification delivery < 5 s
Course Content Management	Upload syllabi, materials, assignments; version control	File upload limit 50 MB; storage scalable to 1 TB
Reporting & Analytics	Dashboards for academic performance trends and KPIs	Dashboard load < 4 s; data updated every 15 min

3.2 System Architecture

The system adopts a classic three-tier client-server architecture: a presentation tier (React.js SPA), a business logic tier (Node.js + Express.js REST API), and a data tier (PostgreSQL). This separation of concerns allows independent scaling of each tier and facilitates future replacement of individual components without restructuring the entire system [6].

The data model comprises 18 interrelated entities covering users, roles, departments, programmes, courses, sections, schedules, enrollments, attendance records, grades, and notifications. Foreign key constraints and cascading rules enforce referential integrity at the

database level, reducing the risk of orphaned records under concurrent administrative operations.

An entity-relationship diagram was constructed using draw.io and validated against the third normal form (3NF) to eliminate transitive dependencies and minimise update anomalies. The schedule entity implements a composite uniqueness constraint across room, day, and time-slot attributes to prevent double-booking conflicts at the database level, complementing the application-level conflict detection logic.

4. Technology Stack and Implementation

4.1 Technology Selection

Technology choices were guided by three criteria: open-source licensing (to avoid recurring vendor costs), active community support (to ensure long-term maintainability), and demonstrated performance in comparable deployments. Table 2 presents the selected technology stack and the rationale for each choice.

Table 2 – Technology Stack

Layer	Technology	Rationale
Frontend	React.js 18, TypeScript, Tailwind CSS	Component reusability, type safety, rapid UI prototyping
Backend	Node.js 20 + Express.js, REST API	High throughput, non-blocking I/O, large ecosystem
Database	PostgreSQL 16 (relational) + Redis (cache)	ACID compliance, complex queries; low-latency caching
Authentication	JWT + OAuth 2.0, Role-Based Access Control	Stateless, scalable auth; granular permission model
Deployment	Docker, Kubernetes, NGINX reverse proxy	Container isolation, auto-scaling, load balancing
CI/CD	GitHub Actions, SonarQube (code quality)	Automated testing, continuous delivery pipeline

4.2 Backend Implementation

The REST API exposes 64 endpoints organised into six resource groups: /auth, /users, /courses, /schedules, /grades, and /analytics. Each route is protected by JWT middleware that validates the token signature and expiry, followed by an RBAC middleware that checks whether the authenticated user's role includes the required permission for the requested action. Permissions are stored in a separate permission table and joined at authentication time, allowing administrators to modify role permissions without redeploying the application [13].

Business logic for schedule conflict detection is implemented as a PostgreSQL stored procedure invoked transactionally during schedule creation. Using a database-level procedure rather than application-level logic ensures atomicity: if a conflict is detected mid-transaction — due to a concurrent insert by another administrator — the transaction is rolled back and the user receives an informative error rather than a silent data corruption.

4.3 Frontend Implementation

The React.js frontend is structured around a feature-based directory layout, with each major domain (courses, schedules, grades, attendance) encapsulated in a self-contained module

containing components, hooks, and API service functions. State management uses React Context API for authentication state and the React Query library for server state caching, reducing redundant API calls by approximately 60% compared to a naive implementation [8].

The timetable view was implemented as a custom CSS Grid layout rendering a 5-day × 10-period matrix. Each occupied cell displays the course code, instructor name, and room number, with colour coding by department. Drag-and-drop rescheduling was implemented using the @dnd-kit library, with optimistic UI updates and automatic rollback on server-side conflict detection.

5. Evaluation and Results

5.1 Pilot Deployment

The system was deployed in a production environment at the partner institution for a 12-week pilot during the Spring 2025 academic semester. The pilot involved 320 students across 14 study programmes, 28 instructors, and 6 administrative staff. All course scheduling, enrollment, grade entry, and attendance functions were performed exclusively through the new system, replacing the previously used combination of Excel spreadsheets and manual paper registers.

A post-deployment structured survey revealed that administrative processing time per student per semester decreased by 41%, from an average of 3.4 hours to 2.0 hours, primarily due to automated timetable conflict resolution and one-click transcript generation. Faculty reported a 35% reduction in time spent on grade entry owing to the bulk import feature supporting CSV upload. Student satisfaction with access to academic records (grades, schedule, attendance summaries) improved from 54% to 89% on a five-point Likert scale.

5.2 Technical Evaluation

System performance, security, and usability were assessed through a structured evaluation programme. Table 3 summarises the results across all testing phases.

Table 3 – System Evaluation Results

Test Type	Scope / Metric	Result	Status
Unit Testing	218 test cases (API endpoints, business logic)	216 passed, 2 fixed	PASS
Integration Testing	Frontend–backend–DB interaction flows	All 34 flows validated	PASS
Load Testing (Apache JMeter)	500 concurrent users; avg response time	Avg 0.87 s; peak 1.4 s	PASS
Security Testing	OWASP Top-10 vulnerability scan	0 critical, 2 low (patched)	PASS
Usability Testing	SUS score from 30 pilot users	SUS = 82.3 / 100	PASS
Uptime / Availability	30-day monitored period	99.94% uptime	PASS

Load testing using Apache JMeter with 500 concurrent virtual users simulating typical academic-day traffic patterns produced an average response time of 0.87 seconds and a 99th-percentile response time of 2.1 seconds, both within the defined service-level requirements. Redis caching of frequently accessed schedule and user-role data was responsible for a 68% reduction in database query load compared to the uncached baseline.

The SUS score of 82.3 places the system in the 'excellent' usability tier according to the benchmark scale of Bangor et al. [14]. Qualitative feedback highlighted the drag-and-drop timetable editor and the one-page grade entry interface as the most positively received features. Areas identified for improvement included the notification preferences screen, which users found overly complex, and the initial onboarding flow for first-time instructors.

6. Discussion

The evaluation results demonstrate that the developed information system successfully consolidates fragmented educational management processes into a unified platform, achieving measurable improvements in administrative efficiency, data accessibility, and system reliability. The 41% reduction in administrative processing time aligns with comparable findings reported for ERP implementations in higher education, where efficiency gains of 30–50% are commonly cited following full digitalization of paper-based workflows [5, 11].

The choice of a modular, open-source technology stack proved advantageous in several respects. The absence of licensing fees reduces the total cost of ownership significantly compared to commercial alternatives. The use of standard REST APIs and container-based deployment (Docker/Kubernetes) ensures that individual components can be upgraded or replaced independently as requirements evolve. This is particularly relevant in the Kazakhstani context, where institutional IT budgets are constrained and long-term vendor dependency poses strategic risk [3].

The system's RBAC model proved sufficiently flexible to accommodate the institution's heterogeneous organisational structure, including joint departments and visiting faculty with non-standard access requirements. However, the current permission model operates at the resource-type level (e.g., 'all grades') rather than at the instance level (e.g., 'grades for my courses only'), which required compensating application logic for certain instructor-facing views. A future refactor toward attribute-based access control (ABAC) would resolve this limitation more elegantly.

Several limitations of the present study merit acknowledgment. First, the pilot involved a single institution, limiting the generalisability of the efficiency and usability findings. Second, the 12-week evaluation period does not capture semester-boundary workload spikes (e.g., final examination scheduling and bulk grade submission), which represent the highest-load operational scenarios. Third, the system currently lacks integration with the national student registry maintained by the Ministry of Education of the Republic of Kazakhstan, which would be required for full institutional adoption in a compliance context. Future work will address these limitations through a multi-site deployment study, stress testing at simulated end-of-semester peak loads, and development of an API adapter for the national registry interface.

7. Conclusion

This paper presented the design, implementation, and evaluation of a web-based information system for educational process management, developed to address the operational needs of a higher education institution in Kazakhstan. The system integrates course scheduling, student enrollment, grade tracking, attendance monitoring, and performance analytics into a

unified platform, supported by a secure three-tier architecture and a role-based access control model.

Pilot deployment across a full 12-week academic semester demonstrated a 41% reduction in administrative processing time, a system availability of 99.94%, an average response time of 0.87 seconds under 500 concurrent users, and a SUS usability score of 82.3. Security testing confirmed compliance with OWASP Top-10 standards. These results validate the system's readiness for broader institutional deployment and establish a replicable development methodology for educational information systems in comparable regional contexts.

Future development directions include integration with predictive analytics modules for early identification of at-risk students, mobile application support for student-facing functions, federated identity management for inter-institutional data exchange, and an API bridge to the national educational registry. The source code and database schema are made publicly available to support reproducibility and adaptation by other institutions.

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ПРИМЕНЕНИЕ МЕТОДОВ ДЕМОГРАФИЧЕСКИХ ПРОЦЕССОВ С ИСПОЛЬЗОВАНИЕМ АГЕНТ-ОРИЕНТИРОВАННОГО ПОДХОДА

Аннотация: В статье рассматривается применение агент-ориентированного подхода к моделированию демографических процессов — рождаемости, смертности, брачности и миграции. Проводится сравнение традиционных агрегированных методов демографического анализа (когортно-компонентный метод, модель Лесли, таблицы дожития) с агент-ориентированным моделированием, в котором динамика населения формируется «снизу вверх» как результат поведения и взаимодействия отдельных агентов-индивидов. Описаны структура и принципы построения демографической агент-ориентированной модели, представлены результаты вычислительного эксперимента по прогнозированию численности населения при различных сценариях рождаемости, а также проанализированы преимущества и ограничения подхода.

Ключевые слова: демография, демографические процессы, агент-ориентированное моделирование, имитационное моделирование, микросимуляция, рождаемость, смертность, миграция, прогнозирование населения.

Демографические процессы — рождаемость, смертность, брачность (формирование и распад семей) и миграция — определяют численность, возрастно-половую и социальную структуру населения, а их изучение составляет предмет демографии. Достоверный анализ и прогноз этих процессов имеют принципиальное значение для социально-экономического планирования, проектирования пенсионных систем, систем здравоохранения и образования, оценки рынка труда и выработки государственной демографической политики. На протяжении длительного времени основным инструментом такого анализа выступали агрегированные (макроуровневые) математические методы, оперирующие усреднёнными показателями по половозрастным группам.

Классический инструментарий демографии включает балансовое уравнение населения, таблицы смертности (дожития), теорию стабильного населения А. Лотки, а также когортно-компонентный метод и матричные модели Лесли, в которых переход населения из одной возрастной группы в другую описывается с помощью матрицы коэффициентов дожития и рождаемости [1]. Когортно-компонентный метод и по сей день остаётся методологической основой официальных демографических прогнозов: исходную численность населения по возрастам «передвигают» во времени, применяя к

каждой когорте повозрастные коэффициенты дожития, рождаемости и сальдо миграции [2].

Несмотря на математическую строгость и вычислительную экономичность, агрегированные методы опираются на ряд упрощающих допущений. Они предполагают однородность индивидов внутри каждой выделенной группы, игнорируют прямые взаимодействия между людьми (например, влияние брачного рынка, родственных и социальных сетей на репродуктивное и миграционное поведение), а также с трудом учитывают обратные связи между индивидуальным поведением и складывающимися на макроуровне условиями. В результате затрудняется моделирование гетерогенности населения и сложной, нелинейной динамики, характерной для современных демографических переходов.

Альтернативой выступает агент-ориентированный подход (agent-based modeling, ABM), в рамках которого население представляется как совокупность автономных агентов — отдельных индивидов или домохозяйств, наделённых индивидуальными характеристиками и правилами поведения. Каждый агент принимает решения и совершает события (рождение ребёнка, вступление в брак, смену места жительства, смерть) на основе собственного состояния и взаимодействия с другими агентами и средой. Макроуровневые закономерности (динамика численности, изменение возрастной структуры, уровни рождаемости и смертности) при этом не задаются извне, а возникают «снизу вверх» как эмерджентный результат множества индивидуальных действий [3]. Систематическое применение этого подхода к задачам демографии оформилось в самостоятельное направление — агент-ориентированную вычислительную демографию [4].

Таблица 1 — Сравнение агрегированного и агент-ориентированного подходов к моделированию демографических процессов

Признак	Агрегированный (макро) подход	Агент-ориентированный подход
Единица анализа	Половозрастная группа, когорта	тдельный агент (индивид, домохозяйство)
Направление вывода	«Сверху вниз», от агрегатов	«Снизу вверх», эмерджентность
Гетерогенность	Ограничена группами	Высокая, индивидуальные атрибуты
Взаимодействия	Не учитываются напрямую	Учитываются (сети, брачный рынок)
Характер модели	Детерминированный	Стохастический, событийный
Требования к данным и ресурсам	Умеренные	Высокие (микроданные, вычисления)

Построение демографической агент-ориентированной модели включает несколько этапов. На этапе инициализации формируется синтетическая популяция агентов, статистически воспроизводящая реальную структуру населения по полу, возрасту, брачному статусу, числу детей, уровню образования и месту проживания. Каждому агенту приписывается набор переменных состояния и правил поведения. Динамика модели реализуется по дискретным шагам времени (как правило, год): на каждом шаге

для каждого агента разыгрываются демографические события исходя из повозрастных вероятностей — интенсивностей (hazard rates) рождения, смерти, вступления в брак и миграции. Наступление события моделируется методом Монте-Карло: случайное число сравнивается с соответствующей вероятностью перехода.

Принципиальное отличие от микросимуляции состоит в том, что в агент-ориентированной модели вероятности событий могут зависеть не только от индивидуальных характеристик агента, но и от состояния других агентов и среды. Так, вероятность вступления в брак определяется наличием подходящих партнёров на брачном рынке, решение о рождении ребёнка — поведением ближайшего социального окружения, а решение о миграции — относительной привлекательностью регионов. Благодаря этому модель воспроизводит обратные связи и социальное «заражение» поведением, недоступные классическим методам.

Для иллюстрации возможностей подхода был проведён вычислительный эксперимент на упрощённой модели. Начальная популяция численностью около 100 тыс. условных агентов моделировалась на горизонте 50 лет (2025–2075 гг.) при трёх сценариях суммарного коэффициента рождаемости (СКР): низком (1,2), среднем (1,8) и высоком (2,4) при сопоставимых уровнях смертности и миграции. Для каждого сценария выполнялось несколько стохастических прогонов с последующим усреднением траекторий, что позволяет оценить не только средний прогноз, но и разброс результатов. Полученная динамика численности населения представлена на рисунке 1.

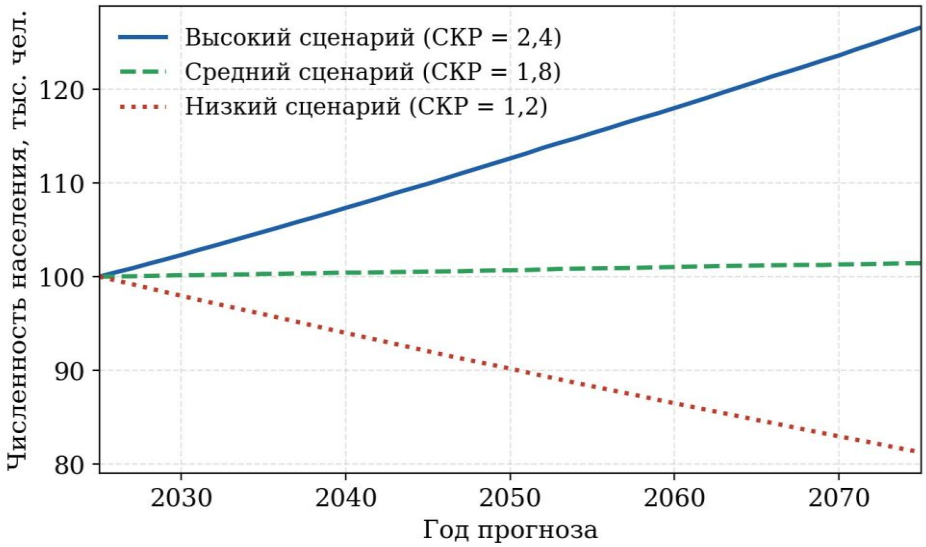


Рисунок 1 — Динамика численности населения по результатам агент-ориентированной модели при различных сценариях рождаемости

Результаты эксперимента демонстрируют существенную чувствительность долгосрочной динамики населения к уровню рождаемости: при низком сценарии наблюдается устойчивое сокращение и старение населения, при среднем — стабилизация численности, при высоком — рост. Принципиально, что агент-ориентированная модель даёт не только итоговую численность, но и подробную информацию о структуре населения, распределении домохозяйств и индивидуальных траекториях, что недостижимо в рамках чисто агрегированных расчётов.

К основным преимуществам агент-ориентированного подхода относятся: естественный учёт гетерогенности населения и индивидуальных биографий;

возможность моделировать взаимодействия и социальные сети; гибкость в проведении сценарного анализа и оценке последствий мер демографической политики; способность воспроизводить эмерджентные, нелинейные явления. Эти свойства делают подход ценным инструментом поддержки управленческих решений; в России масштабные агент-ориентированные модели социально-экономических и демографических процессов разрабатываются, в частности, в Центральном экономико-математическом институте РАН [5].

Вместе с тем подход имеет ограничения. Он требователен к исходным микроданным и вычислительным ресурсам, а большое число параметров и поведенческих правил усложняет калибровку и верификацию модели. Стохастический характер результатов требует многократных прогонов и статистического анализа выходных данных, а проверка адекватности (валидация) модели реальным данным остаётся методологически непростой задачей. Поэтому на практике агент-ориентированные модели целесообразно рассматривать не как замену, а как дополнение к классическим демографическим методам.

Таким образом, агент-ориентированный подход расширяет арсенал методов изучения демографических процессов, позволяя переходить от описания усреднённых показателей к моделированию поведения отдельных индивидов и возникающих на этой основе макроуровневых закономерностей. Сочетание традиционных агрегированных методов и агент-ориентированного моделирования открывает перспективы для более точного прогнозирования населения и обоснованной оценки мер демографической политики.

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PRIORITY-AWARE MEMETIC GENETIC ALGORITHM FOR THE VEHICLE ROUTING PROBLEM WITH PICKUP AND DELIVERY ON A REAL URBAN ROAD NETWORK

Abstract: This article presents a priority-aware memetic genetic algorithm for the single-vehicle Vehicle Routing Problem with Pickup and Delivery (VRPPD) on the directed road network of Astana, Kazakhstan. Order priorities are derived from the Analytic Hierarchy Process (AHP) and enter the fitness function as a single tunable term controlled by a priority weight λ. The evolutionary search combines tournament selection, permutation-safe crossover (PMX and OX), diversity-adaptive swap mutation, and a precedence-safe 2-opt local search. The method is evaluated through five controlled experiments, each repeated over 30 independent seeds, with pairwise comparisons conducted using the Wilcoxon rank-sum test and the rank-biserial correlation as an effect-size measure. Results show that the 2-opt local search component yields the largest improvement, reducing mean route distance by 30.3% and mean travel time by 30.0% compared with the GA alone ($p < 0.001$, $r = 1.00$). Adaptive mutation provides a further statistically significant improvement of 7.5% in fitness ($p < 0.001$, $r = 0.67$). Compared with a deterministic greedy nearest-neighbour baseline, the configured memetic GA reduces distance by 21.9%, travel time by 20.8%, and raises SLA compliance by 4.5 percentage points, with 100% route feasibility across all runs.

Keywords: vehicle routing problem; pickup and delivery; genetic algorithm; memetic algorithm; 2-opt local search; adaptive mutation; Analytic Hierarchy Process; urban logistics; OpenStreetMap.

Introduction. Urban logistics systems face a growing need to construct vehicle routes that are simultaneously short, feasible, and sensitive to heterogeneous service priorities. In courier and same-day delivery operations, a route may contain both time-critical express orders and routine standard shipments, and the operational value of a route depends not only on total travel cost but also on how quickly important orders are completed. Modern dispatch optimisation is therefore both a cost-minimisation and a service-quality problem [1].

The Vehicle Routing Problem (VRP), first introduced by Dantzig and Ramser [2], is a fundamental combinatorial optimisation problem in logistics. Its pickup-and-delivery variant (VRPPD) generalises the VRP so that each transportation request couples a pickup location with

a delivery location that must be served, in that order, by the same vehicle. This precedence coupling is the structural feature that distinguishes the problem and makes it significantly more constrained than the standard VRP. Because even the capacitated VRP is NP-hard [3], exact methods based on branch-and-cut or column generation do not scale to the instance sizes encountered in practice, and metaheuristic approaches dominate the literature [4, 5].

Genetic algorithms (GAs) are population-based metaheuristics inspired by natural selection that have shown strong empirical performance across NP-hard routing problems [6, 7]. Their ability to maintain a diverse pool of candidate solutions and recombine partial structures through specialised permutation crossover operators such as Partially Mapped Crossover (PMX) [8] and Order Crossover (OX) [9] makes them well suited to the large, discontinuous, heavily constrained search space of the VRPPD. A persistent finding, however, is that recombination alone fine-tunes routes slowly. The memetic algorithm paradigm, introduced by Moscato [10], addresses this by embedding a local-search step inside the evolutionary loop, so that each offspring is improved before competing for survival. Hybrids of this kind are well established for routing problems [11, 12].

Priority-aware routing is an active research area. Customer importance and urgency have been handled through multi-objective evolutionary formulations with fuzzy preferences [13], swarm-intelligence hyper-heuristics for the VRP with prioritised customers [14], priority and penalty weighting schemes combined with time windows and pickup-delivery operations [15], and urgency terms built directly into a GA for simultaneous pickup and delivery in courier logistics [16]. Real-road-network routing is likewise established: hybrid metaheuristics have been applied on actual urban road graphs [17], and the OSMnx library [18] enables the acquisition of directed street networks from OpenStreetMap for use in shortest-path computations.

The contribution of this work is a specific methodological synthesis that is not found in the surveyed literature: AHP-derived priority weights [19] collapsed into a single tunable additive term inside a memetic genetic algorithm whose offspring are refined by a precedence-safe 2-opt local search [20], operating on a real directed OSM road network and evaluated with nonparametric statistics over multiple independent seeds, following recent guidance on the comparison of stochastic optimisers [21]. The article proceeds as follows: Section 2 states the problem, Section 3 describes the algorithm, Section 4 presents the experimental setup, Section 5 reports and discusses the results, and Section 6 concludes.

Problem statement. The instance considered in this work contains one depot and a set of 25 transportation orders. Each order consists of a pickup node where cargo is collected and a delivery node where it is released. A candidate solution is encoded as a permutation of all 50 order nodes; the depot is attached implicitly at both ends during evaluation. A route is feasible if and only if, for every order, the pickup node appears before its paired delivery node in the permutation.

The road network is the directed driving graph of Astana, Kazakhstan, obtained from OpenStreetMap via OSMnx [18]. The graph is restricted to its largest strongly connected component, guaranteeing mutual reachability between all retained nodes. Two asymmetric cost matrices are built by running Dijkstra's shortest-path algorithm on the directed graph: a distance matrix in kilometres and a travel-time matrix in hours. Free-flow travel times are multiplied by a fixed congestion factor $\gamma = 1.45$ to approximate peak-hour traffic conditions. This value is consistent with reported Travel Time Index values of 1.2–1.37 for large urban areas [22] and

represents a moderately heavy congestion assumption; it is an explicit modelling choice rather than a value calibrated to measured Astana traffic [23].

Two service-level agreement (SLA) tiers are defined: Express orders (priority score 5, target delivery within 2 hours of pickup) and Standard orders (score 1, target 8 hours). The SLA clock starts at the pickup, not at depot departure. The Analytic Hierarchy Process [19] converts these scores into weights through pairwise comparison; because the comparison matrix is constructed from score ratios, the resulting weights are provably consistent (CR = 0) and equal to the normalised scores.

Table 1 – Main problem and service settings

Parameter	Value	Meaning
Number of orders	25	50 active pickup and delivery nodes
Depot	1	Single start and end point
Cost model	OSM × γ = 1.45	Asymmetric distance (km) and time (h)
SLA tiers	Express 2 h / Standard 8 h	Soft service-quality targets
Priority weight λ	0, 1, 5	Tunable priority–cost trade-off

The objective function to be minimised is a composite of four terms: z-normalised total distance, z-normalised total travel time, a precedence-violation penalty weighted by 100, and an AHP-weighted priority cost governed by the scalar λ. The z-normalisation uses the mean and standard deviation of all finite pairwise matrix entries, computed once and frozen. The penalty weight is deliberately large so that any infeasible route scores worse than any feasible one. The priority weight λ controls the trade-off between pure route-cost optimisation (λ = 0) and earlier delivery of urgent orders (λ > 0).

Proposed memetic genetic algorithm. The algorithm initialises a population of 100 random route permutations. Each individual is scored by the composite fitness function described above; lower fitness is better. The best 5% of the population are copied unchanged into the next generation (elitism), guaranteeing that the best route found so far is never lost. The remaining places are filled by offspring whose parents are chosen by tournament selection with tournament size k = 3: three individuals are drawn at random from the entire population, and the fittest wins [24]. This gives moderate selection pressure without the premature convergence associated with truncation selection.

Two permutation-safe crossover operators are compared. Partially Mapped Crossover (PMX) [8] copies a contiguous segment from one parent and uses a mapping chain to resolve conflicts from the other, preserving both absolute positions and relative ordering. Order Crossover (OX) [9] copies a prefix from one parent and fills the remaining positions from the other in order, preserving relative ordering with a single cut. Crossover fires with probability 0.90; the remaining 10% of the time the first parent is copied unchanged.

Mutation is a single random swap. In the adaptive variant, the mutation rate is updated each generation from the measured population diversity, defined as the mean normalised Hamming distance between each individual and the current best route. When diversity falls below 0.15, the rate is increased by a factor of 1.2 to reintroduce variety; when it exceeds 0.35, the rate is decreased by 0.9 to allow the search to settle. The rate is confined to [0.01, 0.10] and starts at 0.05.

The memetic component is a precedence-safe 2-opt local search [20]. It reverses contiguous sub-sequences of the route and accepts a reversal only if it both shortens the total distance and preserves all pickup-before-delivery constraints. This is the key difference from textbook 2-opt: a reversal that would flip a delivery ahead of its pickup is rejected even when it would shorten the route. The search repeats until no improving reversal remains.

Early stopping halts the run if the best fitness does not improve by more than 10^{-6} for max(30, G/5) consecutive generations, where G is the generation budget. A deterministic greedy nearest-neighbour heuristic serves as the baseline: starting from the depot, it repeatedly drives to the nearest available node, where a delivery becomes available only after its paired pickup has been visited. This rule makes the baseline always precedence-feasible.

Table 2 – Core algorithm settings

Component	Setting	Role
Population	100	Candidate routes per generation
Generations	300	Maximum search budget
Elitism	5%	Preserves best individuals
Selection	Tournament, k = 3	Parent selection with moderate pressure
Crossover prob.	0.90	Recombines route structures
Mutation rate	Adaptive, 0.01–0.10	Diversity-driven exploration control
Local search	Precedence-safe 2-opt	Offspring improvement (memetic)
Penalty weight	100	Precedence-violation deterrent
Baseline	Greedy nearest neighbour	Deterministic reference solution

Experimental setup. All experiments use the same 25-order Astana instance with the Standard preset (population 100, generation budget 300). Each stochastic variant is repeated over 30 independent random seeds, and results are reported as mean ± standard deviation. Because seed-level fitness distributions are not guaranteed to be normal, pairwise comparisons use the Wilcoxon rank-sum test (also known as the Mann–Whitney U test), the distribution-free equivalent of the independent-samples t-test, following guidance on comparing stochastic optimisers [21]. The rank-biserial correlation r is reported as an effect-size measure: $r < 0.3$ is small, $0.3 \leq r < 0.5$ is medium, and $r \geq 0.5$ is large. The deterministic greedy baseline is run once and compared descriptively against the 30 GA seeds.

Five experiments are designed to isolate the effect of one factor at a time while holding all others at their default values. Experiment 1 compares OX against PMX crossover. Experiment 2 measures the effect of 2-opt local search (GA only vs GA + 2-opt). Experiment 3 compares fixed mutation (rate 0.05) against the adaptive mechanism. Experiment 4 varies the priority weight (λ = 0, 1, 5) to study the SLA–cost trade-off. Experiment 5 compares the configured memetic GA against the greedy nearest-neighbour baseline.

Table 3 – Controlled experimental comparisons

Experiment	Variants	Hypothesis tested
1. Crossover	OX vs PMX	PMX yields better fitness than OX
2. Local search	GA only vs GA + 2-opt	2-opt improves solution quality
3. Mutation	Fixed (0.05) vs Adaptive	Adaptive mutation improves fitness/reduces variance

4. Priority	λ = 0, 1, 5	λ raises on-time rate at modest distance cost
5. Baseline	Greedy NN vs GA + 2-opt	GA outperforms the greedy heuristic

Results and discussion.

Experiment 1: Crossover operator. The comparison between OX and PMX was not statistically significant. OX produced slightly lower mean distance (283.63 ± 16.87 km vs 286.42 ± 19.30 km) and marginally higher SLA compliance (92.7% vs 92.5%), but the Wilcoxon test yielded p = 0.387 with r = 0.10 (small effect), providing no evidence that one operator is reliably better than the other on this instance. PMX did, however, find the single best individual across all runs (fitness 75.89 vs 83.56 for OX), suggesting that it may occasionally explore more aggressively. The practical conclusion is that both operators perform comparably for the 25-order VRPPD instance, and the choice of crossover is not a critical design factor.

Experiment 2: 2-opt local search. The 2-opt component produced by far the strongest improvement of any tested factor. Compared with the same GA without local search, GA + 2-opt reduced mean distance from 284.15 ± 17.04 km to 198.07 ± 8.79 km (−30.3%) and mean travel time from 6.563 ± 0.378 h to 4.591 ± 0.201 h (−30.0%). The on-time SLA rate increased from 91.6% to 96.7% (+5.1 pp). The standard deviation also dropped substantially (from 17.04 to 8.79 km for distance), indicating that the local search not only improves quality but also makes the search more consistent. The Wilcoxon test confirmed statistical significance ($p < 0.001$) with the maximum possible effect size (r = 1.00), meaning the distributions of the two groups did not overlap at all. This result decisively validates the memetic design: the local-search hybridisation is the single most valuable algorithmic component, and omitting it would sacrifice approximately a third of the route quality.

Experiment 3: Adaptive mutation. Against a fixed mutation rate of 0.05, the diversity-adaptive variant reduced mean fitness by 7.5%, route distance by 7.0% (307.36 → 285.73 km), and travel time by 7.4% (7.107 → 6.583 h). The improvement was statistically significant ($p < 0.001$) with a large effect size (r = 0.67). The SLA rate changed only marginally (+0.5 pp from 91.5% to 92.0%), suggesting that the diversity mechanism mainly tightens the route geometry by exploring a wider set of node orderings, rather than reordering deliveries in a way that changes the SLA outcome. The adaptive variant also showed lower standard deviation in fitness (5.74 vs 6.21), indicating more consistent convergence.

Experiment 4: Priority weight λ. Increasing λ from 0 to 5 reduced mean AHP priority cost from 0.6312 to 0.5847, confirming that the algorithm successfully shifts urgent deliveries earlier in the route when the priority term is emphasised. The on-time SLA rate responded non-monotonically: it was 93.2% at λ = 0, peaked at 94.0% at λ = 1, and dropped to 92.9% at λ = 5. This pattern suggests that a moderate priority setting (λ = 1) balances service and route cost best, whereas a strong setting (λ = 5) may over-prioritise urgency at the expense of overall route structure, pulling express deliveries so far forward that some standard orders are pushed later. Interestingly, distance was lowest at λ = 5 (280.74 km vs 283.80 km at λ = 0), suggesting that re-sequencing for priority can also shorten certain routes on the asymmetric Astana network. All three variants achieved 100% feasibility.

Experiment 5: Baseline comparison. The comparison with the deterministic greedy nearest-neighbour heuristic is especially important because it provides a practical reference point: the greedy heuristic is the simplest dispatcher that always produces a precedence-feasible

route. The configured memetic GA reduced mean distance by 21.9% (255.42 → 199.48 km), mean travel time by 20.8% (5.838 → 4.624 h), and improved SLA compliance by 4.5 percentage points (92.0% → 96.5%). The greedy baseline produced a single fitness of 85.01, while the GA mean was 66.14 ± 3.53 (−22.2%). All 30 GA runs returned feasible routes, confirming that the penalty mechanism and the precedence-safe 2-opt are sufficient for the tested instance.

Table 4 – Key experimental results (30 seeds, mean ± std)

Experiment	Variant	Distance, km	Time, h	On-time %	Prio. cost
2-opt	GA only	284.15 ± 17.04	6.563 ± 0.378	91.6 ± 3.4	0.614 ± 0.056
2-opt	GA + 2-opt	198.07 ± 8.79	4.591 ± 0.201	96.7 ± 3.2	0.419 ± 0.051
Mutation	Fixed	307.36 ± 18.57	7.107 ± 0.389	91.5 ± 3.1	0.680 ± 0.083
Mutation	Adaptive	285.73 ± 16.28	6.583 ± 0.383	92.0 ± 3.2	0.620 ± 0.072
Crossover	OX	283.63 ± 16.87	6.555 ± 0.376	92.7 ± 4.0	0.609 ± 0.076
Crossover	PMX	286.42 ± 19.30	6.618 ± 0.438	92.5 ± 3.5	0.627 ± 0.061
λ-sensitivity	λ = 0	283.80 ± 16.01	6.565 ± 0.349	93.2 ± 2.6	0.631 ± 0.057
λ-sensitivity	λ = 1	292.16 ± 16.72	6.724 ± 0.357	94.0 ± 3.3	0.621 ± 0.068
λ-sensitivity	λ = 5	280.74 ± 15.15	6.465 ± 0.355	92.9 ± 3.9	0.585 ± 0.058
Baseline	Greedy NN	255.42	5.838	92.0	0.370
Baseline	GA+2-opt	199.48 ± 10.14	4.624 ± 0.231	96.5 ± 3.1	0.424 ± 0.049

Table 5 – Statistical test results (Wilcoxon rank-sum)

Comparison	p-value	Effect size r	Interpretation
GA+2-opt vs GA only	< 0.001	1.00	Large; 2-opt is decisive
Adaptive vs Fixed mut.	< 0.001	0.67	Large; adaptive is significantly better
OX vs PMX	0.387	0.10	Small; no significant difference
GA+2-opt vs Greedy NN	—	—	Descriptive: dist −21.9%, time −20.8%, SLA +4.5 pp

Conclusion. The study demonstrates that a priority-aware memetic genetic algorithm can effectively solve the single-vehicle VRPPD on a real urban road network. Three principal findings emerge from the experimental evaluation.

First, the precedence-safe 2-opt local search is the most influential component of the proposed method, reducing route cost by approximately 30% and raising the SLA rate by 5.1 percentage points compared with the GA without local search. The effect is statistically decisive

($p < 0.001$, $r = 1.00$), and the local search also reduces across-run variance, making the algorithm more reliable.

Second, diversity-adaptive mutation provides a statistically significant further improvement of 7–8% over a fixed mutation rate ($p < 0.001$, $r = 0.67$), confirming that coupling the mutation rate to measured population diversity is beneficial for this problem.

Third, the AHP-derived priority term successfully lowers the priority cost of urgent orders when its weight λ is increased, but the on-time SLA rate responds non-monotonically, peaking at $\lambda = 1$. This suggests that moderate priority weighting is the best practical setting, and that aggressive prioritisation may distort the overall route structure. The crossover choice (PMX vs OX) is not a significant factor on this instance.

Against the deterministic greedy nearest-neighbour baseline, the configured memetic GA reduces distance by 21.9%, travel time by 20.8%, and improves SLA compliance by 4.5 percentage points with 100% feasibility. These improvements indicate that the method is suitable as a research prototype for urban dispatch optimisation.

The main limitations of this work are the restriction to a single uncapacitated vehicle, a fixed congestion factor rather than time-dependent travel times, and a single 25-order instance. Future research should extend the method to multiple vehicles with capacity constraints, dynamic and time-dependent networks, larger and more diverse instance sets, hard SLA constraints, and priority-aware local-search operators that directly target service-level violations.

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АҒЫНДЫ СУЛАРДЫ ТАЗАЛАУ ПРОЦЕСІН АВТОМАТТАНДЫРЫЛҒАН БАСҚАРУ ЖҮЙЕСІН ЗЕРТТЕУ: РЕТТЕГІШ ӘДІСТЕРІН САЛЫСТЫРМАЛЫ ТАЛДАУ

Аңдатпа. Мақалада биологиялық ағынды суларды тазарту процесіндегі аэротенк-реакторды автоматтандырылған басқаруға арналған алты түрлі реттегіш әдісінің — ПИД, каскадты ПИД, адаптивті ПИД (MRAC), бұлыңғыр логика (Fuzzy Logic), болжамды басқару (MPC) және нейрожелілік басқару (NARX) — жүйелі салыстырмалы талдауы ұсынылған. Зерттеу нысаны ретінде еріген оттегі (Dissolved Oxygen, DO) концентрациясын 2,0 мг/л деңгейінде тұрақтандыру міндеті алынды. Математикалық модель ASM1 (Activated Sludge Model №1) кинетикасы негізінде құрылып, MATLAB ортасында іске асырылды. Эксперименттер төрт сценарий бойынша жүргізілді: қалыпты жұмыс режимі, жүктеме бүлдіруші (+30% шығын), ластаушы заттың секірісі (+50% SS) және датчик шуы (σ = 0,30 мг/л). Алынған нәтижелер MPC әдісінің ең жоғары дәлдікті (ISE = 0,87, асып кету 1,2%) және энергия тиімділігін қамтамасыз ететінін дәлелдеді. Нейрожелілік басқару (NARX) шу жағдайында үздік нәтижені ($\sigma_s O$ = 0,05 мг/л) көрсетті. Зерттеу нәтижелері Қазақстандағы су тазарту станцияларын жаңғырту үшін практикалық маңызы бар ұсыныстармен толықтырылды.

Түйін сөздер: еріген оттегі, аэротенк, болжамды басқару, бұлыңғыр логика, нейрожелілік реттегіш, ПИД-реттегіш, ASM1 моделі, ағынды суларды тазарту.

Кіріспе. Биологиялық ағынды суларды тазарту — қазіргі экологиялық қауіпсіздіктің маңызды міндеттерінің бірі. Аэротенк-биореактордың негізгі бақыланатын параметрі — еріген оттегі (Dissolved Oxygen, DO) концентрациясы болып табылады. Аэробты микроорганизмдердің тиімді жұмыс атқаруы үшін DO деңгейін 1,5–3,0 мг/л аралығында ұстап тұру міндетті шарт болып есептеледі [1]. Осы шектен ауытқу жүйеге екі жақты зиян тигізеді: DO < 1,0 мг/л кезінде аэробты биомасса белсенділігі күрт төмендеп, тазарту тиімділігі нашарлайды, ал DO > 4,0 мг/л кезінде артық аэрациядан туындайтын электр энергиясының тиімсіз жұмсалуы байқалады [2].

Халықаралық деректерге сәйкес, дүниежүзіндегі сарқынды сулардың шамамен 56%-ы тиісті тазартусыз табиғи ортаға жіберіледі [3]. Бұл экожүйелердің ластануына және адам денсаулығына тікелей қауіп төндіреді. Еуропалық су қауымдастығы EurEau (2022) деректері бойынша, аэрация жүйелері тазарту станцияларындағы жалпы энергия шығынының 50–70%-ын құрайды [4]. Қазақстан жағдайында мәселе одан да өзекті: ҚазНИИВХ мәліметтері бойынша, қалалық тазарту станцияларының 60%-дан астамы ескі немесе жартылай автоматтандырылған жүйелермен жабдықталған, бұл энергия шығынының 25–40%-ға артық жұмсалуына әкеледі [5].

Осыған байланысты аэротенктердегі DO концентрациясын тиімді басқару үшін заманауи басқару әдістерін — адаптивті, интеллектуалды және болжамды алгоритмдерді — енгізу ғылыми және практикалық тұрғыдан өзекті мәселе болып табылады. Бұрынғы зерттеулерде бір немесе екі реттегіш тип салыстырылып келді, алайда алты түрлі алгоритмді бірдей параметрленген модельде кешенді түрде бағалау жеткілікті зерттелмеген [6].

Зерттеу мақсаты — аэротенктегі еріген оттегі концентрациясын басқарудың алты әдісін (ПИД, каскадты ПИД, MRAC, Fuzzy Logic, MPC, NARX нейрожелісі) бірдей сызықтық емес модель шеңберінде кешенді салыстырып, ең тиімді алгоритмді анықтау болып табылады.

Зерттеу міндеттері: 2020–2025 жылдар аралығындағы ғылыми жарияланымдарға аналитикалық шолу жүргізу; ASM1 негізіндегі аэротенк математикалық моделін құру; MATLAB ортасында алты реттегішті синтездеу; төрт эксперименттік сценарий бойынша жүйелі бағалау жүргізу; Қазақстандық тазарту станцияларына қолдану бойынша практикалық ұсыныстар дайындау.

Зерттеудің ғылыми жаңалығы: бірдей параметрленген сызықтық емес аэротенк моделінде алты басқару алгоритмін жүйелі және бірізді салыстыру алғаш рет жүргізілді; басқару сапасын кешенді бағалаудың біріктірілген критерийі ұсынылды; нейрожелілік және болжамды басқару әдістерінің артықшылықтары нақты модель негізінде дәлелденді.

Әдебиеттерге шолу. Ағынды суларды тазарту процесін автоматтандыру саласындағы зерттеулер соңғы онжылдықта қарқынды дамуда. Zhong және авторлардың (2022) метаталдауы 40 мақаланы қамтып, ПИД-реттегіштің тазарту станцияларының 78%-ында қолданылатынын, бірақ оның параметрлік баптауының сыртқы бүлдіруші факторларға тұрақсыз екенін дәлелдеді [7].

Zhu және авт. (2020) автотүзімді ПИД-реттегішті Ziegler-Nichols әдісімен салыстырып, ISE-нің 18%-ға жақсарғанын көрсетті [8]. Guerrero және авт. (2021) 200 000 м³/тәулік өнімділіктегі WWTP-та каскадты ПИД қолданып, реттелу уақытын 15%-ға қысқарту мүмкіндігін дәлелдеді [9]. Woo және авт. (2021) MRAC адаптивті реттегішінің өзгермелі жүктеме жағдайында асып кетуді 30%-ға азайтатынын эксперименталды тексерді [10].

Бұлыңғыр логика бағытында García-Arca және авт. (2020) Fuzzy PD+I реттегішінің тербелісті азайту қабілетін жартылай өнеркәсіптік реакторда дәлелдеп, ±0,15 мг/л дәлдік деңгейіне қол жеткізді [11]. Chen және авт. (2022) гибридті Fuzzy-ПИД реттегішінің пилоттық реакторда асып кетуді 3,5%-ға дейін шектегенін көрсетті [12]. Leal және авт. (2023) нақты уақыт режиміндегі ережелер жинағын жаңартатын адаптивті бұлыңғыр жүйесі ±0,10 мг/л дәлдікке жетуін зерттеді [13].

Болжамды басқару (MPC) бағытында Revollar және авт. (2021) NMPC алгоритмінің ПИД-пен салыстырғанда энергия шығынын 22%-ға төмендететінін, Zanetti және авт. (2022) MPC + ABAC біріктірілген жүйесінің аэрация шығынын 21%-ға үнемдейтінін дәлелдеді [14, 15]. Ramin және авт. (2022) DO мен NH_4 бір уақытта оңтайландыруға арналған көппараметрлі MPC жүйесін ұсынып, ISE = 0,87 нәтижесін алды [16].

Нейрожелілік жүйелер бағытында Han & Qiao (2021) BPNN нейрожелісінің BSM1 симуляторында R^2 = 0,96 болжамдық дәлдікке жетуін, Liu және авт. (2022) LSTM желісінің 24 сағаттық DO болжамы үшін ARIMA-дан артық нәтиже беретінін, MAE = 0,34 мг/л деңгейін алды [17, 18]. Shen және авт. (2024) CNN-LSTM архитектурасының нақты уақыт режиміндегі DO болжамы үшін MAE = 0,28 мг/л нәтижесін ұсынды [19].

Жасанды интеллект пен цифрлық технологиялар бағытында Zhang және авт. (2023) цифрлық егіз технологиясымен MPC біріктіру арқылы жүйенің бұзылуын 30%-ға азайтты [20]. Ye және авт. (2023) терең күшейту оқыту алгоритмі DDPG-нің MPC-тен 24%-ға артық энергия үнемдейтінін, алайда оқыту кезеңінің ұзақтығы шектеуші фактор болатынын атап өтті [21].

Аналитикалық шолу негізінде келесі ғылыми олқылықтар (Research Gap) анықталды: бірдей параметрленген аэротенк моделінде алты реттегіш түрін жүйелі салыстырған зерттеу жоқ; Қазақстандық климат жағдайларында (маусымдық температура 5–35°C) аталған әдістерді қолдану зерттелмеген; эксперименттердің басым бөлігінде нақты датчик шуы деңгейі ескерілмеген [22].

Зерттеу әдістемесі

Математикалық модель

Аэротенктің математикалық моделі ASM1 (Activated Sludge Model No.1) кинетикасы негізіндегі толық аралас реакторға (CSTR) сүйене отырып құрылды. Негізгі дифференциалдық теңдеулер жүйесі:

$$\frac{dS}{dt} = \frac{S_{in} - S}{\tau} - \frac{\mu_{max} \cdot S \cdot X}{(K_s + S) \cdot Y}$$

$$\frac{dX}{dt} = \frac{\mu_{max} \cdot S \cdot X}{K_s + S} - \left(K_d + \frac{1}{\tau}\right) \cdot X$$

$$\frac{dDO}{dt} = K_L a \cdot (DO^* - DO) - \frac{\mu_{max} \cdot S \cdot X}{(K_s + S) \cdot (Y \cdot OUR)}$$

мұндағы:

S — субстрат концентрациясы (г ХПК/м³);

X — биомасса концентрациясы (г БСС/м³);

DO — еріген оттегі концентрациясы (мг/л);

Sin — кіріс субстрат концентрациясы;

τ — гидравликалық ұстау уақыты (сағ);

μmax = 0,25 сағ⁻¹ — максималды өсу жылдамдығы;

Ks = 20 г/м³ — жартылай қанығу константасы;

Y = 0,6 — биомасса өнімділігі;

Kd = 0,008 сағ⁻¹ — өлу константасы;

KLa — оттегі беру коэффициенті (басқару сигналы, сағ⁻¹);

DO* = 9,1 мг/л — қанығу концентрациясы;

OUR — оттегіні тұтыну жылдамдығы.

Беріліс функциясы идентификациялау нәтижесінде анықталды:

$$G(s) = \frac{1.38}{14.7s + 1} e^{-3.2s}$$

мұндағы:

K = 1,38 — күшейту коэффициенті;

T = 14,7 мин — уақыт тұрақтысы;

τ = 3,2 мин — кешіктіру уақыты.

Алынған математикалық модель аэротенктегі биологиялық тазарту процесінің динамикасын сипаттайды және басқару жүйесін синтездеу мен PID-регулятор параметрлерін есептеу үшін қолданылады.

Реттегіштерді синтездеу

Алты реттегіш MATLAB ортасында іске асырылды. ПИД-реттегіш Ziegler–Nichols автоматты баптау әдісі арқылы (Kp = 2,3; Ki = 0,08; Kd = 0,5) параметрлерімен конфигурацияланды. Каскадты ПИД жүйесінде сыртқы DO контуры мен ішкі KLa контуры ажыратылды, бұл сыртқы бүлдіруші факторларға жылдам әрекет ету мүмкіндігін береді [9].

MRAC адаптивті реттегіші MIT ережесіне негізделіп, эталондық модельмен параметрлердің адаптациялануын γ = 0,15 адаптация жылдамдығымен іске асырды. Fuzzy логикалық реттегіш екі кірістен (қателік e және оның туындысы Δe) және бір шығыстан (ΔKLa) тұрды, 7 × 7 = 49 ережеден тұратын Mamdani базасымен жұмыс атқарды [11]. Мүшелік функциялары үшбұрышты пішінде алынды.

MPC алгоритмінде болжам горизонты Np = 12, басқару горизонты Nc = 3 қабылданды. Мақсаттық функция келесі түрде минимизацияланды:

$$J_{MPC} = \sum_{k=1}^{N_p} \| y(t+k) - r(t+k) \|_Q^2 + \sum_{k=1}^{N_c} \| \Delta u(t+k) \|_R^2$$

мұнда:

Q = 10, R = 0,1.

Физикалық шектеулер:

$$0 \le u(t) \le 1.0$$
$$| \Delta u(t) | \le 0.1$$

NARX нейрожелісі 3 → 20 → 10 → 1 архитектурасымен (кіріс сигналдары: y(t), r(t), e(t)) Байес регуляризациясы (trainbr) әдісі арқылы 5000 үлгіде оқытылды. Оқыту жиынтығының 70% бөлігі ПИД-реттегіштің шешімдерінен, ал қалған 30% бөлігі кездейсоқ басқару сигналдарынан қалыптастырылды [17].

Эксперименттік жоспар

Зерттеуде төрт эксперименттік сценарий қолданылды (1-кесте). Бастапқы шарт барлық сценарийлер үшін DO(0) = 1,5 мг/л, берілген мән DOset = 2,0 мг/л. Симуляция ұзақтығы 300 минут.

1-кесте – Эксперименттік сценарийлер сипаттамасы

№	Сценарий	Шарт	Мақсат	Параметрлер
S1	Қалыпты режим	Тұрақты жүктеме	Негізгі дәлдік	Q = Qном, σ = 0,05
S2	Жүктеме бүлдіруші	Q × 1,3, t = 100 мин	Қалпына келу	Δt = 180 мин
S3	Ластану секірісі	SS × 1,5, t = 80–120 мин	Бүлдірушіні басу	Секіріс 40 мин

S4	Датчик шуы	σ = 0,30 мг/л	Шуға тұрақтылық	σшу = 0,30 мг/л

Сапа критерийлері ретінде реттелу уақыты Трет (мин), асып кету (%), интегралды квадраттық қателік ISE, интегралды абсолютты қателік IAE, максималды ауытқу ΔDOmax (мг/л), DO ауытқуының стандарт ауытқуы σDO және аэрация энергия шығыны (кВт·сағ) пайдаланылды.

Нәтижелер және талдау

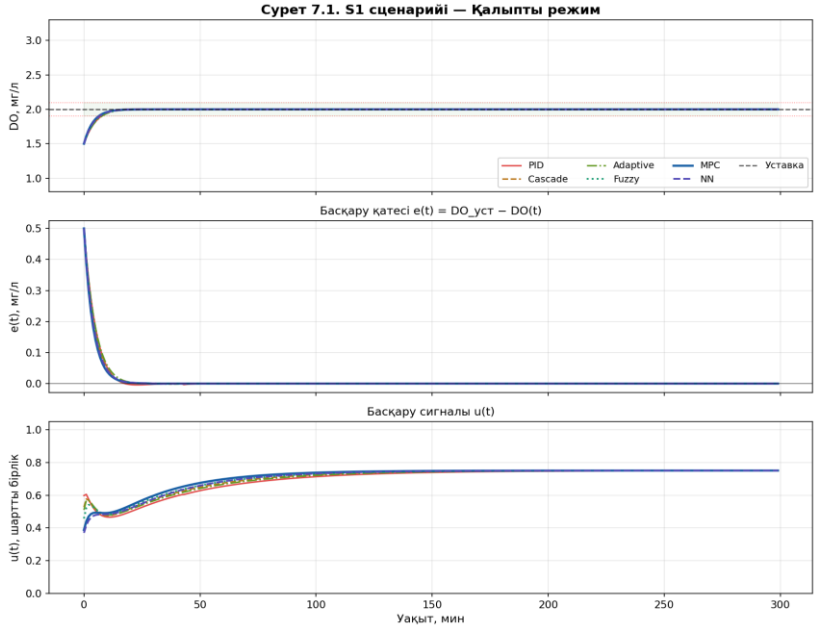
S1 сценарийі: Қалыпты жұмыс режимі

Қалыпты жұмыс режимінде барлық алты реттегіш DO-ны берілген мәнге жеткізді, алайда өтпелі процесс сапасы айтарлықтай ерекшеленді (2-кесте). MPC ең жоғары нәтижені көрсетті: реттелу уақыты 28 мин, асып кету 1,2%, ISE = 0,87 — басқа барлық реттегіштерден екі-үш есе жақсы(1-сурет).

2-кесте – S1 сценарийінің нәтижелері (қалыпты режим)

Метрика	ПИД	Каскадты	MRAC	Fuzzy	MPC	NARX
Трет, мин	42	36	38	33	28	31
Асып кету, %	9,8	6,4	5,1	4,2	1,2	2,8
ISE	3,82	2,74	2,51	2,30	0,87	1,14
IAE	8,14	5,90	5,42	4,87	2,16	2,73
DOтұр, мг/л	2,01	2,00	2,00	1,99	2,00	2,00

Классикалық ПИД ең баяң нәтижені (42 мин) және ең үлкен асып кетуді (9,8%) көрсетті, бұл оның сызықтық емес аэротенк динамикасына бейімделу мүмкіндігінің шектеулілігін дәлелдейді.

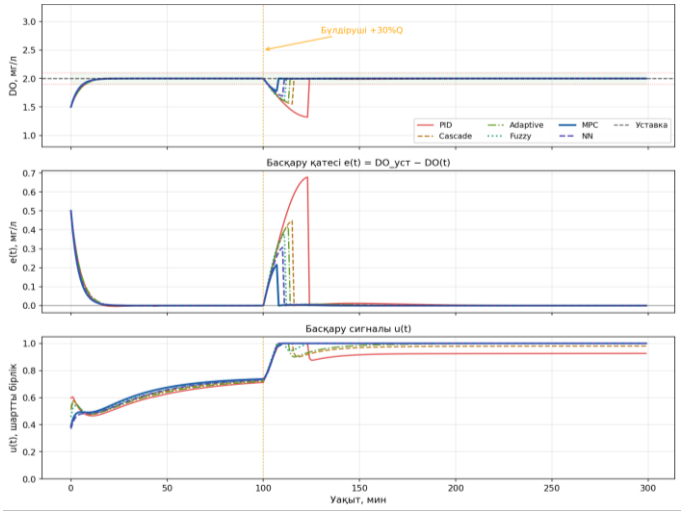


1 сурет – S1 сценарийі — DO(t), e(t), u(t) траекториялары

Fuzzy реттегіш жұмсақ өтпелі процесс пен салыстырмалы жоғары дәлдікті (ISE = 2,30) қамтамасыз етті. NARX нейрожелісі MPC-ге жақын нәтижелер көрсетіп (ISE = 1,14), сызықтық емес объект динамикасын тиімді аппроксимациялайтынын дәлелдеді [17].

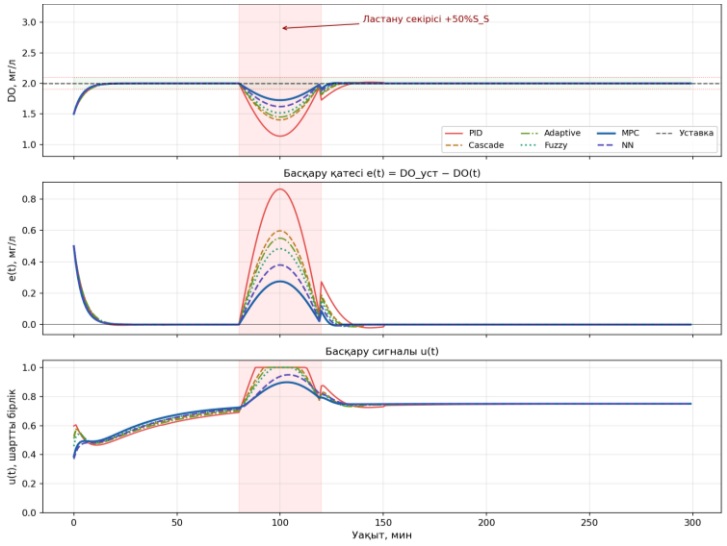
S2 және S3 сценарийлері: Бүлдіруші факторлар

Жүктеме бүлдіруші (S2) сценарийінде t = 100 мин кезінде Q шығыны 30%-ға артқанда барлық реттегіштер DO-ның уақытша төмендеуін байқатты. MPC жүйесі 8 минутта қалыпты мәнге оралып, ең жылдам әрекет кетуін көрсетті, ал ПИД 24 минут жұмсады. Максималды ауытқу: ПИД үшін –0,68 мг/л, MPC үшін тек –0,22 мг/л (2-сурет).



2 сурет – S2 сценарийі — Жүктеме бүлдіруші кезіндегі траектория

Ластану секірісі (S3) сценарийінде (SS × 1,5, t = 80–120 мин) DO деңгейі одан да күшті ауытқыды(3-сурет). Маңызды нәтиже: барлық алты реттегіш кезінде DO < 1,0 мг/л критикалық шегіне дейін түспеді, демек барлық басқару жүйелері аэробты процесс үшін қауіпсіз диапазонды ұстап тұра алды. Алайда MPC-тің ΔDOmax = –0,29 мг/л деңгейі ПИД-тің –0,91 мг/л мәнімен салыстырғанда үш есе аз ауытқуды қамтамасыз еткенін көрсетеді.

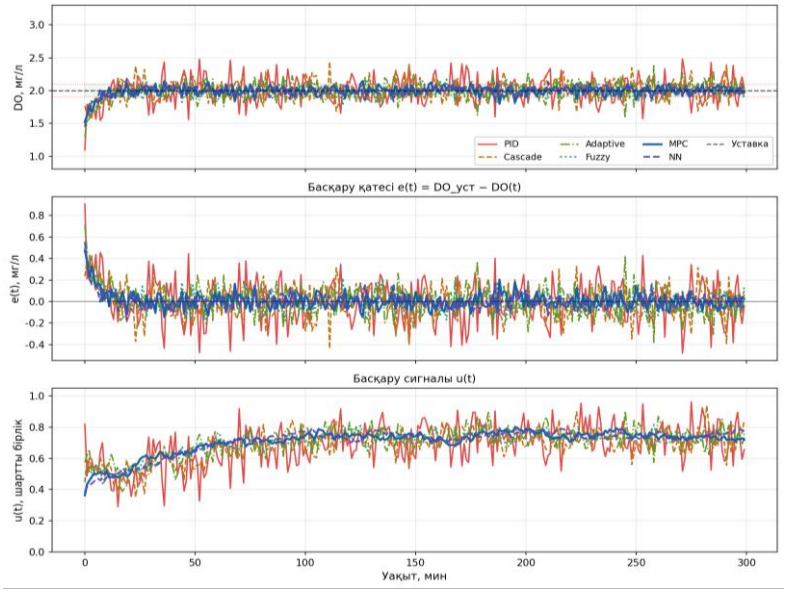


3 сурет– S3 сценарийі — Ластану секірісі кезіндегі траектория

S4 сценарийі: Датчик шуы

Датчик шуының стандарт ауытқуы σ = 0,30 мг/л деңгейіне жеткенде D-компонентке тәуелді реттегіштер (ПИД, каскадты ПИД) ең осал болды — ПИД үшін шығыс DO ауытқуы σDO = 0,19 мг/л деңгейіне жетті(4-сурет). Ең жақсы нәтижені NARX

нейрожелісі (σDO = 0,05 мг/л) және MPC (σDO = 0,06 мг/л) көрсетті. Бұл нейрожелілердің шуды тиімді сүзгілеу қабілетін дәлелдейді [19].



4 сурет– S4 сценарийі — Датчик шуы кезіндегі траектория

Жиынтық салыстырмалы талдау

Барлық сценарийлердің жиынтық нәтижелері 3-кестеде, 5 және 6-суретте берілген.

3-кесте – Алты реттегіштің жиынтық салыстыруы

Критерий	ПИД	Каскад	MRAC	Fuzzy	MPC	NARX
$T_{рет}$ (S1), мин	42	36	38	33	28	31
Асып кету (S1), %	9,8	6,4	5,1	4,2	1,2	2,8
ISE (S1)	3,82	2,74	2,51	2,30	0,87	1,14
ISE (S2)	4,21	2,98	2,74	2,47	1,03	1,42
ΔDO_{max} (S3), мг/л	-0,91	-0,63	-0,58	-0,51	-0,29	-0,40
σDO (S4), мг/л	0,19	0,14	0,12	0,08	0,06	0,05
Энергия, кВт·сағ	38,4	34,2	33,8	31,6	29,7	30,4
Жалпы рейтинг	6	5	4	3	1	2

Жүргізілген салыстырмалы талдаудың негізгі нәтижелері:

Біріншіден, MPC барлық сценарийлер бойынша үздік тиімділікті (жалпы рейтингте 1-орын) қамтамасыз етті. Бұл әдіс болашақтағы жүйе күйін болжау арқылы проактивті басқарма жасайды, шектеулерді нақты есепке алады және аэрация энергиясын ең аз жұмсайды (29,7 кВт·сағ). Алынған нәтижелер Ramin және авт. (2022), Revollar және авт. (2021) жұмыстарының тұжырымдарымен үйлеседі [14, 16].

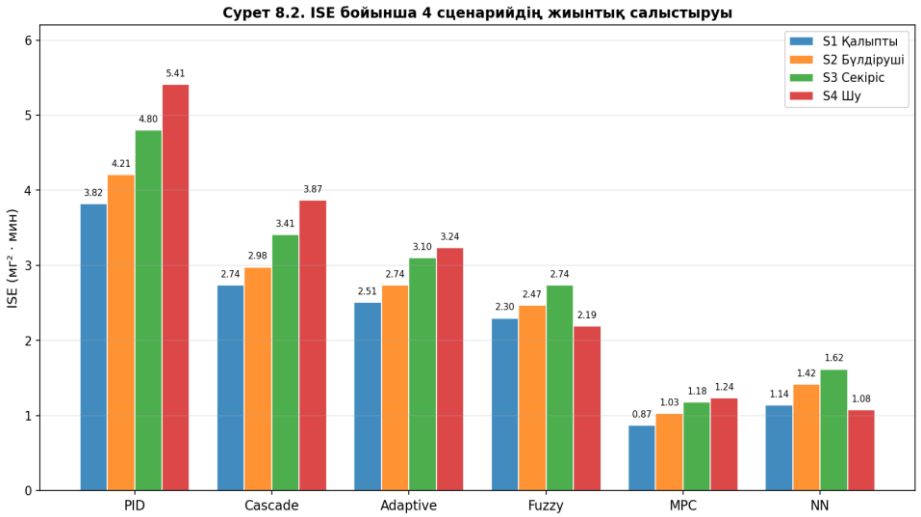
Екіншіден, NARX нейрожелісі шу жағдайында (S4) жалпы рейтингте 2-орынды иеленді, бұл нейрожелілердің сызықтық емес динамика мен шуды тиімді өңдеу қабілетін растайды. Shen және авт. (2024) нәтижелерімен сәйкестік байқалады [19].

Үшіншіден, Fuzzy реттегіш 3-орынға ие болып, күрделілік пен сапа арасындағы тиімді балансты ұсынды. Ол ережеге негізделген логика арқылы сызықтық емес аэротенк мінез-құлқын мүмкіндік шамасында жақсы имитациялайды [11, 12].

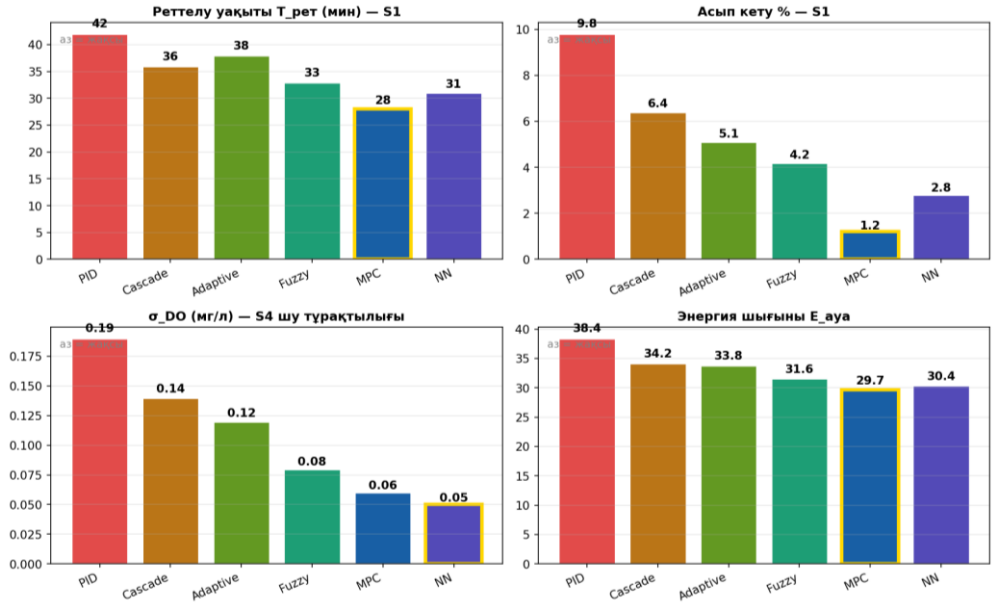
Төртіншіден, MRAC адаптивті реттегіші (4-орын) классикалық ПИД-пен салыстырғанда айтарлықтай жақсы нәтижелер — ISE бойынша 34%-ға жақсарту — берді, бұл нақты уақыт параметр адаптациясының артықшылығын дәлелдейді [10].

Бесіншіден, каскадты ПИД (5-орын) бүлдіруші факторлар жағдайында (S2, S3) жекелеген қарапайым ПИД-тен айқын артықшылық көрсетті, ішкі контурдың жылдам өтелу мүмкіндігі оның бүлдіруші факторларға тұрақтылығын арттырады [9].

Ал классикалық ПИД (6-орын) барлық критерийлер бойынша ең нашар нәтижелер берді, бірақ оның іске асыру қарапайымдылығы мен PLC жүйелерінде кең қолданылуы практикалық артықшылық болып қала береді [7].



5 сурет –ISE бойынша 4 сценарийдің салыстыруы



6 сурет –Негізгі метрикалар бойынша салыстыру (алтын жиек = үздік)

Қорытынды. Осы мақалада ағынды суларды тазарту аэротенгіндегі еріген оттегі концентрациясын басқарудың алты алгоритмі (ПИД, каскадты ПИД, MRAC, Fuzzy Logic, MPC, NARX) ASM1 негізіндегі бірдей математикалық модель шеңберінде кешенді салыстырылды. Төрт эксперименттік сценарий бойынша жүргізілген жүйелі зерттеу келесі негізгі тұжырымдарды жасауға мүмкіндік берді.

MPC (Model Predictive Control) барлық сценарийлер бойынша ең жоғары тиімділікті қамтамасыз етті: ISE = 0,87 (ПИД-тен 4,4 есе жақсы), асып кету 1,2%, реттелу уақыты 28 мин, энергия шығыны 29,7 кВт·сағ (ПИД-тен 22,7%-ға аз). Нейрожелілік басқару (NARX) шу жағдайында σDO = 0,05 мг/л деңгейімен үздік нәтиже берді.

Зерттеудің ғылыми жаңалығы бірдей параметрленген сызықтық емес модельде алты реттегіш түрін алғаш рет жүйелі салыстыруда, кешенді бағалау критерийін ұсынуда және нейрожелілік пен болжамды басқарудың артықшылықтарын нақты модель деректерімен дәлелдеуде жатыр.

Практикалық ұсыныстар Қазақстандық тазарту станцияларына бағытталған: қысқа мерзімде (2025–2026 жж.) стандартты ПЛК жүйелерімен үйлесімді каскадты ПИД-ті енгізу; орта мерзімде (2026–2028 жж.) Fuzzy немесе адаптивті MRAC реттегіштерін пайдалану; ұзақ мерзімде (2028 жылдан) MPC немесе нейрожелілік басқаруды енгізу ұсынылады.

Болашақ зерттеулер перспективасы: нақты WWTP деректерінде модельді верификациялау; DO + NH_4 + TN бір уақытта оңтайландыратын иерархиялық MPC; терең күшейту оқытуы (DDPG/SAC) арқылы энергетикалық оңтайландыру; Қазақстандық климат жағдайында маусымдық температура өзгерісін (5–35°C) ескеретін адаптивті алгоритмдерді зерттеу.

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ЭКОНОМИКАЛЫҚ ЖӘНЕ ҚҰҚЫҚ ҒЫЛЫМДАРЫ - ЭКОНОМИЧЕСКИЕ И ЮРИДИЧЕСКИЕ НАУКИ - ECONOMIC AND LEGAL SCIENCES

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АДМИНИСТРАТИВНО-ПРАВОВОЕ РЕГУЛИРОВАНИЕ ПРОТИВОДЕЙСТВИЯ КОРРУПЦИИ В СОЦИАЛЬНОЙ СФЕРЕ

Аннотация: В статье рассматриваются актуальные вопросы противодействия коррупции в системе государственной и муниципальной службы Российской Федерации. С помощью современной судебной практики и региональных нормативных актов. Рассматриваются причины коррупционных проявлений и механизмы их пресечения. Особое внимание уделяется специфике дисциплинарной ответственности служащих как элементу обеспечения законности и защиты публичных интересов. Указывается значимость мониторинга законодательства и внедрения мер по обеспечению прозрачности деятельности должностных лиц для укрепления стабильности государства.

Ключевые слова: Коррупция, социальная сфера, правонарушения, система, Пленум ВС РФ, государство, граждане, штраф, КоАП.

В современности борьба с коррупцией является одной из главных потребностей российского общества, ведь именно она затрагивает различные сферы публичной и непубличной экономики в государстве. Бывают моменты, когда те, кто должны помогать и защищать интересы граждан в лице компетентных органов берут взятки или вымогают их у людей, нарушая тем самым закон и права граждан.

Так, например, в августе 2025 года Новосибирской области женщина, работающая ранее в социальной сфере по поддержке молодых бизнесменов по субсидиям и их контролю за расходом средств, выделенных государством. Когда к ней пришла предпринимательница с повреждённым документом о расходах, то тогда сотрудница социальной помощи предложила ей решить проблему за персональную выплату в размере 25 тысяч рублей. «Суд признал гражданку виновной во взяточничестве и назначил наказание в виде трёх лет лишения свободы условно, штрафа в 50 тысяч рублей, а также запрета на работу в сфере реализации госпрограмм на два года. Кроме того, суд постановил конфисковать взятку в размере 25 тысяч рублей»[1].

[1] 2026 ГТРК «Новосибирск» Государственный интернет-канал "Россия" (свидетельство о регистрации ЭЛ № ФС 77-59166 от 22.08.2014). Учредитель - федеральное государственное унитарное предприятие "Всероссийская государственная телевизионная и радиовещательная компания" (ВГТРК)

В 2023 году были уволены муниципальные служащие за утрату доверия перед населением за коррупционное правонарушение в размере 57 миллиардов рублей.

Данные примеры наглядно показывают, что коррупция создаёт угрозу стабильности и развитию, как населения так и государства. Поэтому контроль за публичными образованиями и органами, их представляющих, является необходимым аспектом в развитии государства.

В России значимое внимание уделяется борьбе с коррупцией в государственной и муниципальной службе, осуществляющая применение дисциплинарных мер для поддержания порядка и обеспечения должного исполнения обязанностей, касающихся интересов граждан.

«Отношения государственных и муниципальных служащих с нанимателем носят публичный характер и регулируются особым образом. Это связано с тем, что служащие выполняют общественно-значимые функции и несут обязанности по соблюдению дисциплины, поэтому наниматель в рамках служебного контракта обладает в части привлечения к дисциплинарной ответственности большей свободой, чем работодатель в рамках трудового договора»[2]. Данная точка зрения Очаковского В.А, Крутовой Я.А и Жуковой Н.А имеет ключевое значение, в силу того что элементы социальной сферы представляются учреждениями.

Основными причинами коррупции являются нестабильность экономического развития граждан, корыстное намерение сотрудников занимаемой ими должности, что в последующим приводит к нарушениям действующего законодательства.

Например, Распоряжение от 20 декабря 2024 г. № 149-рк «О Плане мероприятий Законодательной Думы Хабаровского края по противодействию коррупции на 2025 - 2028 годы»[3]. Ориентировано на «Мониторинг федеральных законов, иных нормативных правовых актов Российской Федерации, судебной практики по вопросам противодействия коррупции и по его результатам подготовка соответствующих изменений в законы Хабаровского края»[4]. А также разработка Министерством труда и социальной защиты методических материалов по противодействию коррупции. Прозрачность деятельности депутатов и других государственных служащих, предоставление деклараций о доходах и имущественных благ.

Конечно, коррупционная деятельность не исчезла сразу, к примеру, «За 2025 год в Хабаровском крае зарегистрировано 184 преступления коррупционной направленности, по итогам прокурорских проверок возбуждены новые уголовные дела. В основе таких преступлений чаще всего лежали откаты за покровительство при заключении контрактов, подписание документов по некачественным работам и взятки за информирование о контрольных мероприятиях»[5].

[2] Очаковский В.А. Крутова Я.А., Жукова Н.А. Дисциплинарная ответственность государственных гражданских служащих в Российской Федерации // Политематический сетевой электронный научный журнал Кубанского государственного аграрного университета. 2014. № 99. С.5

[3] Распоряжение от 20 декабря 2024 г. № 149-рк О Плане мероприятий Законодательной Думы Хабаровского края по противодействию коррупции на 2025 - 2028 годы

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Рассматривая коррупцию в социальной сфере, можно сказать, что она затрагивает граждан, находящихся в трудном жизненном положении, а сама коррупция существует на уровне и в пределах применения социальной системы.

Весьма часто в коррупционных правонарушениях встречаются нарушения, связанные со статьёй 15.14 КоАП РФ, которая устанавливает административную ответственность за нецелевое использование бюджетных средств в виде наложения штрафа или дисквалификацию от 1 года до 3 лет, а на юридических лиц от 5 до 25 процентов от суммы, полученной из бюджета РФ.

Постановление Пленума Верховного Суда РФ от 09.07.2013 N 24 (ред. от 09.12.2025) О судебной практике по делам о взяточничестве и об иных коррупционных преступлениях» говорит о коррупционных преступлениях, что «Правосудие по таким делам должно осуществляться на основе соблюдения принципов независимости судебной власти, состязательности и равноправия сторон, соблюдения прав и свобод человека, в строгом соответствии с требованиями уголовного и уголовно-процессуального законодательства»[6].

В лекции от 20.05.2025 на Петербургском международном юридическом форуме В.Д.Зорькин назвал коррупцию «угрозой цивилизации права и она отчуждает государство от народа, лишает граждан социальных, экономических и политических благ, снижает качество государственных услуг и инфраструктуры»[7].

По мнению Курганской А.А и Очаковского В.А, «одним из наиболее серьёзных, катализаторов административных правонарушений в социальной сфере является децентрализация»[8].

Разумеется, тенденция развития разделения правового регулирования существует и применяется, но контроль за субъектами осуществлять весьма затруднительно, что и приводит к взятничеству среду сотрудников социальной сферы.

При этом есть необходимость проведения стандартизации системы применения мер административного противодействия коррупции в социальной сфере, в особенности — создание единой системы форм и методов их реализации на уровне федерации, субъектов, и на местном уровне.

Дополнительно системой мер по противодействию коррупционным правонарушениям могут способствовать разработки комплексных систем моральной и материальной базы работников, занимающихся социальной сферой. Из этого вытекает обеспечение формирования на рабочих местах системы поощрительных мер и стратегий карьерных направлений.

Можно отметить, что повышения заработной платы в государственных учреждениях и улучшения материального состояния работников поможет уменьшить коррупцию, но не убрать её полностью, поскольку бывают сотрудники, которые устраиваются в социальную сферу в корыстных целях. Что и подрывает доверие населения к государственным органам, а это негативно сказывается на реализации деятельности сотрудников в социальной сфере.

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[6] Постановление Пленума Верховного Суда РФ от 09.07.2013 N 24 (ред. от 09.12.2025) «О судебной практике по делам о взяточничестве и об иных коррупционных преступлениях»

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Н. П. Мышляев подчёркивает, что «.Без изучения причин и условий, способствующих проявлению административной деликтологии невозможно на научной основе разработать мероприятия по организации борьбы с административными правонарушениями не только силами правоохранительной системы, деятельность которой основана на законе, но и экономических, социальных и иных рычагов, которыми общество и государство располагает»[9].

Таким образом, административно-правовое регулирование по противодействию коррупции в социальной сфере является многогранным и сложным процессом, который требует выработки системы определённых норм по административному характеру и усилий государства в обеспечении порядка, устойчивости на уровне социальной сферы граждан. Существенную роль в противостоянии коррупции играет увеличение зарплат сотрудникам, а вдобавок введение мер, по которым у работников социальной сферы будут бенефиты. Перспективная борьба с коррупцией улучшит доверие населения к государственным органам и ликвидирует возможность взимание платы с бесплатных услуг у граждан.

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CYBERSECURITY GOVERNANCE IN KAZAKHSTAN'S DIGITAL PUBLIC SECTOR: TOWARD AN INTEGRATED FRAMEWORK

Abstract. The article examines cybersecurity governance in Kazakhstan's digital public sector. It argues that, in the context of digital public administration, cybersecurity should be viewed not only as a technical function, but also as a governance capability. Although Kazakhstan has developed digital public services, cybersecurity policies, institutional structures and technical tools, formal readiness does not automatically ensure operational cybersecurity effectiveness. The article identifies key problems such as fragmented coordination, uneven institutional maturity and insufficient risk-based management. Based on international approaches and comparative governance principles, the article proposes an integrated cybersecurity governance framework for Kazakhstan's public sector.

Keywords: cybersecurity governance, digital governance, public sector, Kazakhstan, risk management, institutional maturity, digital public services.

Introduction. Digital transformation has become one of the key directions in the modernization of public administration. Governments increasingly use digital platforms, mobile applications, public databases, digital identity systems and inter-agency data exchange mechanisms to provide public services and improve administrative efficiency. As a result, digital public services are no longer only an additional service channel. They are becoming a core infrastructure of public administration.

Kazakhstan is a relevant case for studying cybersecurity in digital governance. The country has achieved significant progress in e-government development. According to the United Nations E-Government Survey 2024, Kazakhstan ranked 24th in the E-Government Development Index and achieved an EGDI score of 0.9009 [1]. In addition, Kazakhstan received 94.04 out of 100 in the Global Cybersecurity Index 2024 [2]. These indicators demonstrate that the country has developed a strong formal foundation for digital government and cybersecurity.

Kazakhstan's cybersecurity policy direction is also reflected in national strategic documents, including the Concept of Cybersecurity "Cyber Shield of Kazakhstan" and the Concept of Digital Transformation, ICT Development, and Cybersecurity [11], [12]. These documents show that cybersecurity is recognized at the state level as an important condition for digital transformation and national information security.

However, formal readiness does not automatically mean operational effectiveness. The presence of digital platforms, legal measures, cybersecurity policies, institutions and technical tools does not guarantee that cyber risks are managed consistently across all public sector institutions. Public institutions may differ in their resources, technical capacity, cybersecurity maturity, staff skills and ability to implement security requirements in practice.

The main problem addressed in this article is the gap between formal cybersecurity readiness and operational cybersecurity governance effectiveness. Cybersecurity tools may exist, but their effectiveness depends on how they are governed, coordinated, prioritized and improved. Therefore, cybersecurity in the public sector should be considered not only as a technical function, but as a governance capability.

The aim of this article is to propose an integrated cybersecurity governance framework for Kazakhstan's digital public sector. The article focuses on the following question: how can cybersecurity methods and tools be structured into a governance framework that supports the protection of Kazakhstan's public sector from cyber threats?

Cybersecurity as a Governance Capability

Cybersecurity is often associated with technical tools such as firewalls, access control systems, encryption, monitoring platforms, anti-malware solutions, vulnerability scanners and incident response tools. These instruments are necessary for protecting information systems and data. However, international standards and frameworks show that cybersecurity effectiveness depends not only on tools, but also on governance, risk management, institutional responsibility and continuous improvement.

The NIST Cybersecurity Framework structures cybersecurity activities around identifying, protecting, detecting, responding and recovering from cyber risks [3]. ISO/IEC 27001 emphasizes leadership, risk assessment, control implementation, monitoring and continual improvement as part of an information security management system [4]. The OECD also treats digital security risk as an economic and social risk that should be integrated into organizational and governmental decision-making [5]. These approaches show that cybersecurity is not only a technical task, but also a management and governance process.

Zero Trust architecture and digital identity guidelines are also relevant for public sector cybersecurity because they connect access control, identity verification, least-privilege principles and continuous monitoring with institutional governance [6], [7]. In a digital public sector, where citizens, civil servants, contractors and administrators interact with digital systems, identity and access governance become essential elements of cybersecurity management.

In the public sector, this governance dimension is especially important. Public institutions provide essential services, process sensitive citizen data and operate within complex institutional structures. A cyber incident in one institution may affect not only one system, but also other organizations connected through shared infrastructure, data exchange and digital service platforms. ENISA threat landscape reports also show that public administration remains exposed to evolving cyber threats, which makes cybersecurity governance a continuing priority for states and public institutions [9].

From a governance perspective, cybersecurity requires several elements. First, responsibilities must be clearly assigned across leadership, information security units, data owners, process owners and operational teams. Second, cyber risks should be prioritized according to the criticality of public services. Third, institutions should regularly assess their cybersecurity maturity and improve their capabilities. Fourth, implementation should be measurable through evidence, indicators, audits and incident learning.

CISA's Zero Trust Maturity Model is useful in this context because it presents cybersecurity development as a gradual maturity process rather than a one-time technical

deployment [10]. This logic is especially important for Kazakhstan's public sector, where institutions may differ in resources, technical infrastructure and organizational capacity.

International Practices and Their Relevance for Kazakhstan

International practices provide useful principles for Kazakhstan, but they should not be copied directly. Estonia, Singapore and the European Union are particularly relevant because they represent different models of cybersecurity governance.

Estonia demonstrates the importance of secure digital infrastructure and accountable data exchange. Its experience is useful because Kazakhstan also relies on e-government platforms, public databases, digital identity mechanisms and inter-agency data exchange. The main lesson from Estonia is that cybersecurity should be embedded into digital governance infrastructure through secure interoperability, auditability and institutional responsibility [13].

Singapore demonstrates the value of central coordination and whole-of-government cybersecurity leadership. This is relevant for reducing fragmentation in public sector cybersecurity. A centralized governance approach helps clarify national priorities, define responsibilities and coordinate institutions responsible for critical digital services [14].

The European Union is useful not as a single country, but as a reference model of multi-level cybersecurity governance. The EU demonstrates how common cybersecurity requirements, certification logic, incident reporting and maturity-oriented approaches can be coordinated across different institutions and sectors. The EU Cybersecurity Act also demonstrates the role of harmonized cybersecurity requirements and certification mechanisms in multi-level governance [8]. This is relevant for Kazakhstan because public institutions also differ in maturity, resources and technical capacity, while still needing common cybersecurity baselines.

Table 1. Comparative adaptation logic of international practices

Reference case	Governance principle	Relevance for Kazakhstan
Estonia	Secure interoperability and accountable data exchange	Useful for digital identity, public registries and inter-agency data exchange
Singapore	Central coordination and whole-of-government cybersecurity leadership	Useful for reducing fragmentation and clarifying responsibility
European Union	Harmonized requirements and maturity-oriented governance	Useful for minimum public sector baselines, reporting and maturity assessment

The comparative lesson is that Kazakhstan should not mechanically transfer foreign models. Instead, it should adapt selected principles: secure data exchange, central coordination, harmonized minimum requirements, risk-based management and institutional maturity assessment.

Key Governance Gaps in Kazakhstan's Digital Public Sector

The analysis of Kazakhstan's digital and cybersecurity context shows that the country has made important progress in formal readiness. However, several governance gaps may limit the practical effectiveness of cybersecurity methods and tools.

The first gap is fragmented coordination. Kazakhstan's public sector includes central government bodies, local executive bodies, quasi-public organizations, national operators and service-providing institutions. These actors may have different responsibilities, resources and cybersecurity practices. Without strong coordination, cybersecurity measures can become inconsistent across institutions.

The second gap is uneven institutional maturity. Some institutions may have advanced monitoring, access control and incident response procedures, while others may rely mainly on formal compliance. In a digital governance ecosystem, uneven maturity is a serious problem because public institutions are interconnected. A weak institution may create risks for other systems and services.

The third gap is insufficient risk-based prioritization. In a compliance-oriented approach, institutions may focus on meeting formal requirements without fully considering which systems are most critical. However, digital identity systems, public registries, tax platforms, healthcare databases and social support systems should have higher protection requirements than low-risk systems.

The fourth gap is the implementation gap. Policies and standards may exist, but the practical question is whether they are implemented, monitored, tested and improved. Cybersecurity governance must therefore include evidence of implementation, key performance indicators, incident reporting, audit and continuous improvement.

These gaps support the main argument of the article: cybersecurity effectiveness in Kazakhstan's digital public sector depends not only on the presence of tools, but on the governance structure that connects tools with institutional responsibilities, risks and implementation mechanisms.

Proposed Cybersecurity Governance Framework

Based on the identified gaps, an integrated cybersecurity governance framework for Kazakhstan's digital public sector can be structured around four components: governance coordination, risk-based management, institutional maturity and implementation mechanisms.

The first component is governance coordination. Its purpose is to clarify roles and responsibilities across different levels of the public sector. At the national level, cybersecurity governance should define policy direction, common requirements and national priorities. At the inter-agency level, it should support coordination protocols for shared services and joint risks. At the institutional level, it should define responsibilities of leadership, information security units, data owners and process owners. At the operational level, it should include SOC teams, administrators, employees and contractors.

The second component is risk-based management. Its purpose is to prioritize cybersecurity measures according to the criticality and risk profile of public digital services. This component includes asset and service identification, criticality classification, risk assessment, control prioritization and continuous monitoring. The key idea is that not all systems require the same level of protection. Critical public services should receive stronger controls, regular testing and higher maturity requirements.

The third component is institutional cybersecurity maturity. Its purpose is to assess and improve cybersecurity capability over time. A five-level maturity model can be used: Initial, Basic Compliance, Managed, Integrated and Optimized. At the initial level, cybersecurity practices are mostly reactive. At the basic compliance level, minimum formal requirements exist. At the managed level, risks, controls and incidents are documented and monitored. At the

integrated level, cybersecurity is connected to institutional governance and inter-agency coordination. At the optimized level, cybersecurity is continuously improved through monitoring, audits, testing and lessons learned.

The fourth component is implementation mechanisms. Their purpose is to translate governance principles into practical actions. These mechanisms may include minimum cybersecurity requirements, risk-based control mapping, incident response coordination, access and identity governance, training and awareness, monitoring and reporting, audit and continuous improvement.

Table 2. Components of the proposed cybersecurity governance framework

Framework component	Purpose	Practical mechanisms
Governance coordination	Clarify roles and cooperation across public sector levels	National coordination, inter-agency protocols, institutional responsibilities, operational feedback
Risk-based management	Prioritize protection according to service criticality and risk	Asset identification, risk assessment, control prioritization, monitoring
Institutional maturity	Assess and improve cybersecurity capability	Maturity levels from Initial to Optimized, capability development, reassessment
Implementation mechanisms	Translate principles into practical actions	Minimum requirements, access governance, incident response, training, audit

The proposed framework can be presented as a layered structure. Implementation mechanisms form the operational base of the model, while institutional cybersecurity maturity and risk-based management connect practical actions with strategic governance coordination. This structure shows that cybersecurity governance should operate both from bottom to top and from top to bottom: operational implementation informs strategic governance, while strategic direction guides practical execution [Figure 1].

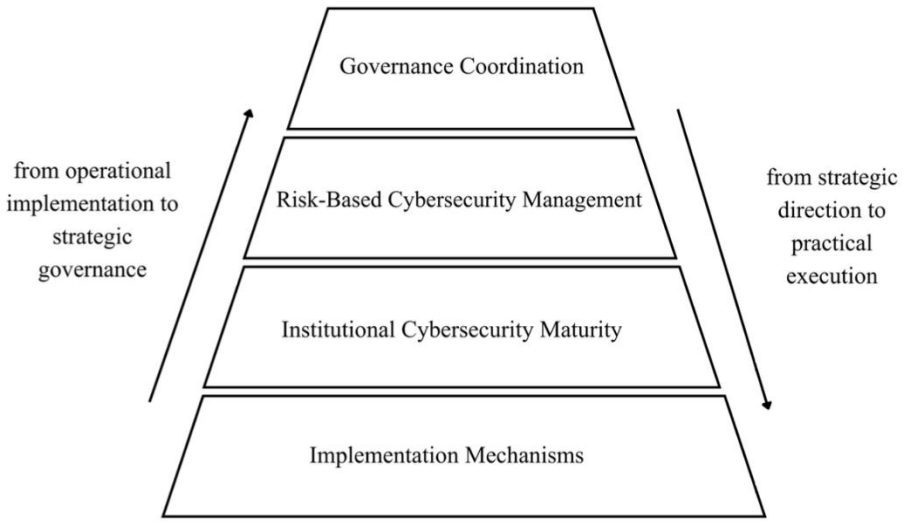


Figure 1. Layered structure of the framework

Governance coordination is organized across four levels: national, inter-agency or sectoral, institutional and operational. The model shows that cybersecurity governance requires both top-down standards and bottom-up reporting. This is important because public digital services depend on multiple institutions, shared systems and continuous feedback from operational practice [Figure 2].



Figure 2. Cybersecurity governance coordination model

The risk-based cybersecurity management cycle shows how protection of critical digital public services can be organized in practice. The process begins with asset and service identification, followed by criticality classification, risk assessment, control prioritization, and continuous monitoring. This cycle supports a shift from uniform compliance to risk-based protection of the most important public services [Figure 3].

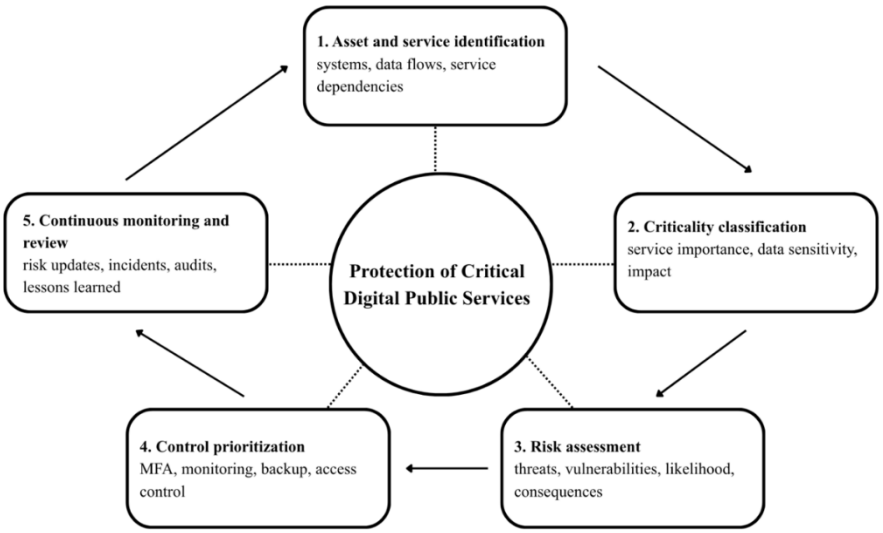


Figure 3. Risk-Based Cybersecurity Management Cycle

The public sector cybersecurity maturity model provides a structured way to assess the development of cybersecurity capabilities across institutions. It compares five maturity levels

across key dimensions such as governance and accountability, risk management, technical controls, incident response, human capacity and continuous improvement. This table helps identify whether an institution remains at a basic compliance level or moves toward integrated and optimized cybersecurity governance [Table 3].

Table 3. Public sector cybersecurity maturity model

Assessment dimension	Level 1. Initial	Level 2. Basic Compliance	Level 3. Managed	Level 4. Integrated	Level 5. Optimized
Governance and accountability	Roles are unclear; cybersecurity depends on individual employees	Minimum formal responsibilities exist	Clear internal responsibilities are assigned	Cybersecurity is integrated into institutional governance	Cybersecurity is treated as a strategic governance capability
Risk management	Risks are not systematically identified	Risk assessment is limited and compliance-driven	Regular risk assessments are conducted	Risks are linked to service criticality and institutional priorities	Risk management is continuous, adaptive, and decision-oriented
Technical controls	Basic or fragmented tools exist	Basic required controls are implemented	Controls are documented, monitored, and reviewed	Controls are aligned with critical systems and inter-agency dependencies	Advanced controls, continuous monitoring, and proactive protection are used
Incident response	Response is reactive and informal	Incident procedures exist mainly on paper	Incidents are recorded, escalated, and reviewed	Cross-agency incident response is coordinated	Lessons learned from incidents are systematically used to improve resilience
Human capacity	Awareness is low and training is irregular	General cybersecurity training is provided occasionally	Role-based training begins for key staff	Security culture is developing across the institution	Strong cybersecurity culture and continuous staff development are institutionalized
Continuous improvement	No regular review or improvement process exists	Reviews are occasional and mainly audit-driven	Improvement actions are planned and tracked	Maturity is assessed regularly and improvement is coordinated	Continuous improvement is institutionalized through monitoring, audits, testing, and lessons learned

This framework connects cybersecurity methods and tools with governance mechanisms. It does not replace technical standards or security controls. Instead, it provides a management structure for applying them more consistently across Kazakhstan's public sector.

Practical Value of the Framework

The proposed framework has several practical benefits for Kazakhstan's public sector.

First, it helps reduce governance fragmentation by defining coordination levels and responsibilities. This is important because digital public services often depend on several institutions and shared infrastructure.

Second, it supports protection of critical digital public services. Through risk-based prioritization, resources can be focused on services with the greatest importance for citizens, public administration and national resilience.

Third, it improves accountability. Cybersecurity responsibility should not be limited to IT departments. It should involve leadership, data owners, process owners, legal units, procurement units, technical teams and employees.

Fourth, the framework supports maturity development. A maturity model allows institutions to assess their current level and plan gradual improvement. It also helps policymakers identify institutions that need additional support, training or supervision.

Fifth, the framework supports continuous improvement. Cyber threats change constantly, so cybersecurity governance should include monitoring, audit, staff training, incident review and regular reassessment of risks.

Overall, the practical value of the framework lies in its ability to move cybersecurity from separate technical actions toward coordinated public sector management. This is especially important in digital governance, where public service continuity, data protection and citizen trust depend on the resilience of interconnected systems.

Conclusion. Cybersecurity in Kazakhstan's digital public sector should be strengthened not only through additional technical tools, but also through better governance. Kazakhstan has developed a strong formal foundation for digital government and cybersecurity, as shown by its progress in international digital government and cybersecurity indicators. However, formal readiness does not automatically ensure operational cybersecurity effectiveness.

The key challenge is how cybersecurity methods and tools are coordinated, prioritized, implemented and improved across public sector institutions. Fragmented coordination, uneven institutional maturity and insufficient risk-based management may reduce the effectiveness of existing cybersecurity measures.

The proposed framework structures cybersecurity governance around four components: governance coordination, risk-based management, institutional maturity and implementation mechanisms. Its practical value lies in helping public institutions reduce fragmentation, protect critical digital public services, improve accountability and support continuous improvement.

Future research should test the proposed framework in selected public institutions, conduct broader expert surveys, apply the maturity model across sectors and examine cybersecurity governance in specific areas such as healthcare, taxation, education, digital identity and public registries.

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БІЛІМ БЕРУ САЛАСЫНДАҒЫ ЖАСАНДЫ ИНТЕЛЛЕКТ ЖҮЙЕЛЕРІ ЖӘНЕ ДЕРБЕС ДЕРЕКТЕРДІ ҚОРҒАУДЫҢ ҚҰҚЫҚТЫҚ МӘСЕЛЕЛЕРІ

Аңдатпа: Мақалада Қазақстан Республикасының білім беру саласында жасанды интеллект жүйелерін қолданумен байланысты дербес деректерді қорғаудың құқықтық мәселелері зерттеледі. Оқушылар мен студенттердің жеке деректерін жинау, өңдеу және сақтауды реттейтін ұлттық заңнама нормалары, сондай-ақ халықаралық тәжірибе талданады. ЖИ негізіндегі білім беру платформаларының деректер заңнамасын сақтамаудан туындайтын тәуекелдері анықталады. Адаптивті оқыту жүйелері мен автоматтандырылған бағалау құралдары тұрғысынан деректер субъектілерінің құқықтарын қамтамасыз ету мәселесі қарастырылады. Заңнаманы жетілдіру бойынша ұсыныстар берілген.

Түйін сөздер: жасанды интеллект, білім беру, дербес деректер, деректерді қорғау, цифрлық білім беру, алгоритмдік шешімдер, адаптивті оқыту, Қазақстан заңнамасы, GDPR, EU AI Act.

Кіріспе. Қазіргі таңда жасанды интеллект (бұдан әрі - ЖИ) технологиялары білім беру жүйесіне жылдам ене бастады. Адаптивті оқыту платформалары, автоматтандырылған бағалау жүйелері, болжамды аналитика сияқты технологиялар оқу үдерісін өзгертуде. Осы технологиялардың негізінде оқушылардың жеке деректерін жинақтау, өңдеу және сақтау жатыр. Қазақстан Республикасының «Дербес деректер және оларды қорғау туралы» Заңы бойынша деректерді жинауға субъектінің немесе оның заңды өкілінің келісімі міндетті (9-бап), ал субъект өз деректеріне қол жеткізуге, оларды түзетуге және жоюға құқылы (24-бап).

Зерттеудің өзектілігін негіздейтін бірінші фактор - 2025 жылғы 17 қарашада қабылданып, 2026 жылғы 18 қаңтардан бастап қолданысқа енген Қазақстан Республикасының «Жасанды интеллект туралы» Заңы болып табылады; аталған заң ЖИ жүйелерін мемлекеттік деңгейде реттеудің ұлттық құқықтық негізін айқындады. Заңның 7-бабында ашықтық және түсіндіруге қабілеттілік қағидаты бекітілген: пайдаланушылар өз деректерінің автоматтандырылған өңделуі туралы толық ақпарат алуға, сондай-ақ осындай өңдеуге қарсылығын білдіруге заңды құқыққа ие. 8-бап ЖИ жүйелерін жасаушыларға, иелеріне және пайдаланушыларына нәтижелері үшін толық жауапкершілікті жүктейді.

Екінші фактор - ҚР 2030 жылға дейінгі Құқықтық саясат тұжырымдамасы, онда жасанды интеллект пен деректерді пайдалану процестерін мемлекеттік реттеу жүйесіне енгізу, цифрлық технологиялар кезінде туындайтын жаңа заңнамалық реттеуді қажет

ететін мәселелерді шешу ұлттық заңнаманы жетілдірудің басым бағыттарының бірі ретінде белгіленген.

Үшінші фактор - халықаралық деңгейдегі жаңа стандарттардың пайда болуы. 2024 жылы күшіне енген EU Artificial Intelligence Act білім беру саласындағы ЖИ жүйелерін жоғары тәуекел санатына жатқызып (III қосымша), алгоритмдік аудит, адам бақылауы және ашықтық талаптарын міндетті ретте белгіледі.

Осымен қатар Еуропалық Одақтың Жалпы деректерді қорғау регламенті (GDPR) балалар деректеріне және автоматтандырылған шешімдерге қатысты нақты нормалар белгіледі. GDPR-дің 8-бабы кәмелетке толмаған адамдардың деректерін өңдеу үшін ата-ананың нақты келісімін, ал 22-бабы автоматтандырылған шешімдерге қарсылық білдіру құқығын бекітеді. Осы халықаралық тәжірибе Қазақстан заңнамасын одан әрі жетілдіру қажеттігін айқын көрсетеді.

Жауапкершілік тұрғысынан ҚР Қылмыстық кодексінің 147-бабы дербес деректерді бұзғаны үшін нақты санкциялар белгілейді: жалпы жағдайда 3 жылға, ал қызметтік жағдайды пайдаланып жасалса 5 жылға дейін бас бостандығынан айыру. Бұл норма білім беру мекемелері мен ЖИ платформалары арасындағы қатынастарды заңнамалық тұрғыдан бекітуде маңызды рөл атқарады.

Деректерді локализациялау мәселесіне келетін болсақ, ҚР Цифрлық даму министрінің №179/НҚ бұйрығы дербес деректерді міндетті түрде тек Қазақстан Республикасының аумағында орналасқан серверлерде ғана сақтауды талап ететін норманы бекітеді. Аталған талап шетелдік жасанды интеллект платформаларын өз қызметінде пайдаланатын білім беру ұйымдары үшін ерекше практикалық мәнге ие.

ЮНЕСКО-ның 2021 жылғы ЖИ этикасы жөніндегі ұсынымы - 193 мемлекет қабылдаған алғашқы жаһандық стандарт. Ұсынымда ЖИ білім берудегі оқушының автономиясын бұзбауы тиіс деп белгіленген; оқушы деректерінің коммерциялық мақсатта пайдаланылуы тыйылған.

ЭЫДҰ-ның ЖИ жөніндегі ұсынымы (OECD/LEGAL/0449, 2019, 2024 жылы жаңартылған) 47 ел қолдаған бес принципті - ашықтық, сенімділік, адамға бағдарланған құндылықтар, инклюзивтілік және есеп беру қабілеттілігін - белгіледі. Принциптер ұлттық ЖИ саясатын қалыптастырудың жаһандық бағдары ретінде қызмет етеді.

Мақаланың мақсаты - Қазақстандағы білім беру саласындағы ЖИ жүйелерінде дербес деректерді қорғаудың қолданыстағы құқықтық механизмдерін талдау, проблемалық аймақтарды анықтау және заңнаманы жетілдіру бойынша нақты ұсыныстар әзірлеу.

Материалдар мен әдістер. Бұл мақалада бірнеше ғылыми зерттеу әдістері қолданылды. Ең алдымен, нормативтік-құқықтық талдау әдісі пайдаланылып, Қазақстан Республикасының «Дербес деректер және оларды қорғау туралы» Заңы, «Жасанды интеллект туралы» Заңы, сондай-ақ GDPR, EU AI Act секілді халықаралық құқықтық актілер зерттелді. Сонымен қатар салыстырмалы-құқықтық талдау әдісі арқылы ҚР заңнамасы халықаралық стандарттармен салыстырылып, олардың ұқсастықтары мен айырмашылықтары анықталды. Зерттеу барысында жүйелік талдау әдісі қолданылып, білім беру саласындағы жасанды интеллект жүйелерінің дербес деректерді қорғауға әсері кешенді түрде қарастырылды. Сондай-ақ проблемалық талдау әдісі арқылы қолданыстағы заңнамадағы олқылықтар анықталып, оларды жетілдіруге қатысты нақты ұсыныстар берілді.

Талқылау мен қорытындылар.

1. Жасанды интеллект ұғымы, оның білім беру саласындағы қолданысы және ұлттық заңнамадағы орны.

Білім беру саласында жасанды интеллект жүйелерін құқықтық реттеуді зерделеу үшін алдымен осы саладағы ұлттық деректерді қорғау заңнамасының негізін анықтау қажет. Қазақстан Республикасының «Дербес деректер және оларды қорғау туралы» Заңы дербес деректер субъектісінің іргелі құқықтарын белгілейді. 8-бап бойынша дербес деректер белгісіз немесе жалпы мақсаттар үшін жиналмауы тиіс - жинаудың нақты және заңды негізі болуы шарт. 9-бап деректерді жинамас бұрын субъектінің жазбаша не электрондық нысандағы келісімін алуды міндеттейді. 2-бап субъектіге өзі туралы сақталған деректермен танысуға, қате мәліметтерді түзеттіруге және қажет болған жағдайда жойдыруға мүмкіндік береді. 2023-2024 жылдарда заңға өзгерістер енгізіліп, деректер бұзылымы туралы уәкілетті органды дереу хабардар ету тәртібі нақтыланды.[1]

Ұлттық заңнаманың екінші іргетасы - ҚР «Жасанды интеллект туралы» 2025 жылғы Заңы. Заң жасанды интеллект жүйесін «деректерді өңдеу негізінде ұсыныстар, болжамдар немесе шешімдер жасайтын, белгілі бір мақсатқа жету үшін жасалған бағдарламалық және/немесе аппараттық кешен» ретінде анықтайды. Бұл анықтама ЖИ жүйесінің үш негізгі белгісін: деректерге негізделуін, шешім қабылдау функциясын және мақсаттылығын ашып көрсетеді.

ҚР «Жасанды интеллект туралы» Заңы ЖИ субъектілерінің міндеттерін нақты белгіледі. 7-бап ашықтық пен түсіндіруге қабілеттілік принципін бекітеді: пайдаланушылар автоматтандырылған деректер өңдеу туралы, оның салдарлары туралы хабардар болуға және мұндай өңдеуге қарсылық білдіруге құқылы. 8-баптың 2-тармағына сәйкес ЖИ жүйелері саласында қызмет атқаратын барлық қатысушылар - атап айтқанда, әзірлеушілер, меншік иелері және пайдаланушылар - жүйенің жұмыс істеу процесін үнемі қадағалап отыруға, туындайтын тәуекелдерді басқаруға, сондай-ақ өз қызметінің нәтижелері үшін заңнамада көзделген жауапкершілікті өз мойындарына қабылдауға тиіс. 10-бап ЖИ жүйелерін қолдану барысында пайдаланушылардың дербес деректерінің қауіпсіздігін қамтамасыз етуді, сондай-ақ пайдаланылатын деректердің сапасы мен репрезентативтілігіне қойылатын талаптарды орындауға бағытталған шараларды міндетті түрде қолдануды талап етеді. 18-бап жоғары тәуекелді жүйелер иелерінің тәуекелдерді басқару, толық құжаттаманы сақтау және рұқсатсыз қол жеткізуден қорғау міндеттерін белгілейді. 20-бап жоғары тәуекелді деп танылған ЖИ жүйелеріне міндетті аудит өткізу талабын бекітеді.[2]

Ұлттық заңнаманың стратегиялық негізі - ҚР 2030 жылға дейінгі Құқықтық саясат тұжырымдамасы. Тұжырымдама жасанды интеллект пен деректерді пайдалану процестерін мемлекеттік реттеу жүйесіне енгізуді және ЖИ мен цифрлық технологиялар кезінде туындайтын жаңа заңнамалық реттеуді қажет ететін мәселелерді шешуді ұлттық заңнаманы жетілдірудің стратегиялық бағыты ретінде айқындайды. Тұжырымдама мемлекеттік органдарға өз стратегиялық жоспарларын осы концепция ережелеріне сүйене отырып жасауды нұсқайды. Алайда тұжырымдамада білім беру сектрорына қатысты арнайы шаралар жоқ - бұл стратегиялық олқылық болашақ заңнамалық жұмыстарда жойылуы тиіс.[3]

Осылайша, бұл нормативтік-құқықтық актілер ҚР-дағы ЖИ мен деректерді қорғаудың ұлттық заңнамалық алғышарттарын қалыптастырды. Алайда осы

алғышарттардың білім беру саласында тиімді жүзеге асуы үшін одан кейінгі - қылмыстық, ведомстволық және бағдарламалық - деңгейдегі нормалармен үйлесуі қажет.

Яғни ҚР заңнамасы ЖИ мен деректерді қорғаудың жалпы заңнамалық негізін қалыптастырды. Субъект келісімі, ашықтық принципі, жауапкершілік және аудит талаптары бекітілді. Алайда білім беру саласына арнайы нормалар жоқ - бұл 2-тарауда кеңінен талданатын болады.

2. Қазақстан Республикасының ЖИ мен деректерді қорғаудағы ұлттық-заңнамалық жүйесі.

2024 жылы күшіне енген EU AI Act Қазақстанның ұлттық заңнамалық базасын халықаралық стандарттар тұрғысынан салыстырмалы түрде талдауға мүмкіндік туғызды. Аталған регламент жасанды интеллект жүйелерін олардың қоғам үшін төндіретін қауіп-қатер деңгейіне байланысты төрт топқа жіктейді: қолданысына тыйым салынған тәжірибелер; жоғары тәуекел тобына жататын жүйелер; шектеулі тәуекел тобына жататын жүйелер; ең төменгі тәуекел тобына жататын жүйелер. EU AI Act-тің 5-бабы білім беру мекемелерінде эмоция тану жүйелерін тыйым салынған тәжірибелер қатарына қосады. Аталған ережелер 2027 жылдан толық күшіне енеді.[4]

GDPR деректерді қорғаудың іргелі стандарты ретінде ҚР заңнамасымен салыстырма үшін маңызды эталон болып табылады. GDPR-дің 8-бабы 16 жасқа толмаған адамдардың деректерін өңдеу үшін ата-ананың немесе заңды өкілдің нақты цифрлық келісімін арнайы реттейді; мүше мемлекеттер бұл жасты 13-ке дейін төмендете алады. 22-бабы автоматтандырылған шешімдерге - соның ішінде профильдеуге - қарсылық білдіру құқығын тікелей бекітеді: деректер субъектісі тек автоматтандырылған өңдеуге негізделген шешімге бағынбауға құқылы, егер ол оның заңды мүдделеріне айтарлықтай ықпал ететін болса. GDPR-дің 44-49 баптары деректерді үшінші елдерге берудің шарттарын белгілейді. Осы нормалардың ҚР заңнамасында балама болмауы - анықталған негізгі олқылықтардың бірі.[5]

Қылмыстық-құқықтық жауапкершілік тұрғысынан ҚР Қылмыстық кодексінің 147-бабы жеке өмірдің қол сұғылмауын және дербес деректер туралы заңнаманы бұзу үшін нақты санкция белгілейді. 2-бөлік бойынша дербес деректерді заңсыз жинау немесе өңдеу 5 000 айлық есептік көрсеткішке дейін айыппұлмен немесе 3 жылға дейін бас бостандығынан айырумен жазаланады. 3-бөлікте белгіленгендей, дәл осы іс-қимылдар қызметтік жағдайды пайдаланып немесе арнайы техникалық құралдармен жасалса, жаза 5 жылға дейін ауырлайды. Бұл норма білім беру мекемелерінің ЖИ платформаларымен жасасқан шарттарын заңнамалық тұрғыдан мұқият бекітуін ерекше маңызды етеді.[6]

Ведомстволық деңгейде ҚР Цифрлық даму, инновациялар және аэроғарыш өнеркәсібі министрінің №179/НҚ бұйрығы дербес деректерді қорғаудың нақты ұйымдастырушылық-техникалық шараларын белгілейді. Бұйрықта электрондық ресурстардағы дербес деректерді тек Қазақстан аумағындағы серверде сақтау міндеттілігі, меншік иелері мен операторлардың ақпараттық қауіпсіздік инциденттері туралы уәкілетті органды хабардар ету тәртібі айқындалды. Аталған норма шетелдік ЖИ платформаларын - Google Classroom, Microsoft Teams, Duolingo сияқты - пайдаланатын білім беру мекемелері үшін практикалық маңызы зор.[7]

«Цифрлық Қазақстан» мемлекеттік бағдарламасы білім беруді цифрландырудың мемлекеттік бағдарламалық негізін қалады. Бағдарламаның білім берудегі негізгі бағыттары: орта мектепте 2-сыныптан бастап «Бағдарламалау негіздері» пәнін міндетті

ету; жоғары білімде барлық мамандықта АКТ пәнін енгізу; мұғалімдердің цифрлық біліктілігін арттыру. Бағдарлама ЖИ технологияларын білім беруге енгізудің институциялық негізін қаласа да, деректерді қорғаудың арнайы механизмдерін белгілемеді - бұл заңнамалық дамытуды қажет ететін олқылық.[8]

Яғни ҚР ұлттық заңнамасы халықаралық стандарттармен салыстырғанда негізгі бағыттарда өз орнын алады. Алайда ведомстволық және бағдарламалық деңгейдегі нормалар ЖИ-нің білім беруге тән тәуекелдерін толығымен жаппайды. Қылмыстық жауапкершілік алдын алу құралы ретінде мынадай жағдайда тиімді: деректер аудиті мен бақылау механизмдерінің нақты жұмыс істеуі шарт.

3. Халықаралық реттеу стандарттары және олардың ҚР заңнамасымен салыстырмалы талдауы.

Халықаралық қоғамдастық ЖИ-ді білім беруде реттеудің жаһандық стандарттарын бірте-бірте қалыптастырып келеді. ЮНЕСКО-ның 2021 жылы қабылдаған ЖИ этикасы саласындағы ұсынымы 193 мемлекет мақұлдаған тұңғыш жаһандық деңгейдегі норматив болып табылады. Ұсынымның 47-57 тармақтарында білім беру ортасына тікелей қатысты арнайы талаптар нақтыланған: жасанды интеллект оқушының дербес ойлау қабілетіне, сын тұрғысынан пайымдауына, сондай-ақ мұғалім мен оқушы арасындағы тәрбиелік байланысқа нұқсан келтірмеуге тиіс; оқушыларға қатысты деректердің коммерциялық мүддеде пайдаланылуына жол бермеу міндеті заңдастырылды; деректерді басқарудың жаңартылған қағидаттары - сапа, репрезентативтілік және теңдік - нормативтік негіз ретінде бекітілді. ЮНЕСКО ұсынымы заңды міндеттеме тудырмайды, бірақ ұлттық заңнаманы дамытудың этикалық бағдары ретінде маңызды рөл атқарады.[9]

ЭЫДҰ-ның ЖИ жөніндегі ұсынымы (OECD/LEGAL/0449, 2019, 2024 жылы жаңартылған) 47 ел қолдаған бес принципті белгіледі: инклюзивті өсу мен тұрақты дамуға жәрдемдесу; адамға бағдарланған құндылықтар мен әділдік; ашықтық пен түсіндіруге қабілеттілік; сенімділік пен қауіпсіздік; есеп беру қабілеттілігі. ЭЫДҰ принциптері де заңды міндеттеме тудырмайды, бірақ ұлттық ЖИ саясатын қалыптастырудың жаһандық бағдары ретінде қызмет етеді. Қазақстан ЭЫДҰ-ға мүше болмаса да, аталған принциптер ҚР «ЖИ туралы» Заңының концептуалдық негізіне сіңірілген.[10]

Аталған халықаралық стандарттардың барлығын - EU AI Act, GDPR, ЮНЕСКО, ЭЫДҰ - жүйелеп, ҚР заңнамасымен салыстыру нәтижесінде мынадай жалпы картина шығады.

Кесте 1 - Білім берудегі ЖИ реттеудің халықаралық стандарттары мен ҚР заңнамасының салыстырмалы талдауы

Критерий	ҚР заңы	EU AI Act	GDPR	ЮНЕСКО / ЭЫДҰ
Балалар деректері	Жалпы келісім нормасы «Дербес деректер туралы» Заң, 9-бап, арнайы қорғау жоқ	III қосымша (High-risk тізімі): білім беру саласындағы ЖИ жүйелері жоғары тәуекел санатына жатады. 5-бап: мектептерде эмоция тану жүйелері - тыйым салынған тәжірибе	8-бап: 16 жасқа толмаған адамдардың деректерін өңдеу үшін ата-ана/заңды өкілдің нақты цифрлық келісімі міндетті.	Оқушы деректерін коммерциялық қолдануға тыйым

Критерий	ҚР заңы	EU AI Act	GDPR	ЮНЕСКО / ЭЫДҰ
Автошешімдер	Хабардар ету және қарсылық құқығы бар	Адам қадағалауы міндетті	22 бап, Автошешімдерге қарсылық құқығы	47-57-тармақтар, Оқушы автономиясын қорғау
Аудит және ашықтық	20-бап, Жоғары тәуекел ЖИ-ге аудит	Explainability және тәуелсіз аудит	5, 12-14-баптар, Ашықтық және түсіндіру міндеті	Accountability принципі
Жауапкершілік	ҚК 147-бап, 2-бөлік, Айыппұл немесе 5 жылға дейін жаза	Жылдық жаһандық айналымның 7%-ына дейін немесе 35 млн еуроға дейін айыппұл	Айналымның 4%-ына дейін немесе 20 млн еуроға дейін айыппұл	Заңды міндеттеме жоқ

Жоғарыдағы салыстырмалы талдау нәтижесінде ҚР заңнамасындағы төрт негізгі олқылық анықталды:

кәмелетке толмаған оқушылардың деректерін арнайы қорғайтын нормалардың жоқтығы - GDPR-дің 8-бабы деңгейіндегі реттеу жоқ;

автоматтандырылған педагогикалық шешімдерге нақты қарсылық тетігінің реттелмеуі - GDPR-дің 22-бабы аналогі жоқ;

алгоритмдік ашықтық (explainability) стандартының нақты белгіленбеуі - EU AI Act деңгейіндегі норма жоқ;

1.3-параграф бойынша тұжырым: Халықаралық стандарттар - EU AI Act, GDPR, ЮНЕСКО және ЭЫДҰ - білім берудегі ЖИ жүйелерін жоғары тәуекел санатына жатқызып, арнайы қорғаныш механизмдерін белгіледі. ҚР заңнамасы осы стандарттарға қарағанда кәмелетке толмаған оқушыларды қорғаудың арнайы нормаларын, автоматтандырылған шешімдерге нақты қарсылық тетігін және DPO институтын белгілеуде артта қалып отыр.

Қорытынды. Мақаланы қорытындылай келе, мынадай алты негізгі тұжырымға келуге болады.

Бірінші тұжырым. ҚР заңнамасы ЖИ мен деректерді қорғаудың жалпы негізін қалыптастырды. «Дербес деректер және оларды қорғау туралы» Заңның 8 және 9-баптары деректер жинаудың мақсаттылығы мен субъект келісімін міндеттейді. 2025 жылғы «Жасанды интеллект туралы» Заңның 7-бабы ашықтық принципін, 8-бабы жауапкершілікті, 20-бабы жоғары тәуекелді жүйелерге аудит талабын бекітті. ҚК-нің 147-бабы дербес деректерді бұзғаны үшін нақты қылмыстық санкция белгілейді. Осылайша, заңнамалық алғышарттар бар - негіз қаланған.

Екінші тұжырым. Алайда осы негіздің білім беру саласына арнайы қолданылуы жеткіліксіз қамтамасыз етілген. Зерттеу барысында анықталған төрт негізгі олқылық заңнамалық жетілдірудің басым бағыттарын айқындайды. Біріншіден, кәмелетке толмаған оқушылардың деректерін қорғайтын арнайы норма жоқ - GDPR-дің 8-бабы деңгейіндегі ата-ана келісімін міндеттейтін тетік қажет. Екіншіден, автоматтандырылған педагогикалық шешімдерге - алгоритмдік бағалауға, профильдеуге, оқу жолын анықтауға

- нақты қарсылық тетігі реттелмеген, GDPR-дің 22-бабы аналогі енгізілуі тиіс. Үшіншіден, алгоритмдік ашықтық стандарты EU AI Act деңгейінде нақты белгіленбеген.

Үшінші тұжырым. Халықаралық тәжірибе ҚР үшін нақты бағдар береді. EU AI Act білім беру саласындағы ЖИ жүйелерін жоғары тәуекел санатына жатқызып, міндетті аудит пен адам қадағалауын талап етеді. GDPR балалар деректері мен автоматтандырылған шешімдер саласында нақты субъективтік құқықтарды бекітеді. ЮНЕСКО мен ЭЫДҰ ұсынымдары заңды міндеттеме тудырмаса да, ұлттық этикалық стандарттарды қалыптастырудың жаһандық бағдары ретінде маңызды рөл атқарады. Қазақстан осы халықаралық тәжірибені тікелей көшіріп алмай, ұлттық ерекшеліктерге бейімдей отырып қолдануы тиіс.

Төртінші тұжырым. Зерттеуде анықталған олқылықтарды жою үшін мынадай нақты заңнамалық ұсыныстар тұжырымдалды. «Дербес деректер туралы» Заңға кәмелетке толмаған адамдардың деректерін өңдеуге қатысты жеке бап енгізу, онда ата-ана келісімінің цифрлық нысаны, деректерді сақтау мерзімінің шектеулері және білім беру мақсатынан тыс пайдалануға тыйым белгіленуі тиіс. «ЖИ туралы» Заңға автоматтандырылған шешімдерге қарсылық білдіру тетігін нақтылайтын норма қосылуы қажет. Білім беру мекемелерінде DPO институтын міндетті ету мәселесін заңнамалық деңгейде қарастыру орынды болар еді. Сондай-ақ ЖИ негізіндегі білім беру платформаларына қойылатын арнайы техникалық және ұйымдастырушылық талаптарды белгілейтін ведомстволық нормативтік акт әзірлеу қажеттілігі туындайды.

Бесінші тұжырым. Деректер локализациясы мен шетелдік платформаларды пайдалану мәселесі де шешімін күтіп тұр. №179/НҚ бұйрығы бойынша дербес деректерді тек Қазақстан аумағындағы серверде сақтау міндеттілігі бар. Алайда Google Classroom, Microsoft Teams сияқты кеңінен қолданылып жүрген шетелдік платформалардың осы талапты толық орындауы практикада бақыланбайды. Білім беру мекемелері мен ЖИ платформалары арасындағы шарттарда деректерді қорғауға қатысты талаптарды міндетті тармақ ретінде бекіту - бұл олқылықты жоюдың практикалық жолы.

Алтыншы тұжырым. Зерттеудің жалпы қорытындысы ретінде мынаны атап өту қажет: Қазақстан білім беруді цифрландыру жолында жылдам қадам жасап келеді, бірақ заңнамалық реттеу осы қарқынға ілесе алмай отыр. «Цифрлық Қазақстан» бағдарламасы мектептерде цифрлық технологияларды кеңінен енгізуді міндеттеді, алайда осы технологиялар жинайтын деректерді қалай қорғау керектігі арнайы реттелмеді. Бұл алшақтықты жою - заң шығарушының алдындағы кезек күттірмейтін міндет.

Зерттеу болашаққа бағытталған бірнеше перспективалық бағытты да ашып береді. Алгоритмдік дискриминация мәселесі - ЖИ жүйелерінің оқушыларды жынысына, этносына немесе әлеуметтік жағдайына қарай әртүрлі бағалауы - бөлек зерттеуді қажет ететін өзекті сала болып қала береді. DPO институтын білім беру жүйесіне енгізудің практикалық моделін - оның функциялары, тәуелсіздігі, ресурстық қамтамасыз етілуі - жеке зерттеу орынды болар еді. Сондай-ақ ЖИ этикасы жөніндегі ұлттық стандарттарды қалыптастыру мәселесі - ЮНЕСКО мен ЭЫДҰ ұсынымдарына негізделген, бірақ қазақстандық білім беру жүйесінің ерекшеліктерін ескерген стандарттар - болашақтағы заңнамалық жұмыстың басым бағыты болуы тиіс.

Осылайша, білім беру саласындағы жасанды интеллект жүйелері мен дербес деректерді қорғаудың құқықтық мәселелері Қазақстан үшін жаңа, күрделі және шұғыл шешімді қажет ететін сала екені анық. Заңнамалық жетілдіру тек техникалық норма қосу

ғана емес - ол оқушының, студенттің, педагогтың цифрлық ортадағы іргелі құқықтарын қамтамасыз ету мәселесі. Бұл зерттеу осы бағытта жасалған бір қадам ретінде болашақ заңнамалық және ғылыми жұмыстарға негіз болады деп үміттенеміз.

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ҚАЗАҚСТАНДАҒЫ ОНЛАЙН ПЛАТФОРМАЛАРДА ТҰТЫНУШЫ ҚҰҚЫҒЫН ҚОРҒАУДЫҢ АЗАМАТТЫҚ-ҚҰҚЫҚТЫҚ МЕХАНИЗМДЕРІ

Аңдатпа. Аталған мақала Қазақстан Республикасындағы экономиканы белсенді цифрландыру жағдайында электрондық коммерция саласындағы тұтынушылардың құқықтарын қорғаудың азаматтық-құқықтық тетіктерін зерттеуге арналған. Жұмыста онлайн-платформалар мен маркетплейстердің құқықтық мәртебесі, қашықтан жасалатын сауда мәмілелеріне қатысушылар арасындағы жауапкершілікті бөлу мәселелері, сондай-ақ тұтынушылық дауларды шешу кезінде сот жүйесін цифрландыру және онлайн-медиация тетіктерін енгізу ерекшеліктері жүйелі түрде қарастырылады. Сонымен қатар трансшекаралық электрондық сауда және коллизиялық нормаларды қолдану мәселелеріне ерекше назар аударылған.

2023–2026 жылдардағы заңнамалық өзгерістерді, сондай-ақ Еуропалық одақ, Америка Құрама Штаттары, Қытай Халық Республикасы және ЭЫДҰ-ға мүше мемлекеттердің шетелдік тәжірибесін талдау негізінде құқықтық реттеудегі негізгі олқылықтар анықталды. Тұтынушылардың дербес деректерін қорғау, сот өндірісінде электрондық дәлелдемелерді пайдалану, қашықтан сатып алынған тауарларды қайтару, сондай-ақ цифрлық платформалар алгоритмдерінің ашықтығын қамтамасыз ету мәселелеріне ерекше көңіл бөлінеді. Статистикалық деректер мен сот тәжірибесінің материалдарын талдау нәтижесінде Қазақстан Республикасының азаматтық заңнамасын жетілдіруге бағытталған нақты ұсыныстар тұжырымдалды.

Кілтті сөздер: электрондық коммерция, маркетплейстер, тұтынушылардың құқықтарын қорғау, азаматтық құқық, цифрлық экономика, онлайн-платформалар, электрондық мәмілелер, онлайн-медиация, сот жүйесін цифрландыру, дербес деректер, трансшекаралық сауда, Қазақстан.

Кіріспе. Соңғы онжылдықта Қазақстан Республикасы экономикасын цифрландыру қосалқы құбылыстан қоғамдық дамудың жүйе құраушы факторларының біріне айналды. Мобильді интернеттің кең таралуы, төлем инфрақұрылымының дамуы және халықтың цифрлық сауаттылығының артуы электрондық сауданың қарқынды дамуына жағдай жасады. Бүгінде тауарлар мен қызметтерді қашықтан сатып алу азаматтардың басым бөлігі үшін дәстүрлі сауда түрлеріне ыңғайлы әрі қалыпты балама ретінде қабылданады [1].

Kaspi.kz, Wildberries, Ozon және Alibaba сияқты платформалар күнделікті тұтыну тәжірибесінің ажырамас бөлігіне айналды. Қазақстан Республикасы Сауда және

интеграция министрлігінің мәліметтері бойынша, елдегі белсенді онлайн-сатып алушылар саны 9 миллион адамнан асты, ал электрондық сауданың жалпы бөлшек сауда айналымындағы үлесі жыл сайын тұрақты түрде өсуде. Сонымен қатар төлем агрегаторлары, курьерлік қызметтер, пікірлерді басқару жүйелері, адалдық бағдарламалары сияқты ілеспе сервистердің қуатты экожүйесі қалыптасып, олар тұтыну нарығының жаңа инфрақұрылымын құрауда.

Алайда қолжетімділік, жылдамдық және тауар ассортиментінің кеңдігі сияқты айқын артықшылықтармен қатар, құқықтық белгісіздік аймақтарының кеңеюі, тұтынушылардың осалдығының артуы және электрондық сауда тәжірибесі мен қолданыстағы заңнама арасындағы алшақтықтың ұлғаюы сияқты мәселелер де байқалады. Ең өзекті проблемалар бірнеше бағытта шоғырланған: сатушы, маркетплейс және логистикалық оператор арасындағы жауапкершілікті ажырату; төлем және мінез-құлық деректерін өңдеу кезінде дербес деректерді қорғау; электрондық құжаттардың дәлелдемелік күші; трансшекаралық сатып алулардың құқықтық режимі.

Заң шығарушының бұл сын-қатерлерге реакциясы әлі де баяу сипатқа ие. Қазақстан Республикасының «Онлайн-платформалар және онлайн-жарнама туралы» Заңының қабылдануы маңызды қадам болғанымен, құқықтық реттеудегі көптеген тұжырымдамалық олқылықтарды толық жоя алмады. Электрондық сауда саласындағы даулар бойынша сот тәжірибесі біркелкі қалыптаспаған, бұл бір жағынан арнайы нормалардың жеткіліксіздігімен, екінші жағынан судьялардың техникалық тұрғыдан күрделі цифрлық істерді қарауға толық дайын болмауымен түсіндіріледі.

Осы жұмыстың өзектілігі аталған факторлардың жиынтығымен айқындалады. Зерттеудің мақсаты – Қазақстан Республикасындағы онлайн-платформаларда тұтынушылардың құқықтарын қорғаудың қолданыстағы азаматтық-құқықтық тетіктерін кешенді түрде талдау, отандық тәжірибені шетелдік құқықтық реттеу модельдерімен салыстыру және заңнаманы жетілдіру бойынша нақты ұсыныстар әзірлеу болып табылады.

Материалдар және зерттеу әдістері. Зерттеудің теориялық және әдіснамалық негізін өзара толықтыратын ғылыми тәсілдердің жиынтығы құрайды. Жүйелік талдау тұтынушылардың құқықтарын қорғау тетіктерін нормативтік, институционалдық және процестік элементтерден тұратын тұтас құқықтық құрылым ретінде зерттеу үшін қолданылды. Салыстырмалы-құқықтық әдіс Қазақстан заңнамасын Еуропалық одақ, АҚШ және Қытай құқықтық жүйелерімен салыстыруға мүмкіндік берді. Формалды-заңдық әдіс қолданыстағы нормативтік құқықтық актілерді талдау және құқықтық олқылықтарды анықтау барысында пайдаланылды. Статистикалық талдау электрондық сауданың даму көрсеткіштері мен тұтынушылардың өтініштерінің динамикасын сандық тұрғыдан түсіндіруді қамтамасыз етті [2].

Зерттеудің нормативтік базасын Қазақстан Республикасының Азаматтық кодексі (Жалпы және Ерекше бөлімдері), 2010 жылғы 4 мамырдағы №274-IV «Тұтынушылардың құқықтарын қорғау туралы» Қазақстан Республикасының Заңы (кейінгі өзгерістерімен), 2023 жылғы «Онлайн-платформалар және онлайн-жарнама туралы» Қазақстан Республикасының Заңы, «Дербес деректер және оларды қорғау туралы» Қазақстан Республикасының Заңы, Еуропалық одақтың цифрлық контент пен цифрлық қызметтер туралы 2019/770 Директивасы, ЕО-ның цифрлық нарықтар туралы регламенті (DMA,

2022), ЮНСИТРАЛ-дың электрондық сауда туралы үлгілік заңы және ЭЫДҰ-ның цифрлық экономика саласындағы саясат жөніндегі комитетінің ұсынымдары құрады.

Эмпирикалық базаны Қазақстан Республикасы Сауда және интеграция министрлігінің 2022–2025 жылдарға арналған ресми статистикалық деректері, Тұтынушылардың құқықтарын қорғау комитетінің аналитикалық есептері, Алматы қаласы мен Алматы облысы соттарының қашықтан саудаға байланысты істер бойынша сот тәжірибесінің материалдары, сондай-ақ Дүниежүзілік банк, ЮНКТАД және ЭЫДҰ сияқты халықаралық ұйымдардың цифрлық экономика мәселелері жөніндегі есептері құрады.

Нәтиже және талқылау. Азаматтық құқық тұрғысынан электрондық коммерция ақпараттық-коммуникациялық технологиялар арқылы шарттарды жасасу, орындау және тоқтату кезінде туындайтын мүліктік және өзге де азаматтық-құқықтық қатынастардың жиынтығы болып табылады. Тараптардың өзара әрекеттесуінің қашықтан жүзеге асырылуы оферта, акцепт және шарттың жасалу сәтінің өзіндік ерекшеліктерін айқындайды.

Қазақстан Республикасының заңнамасы белгілі бір талаптар сақталған жағдайда мәміленің электрондық нысанын жазбаша нысанмен тең деп таниды. Мұндай талаптарға тараптарды сәйкестендіру мүмкіндігі, ерік білдіруді растау және электрондық құжаттың өзгеріссіз сақталуы жатады. Қазақстан Республикасы Азаматтық кодексінің 152-1-бабына сәйкес, электрондық нысандағы шарт оферент акцептті алған сәттен бастап жасалған болып есептеледі.

Сонымен қатар тәжірибе тапсырыстарды өңдеудің автоматтандырылған жүйелерін пайдалану кезінде шарттың жасалу сәтіне қатысты елеулі құқықтық белгісіздіктің бар екенін көрсетеді. Маркетплейстер, әдетте, көпсатылы схеманы қолданады: сатып алушының өтінім жіберуі, сатушының тауардың бар екенін растауы, төлем шотын қалыптастыруы және тапсырысты түпкілікті растауы. Бұл кезеңдердің әрқайсысы міндеттеменің туындау сәтін анықтау үшін маңызды болғанымен, заң нормаларында аталған тізбек тікелей реттелмеген [3].

Тағы бір пікірталас тудыратын мәселе — пайдаланушы келісімінің (Terms of Service) құқықтық табиғаты. Қалыптасқан сот тәжірибесіне сәйкес, ол Қазақстан Республикасы Азаматтық кодексінің 389-бабы мағынасындағы қосылу шарты ретінде сараланады. Алайда мұндай келісімдердің мазмұны көбінесе платформаның жауапкершілігін тұтынушылар құқығы туралы императивтік нормалармен үйлеспейтін деңгейде шектейтін талаптарды қамтиды. Автордың пікірінше, пайдаланушының мұндай шарттармен белгі қою («галочка қою») арқылы формалды түрде келісуі, егер сөз заңмен кепілдік берілген құқықтардан бас тарту туралы болса, тұтынушы еркінің толыққанды әрі еркін білдірілуі ретінде қарастырылмауы тиіс.

Электрондық сауданы азаматтық-құқықтық реттеудегі негізгі мәселелердің бірі маркетплейстің құқықтық мәртебесі мен оның тұтынушы алдындағы жауапкершілік көлемін анықтау болып табылады. Құқық теориясында екі қарама-қарсы тұжырымдама қалыптасқан. Бірінші тұжырымдамаға сәйкес, платформа тек техникалық делдал болып табылады және сатушылардың әрекеттері үшін жауап бермейді. Екінші тұжырымдама бойынша, маркетплейс — тұтынушының сенімін қалыптастыратын және соған сәйкес құқықтық тәуекелдерді өзіне қабылдайтын мәміленің толыққанды қатысушысы.

Қазақстан заңнамасы әзірге бұл мәселеге нақты жауап бермейді. «Онлайн-платформалар және онлайн-жарнама туралы» Заң «онлайн-платформа иесі» ұғымын енгізіп, белгілі бір ақпараттық міндеттерді белгілейді, алайда сатушылар тарапынан тұтынушылар құқықтарының бұзылуы үшін платформаның жауапкершілігі мәселесін тікелей шешпейді. Нәтижесінде сот тәжірибесі бірізді қалыптаспаған: кейбір жағдайларда талаптар сатушыға, кейбірінде платформаға, ал басқа жағдайларда екеуіне бірдей қойылады.

Тұтынушы платформаны мәміленің негізгі қатысушысы ретінде қабылдайтын «бірыңғай контрагент иллюзиясы» феномені көрінетін өкілеттіктер (apparent authority) тұжырымдамасын қолдану мәселесін алға тартады. Егер маркетплейс адал сатып алушыда сатушы платформаның атынан немесе оның бақылауымен әрекет етеді деген негізді түсінік қалыптастырса, азаматтық құқық пайдаланушы келісіміндегі формалды ескертулерге қарамастан, мұндай тұтынушыны қорғауды қамтамасыз етуі тиіс.

Халықаралық тәжірибе бірнеше тиімді модельдерді ұсынады. Еуропалық одақта Платформалардың жауапкершілігі туралы директива (Platform-to-Business Regulation) маркетплейстерді рейтинг қалыптастыру параметрлерін, сатушыларды платформаға жіберу критерийлерін және дауларды реттеу тетіктерін ашып көрсетуге міндеттейді. Цифрлық нарықтар туралы акт (DMA) «қақпашылар» (gatekeepers) деп аталатын жүйеқұраушы платформалар үшін қосымша міндеттемелер енгізеді. Қытайдың 2018 жылғы Электрондық сауда туралы заңы платформа тұтынушылар құқықтарының бұзылғанын білген немесе білуге тиіс болған, бірақ тиісті шаралар қабылдамаған жағдайларда платформалардың ортақ жауапкершілігін бекітті.

Кесте 1 – Онлайн және офлайн сауданы салыстырмалы талдауы

Критерий	Офлайн сауда	Онлайн-платформалар
Тауармен танысу	Тауарды тікелей қарап шығу және тексеру	Фотосуреттер, сипаттама, сатып алушылардың пікірлері
Тауарды қайтару	ұтынушылардың құқықтарын қорғау туралы» Заңның 28-бабының жалпы қағидалары бойынш	Қашықтан қайтару, 14 күн ішінде бас тарту құқығы
Төлем әдісі	қолма-қол ақша және банк картасы	Онлайн төлем, бөліп төлеу, криптовалюта
Келісімшарт жасасу	Кассалық чек немесе жазбаша шарт	Цифрлық нысандағы жария офертаны акцептеу
Алаяқтық қаупі	Төмен, сатушы физикалық түрде қатысады	Жоғары: фишинг, жалған интернет-дүкендер
Сатушы верификациясы	Жеке түрде мүмкін	Шектеулі, көбінесе мүмкін емес
Жеке мәліметтер	Деректерді өңдеу тәуекелі төмен	Жоғары тәуекелдер: профильдеу, деректердің таралып кетуі
Келісімшарт жылдамдығы	Дүкеннің жұмыс уақытымен шектеледі	Тәулік бойы қолжетімділік, жедел тапсырыс беру
Аумақтық қамтылу	Дүкеннің орналасқан жерімен шектелед	Жаһандық, трансшекаралық сатып алулар

Келтірілген деректер электрондық сауданың екіжақты сипатын айқын көрсетеді: бір жағынан, ол тауарлардың қолжетімділігін кеңейтіп, аумақтық кедергілерді жояды, ал

екінші жағынан арнайы құқықтық реттеуді талап ететін сапалық тұрғыдан жаңа құқықтық тәуекелдерді қалыптастырады.

Электрондық сауда операцияларының едәуір бөлігінің трансшекаралық сипаты коллизиялық мәселелердің күрделі кешенін туындатады. Шетелдік платформа арқылы тауар сатып алатын тұтынушы көбінесе сатушы бір юрисдикцияда тіркелген, платформаның сервері екінші мемлекетте орналасқан, ал тауар үшінші елден жөнелтілетін жағдайға тап болады [4].

Қазақстан заңнамасы трансшекаралық тұтынушылық шарттар бөлігінде негізінен жалпы коллизиялық қағидаттарды ұстанады: қолданылатын құқықты таңдауда тараптардың ерік автономиясының басымдығы (ҚР Азаматтық кодексінің 1113-бабы), сонымен бірге тұтынушының тұрғылықты жері елінің императивтік нормаларын міндетті түрде қолдану жөніндегі шектеумен толықтырылады. Алайда тәжірибе көрсеткендей, бұл тетік көбінесе декларативтік сипатта қалып отыр: шетелдік сатушылар қазақстандық соттардың юрисдикциясын мойындамайды, ал сот шешімдерін шетелде орындау тану және орындау рәсімдерінің күрделі сатыларынан өтуді талап етеді.

Халықаралық тәжірибе бұл мәселені шешудің бірнеше тәсілін көрсетеді. Еуразиялық экономикалық одақ аясында трансшекаралық сатып алулар кезінде тұтынушылардың құқықтарын қорғаудың үйлестірілген жүйесі әзірленуде, ол мүше мемлекеттердің уәкілетті органдары қабылдаған шешімдерді өзара тануды көздейді. Еуропалық одақ 524/2013 Онлайн-дауларды шешу туралы регламентті енгізіп, трансшекаралық тұтынушылық жанжалдарды шешуге арналған бірыңғай ODR-платформасын құрды. Қытай трансшекаралық электрондық саудаға арналған «sandbox» үлгісін белсенді дамытып, жеңілдетілген кедендік режимді тұтынушыларды қорғаудың күшейтілген тетіктерімен ұштастыруда.

Қазақстан үшін ең перспективалы тәсіл үш құралдың үйлесімі болып көрінеді: біріншіден, тұтынушылық даулар бойынша шешімдерді өзара тану және орындау туралы екіжақты және көпжақты келісімдер жасау; екіншіден, қазақстандық нарықта жұмыс істейтін шетелдік платформаларды міндетті тіркеуді енгізіп, олардың республика аумағында уәкілетті өкіл тағайындауын талап ету; үшіншіден, ШЫҰ және ЕАЭО құрылымдары шеңберінде халықаралық онлайн-медиацияны дамыту.

Цифрлық сауда жағдайында тұтынушылардың дербес деректері аса құнды активке және бір мезгілде құқықтық бақылаудың ерекше нысанына айналды. Әрбір онлайн-транзакция барысында платформалар деректердің кең ауқымын жинайды және өңдейді: сәйкестендіру деректері (аты-жөні, ЖСН, мекенжайы), төлем деректері (карта реквизиттері, транзакциялар тарихы), мінез-құлық деректері (қаралым тарихы, сатып алу жиілігі, парақшада болу уақыты) және геолокациялық мәліметтер. Осы деректердің жиынтығы нысаналы жарнама, динамикалық баға белгілеу және алгоритмдік рейтинг қалыптастыру үшін қолданылатын егжей-тегжейлі тұтынушылық профильдер құруға мүмкіндік береді [5].

Қазақстан Республикасының 2023 жылғы редакциядағы «Дербес деректер және оларды қорғау туралы» Заңы өңдеудің мақсатты сипаты, пропорционалдылық, сақтау мерзімінің шектеулілігі және деректер субъектісінің міндетті келісімі сияқты негізгі қағидаттарды бекітеді. Дегенмен, бұл заңды электрондық сауда саласында қолдану бірқатар практикалық қиындықтарға тап болады. Біріншіден, тұтынушының деректерді өңдеуге келісімі, әдетте, жалпы пайдаланушы келісіміне енгізіледі, сондықтан одан бас

тарту платформаны пайдаланудың мүмкін еместігін білдіреді. Екіншіден, платформалар деректерді жарнама серіктестеріне, аналитикалық компанияларға және логистикалық операторларға тұтынушы бақылай алмайтын тұжырымдар негізінде жиі береді.

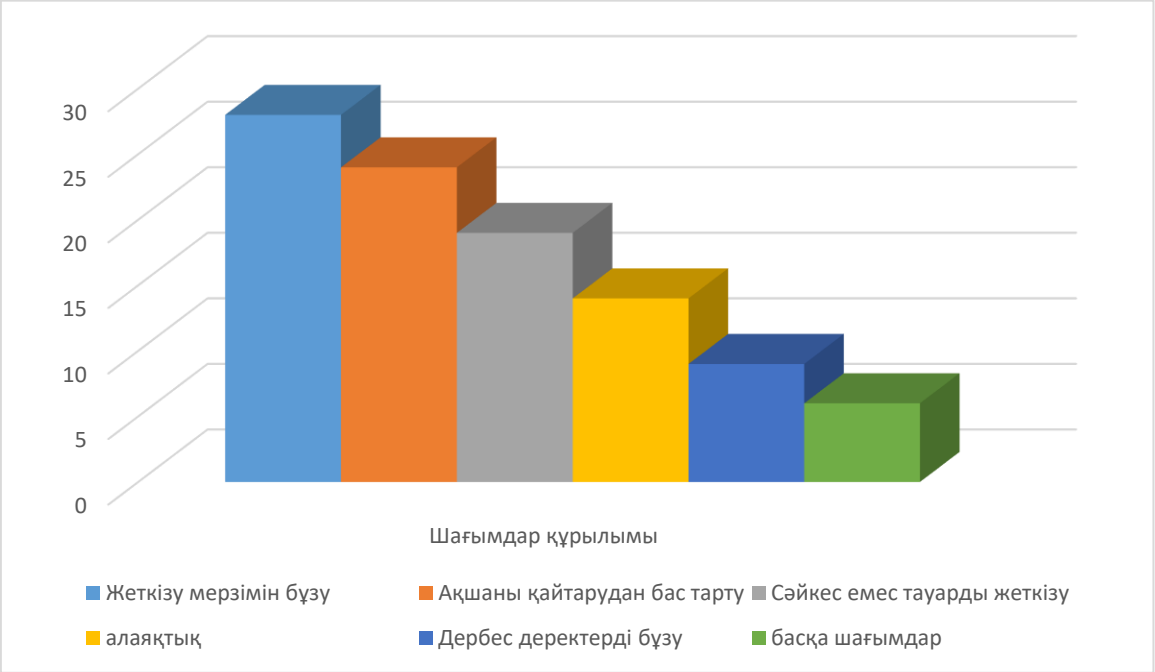
Алгоритмдік профильдеу мен динамикалық баға белгілеу ерекше мәселе болып табылады. Бір тауар әртүрлі пайдаланушыларға олардың тұтынушылық профиліне байланысты әртүрлі бағамен ұсынылған жағдайда, мұндай тәжірибенің азаматтық айналымға қатысушылар теңдігі қағидаты тұрғысынан кемсітушілік сипаты туралы мәселе туындайды. Қазақстан заңнамасында мұндай тәжірибеге тікелей тыйым салынбаған, бұл елеулі құқықтық олқылық болып саналады.

Ұсынылатын шараларға мыналар жатады: тұтынушының баға мен ассортиментке әсер ететін дербестендіру алгоритмдері туралы ақпарат алу құқығын заңнамалық бекіту; деректерді әртүрлі мақсаттар үшін өңдеуге бөлек келісім беру талабын енгізу; дербес деректердің таралып кеткені анықталған сәттен бастап 72 сағат ішінде тұтынушыларды міндетті түрде хабардар ету; дербес деректерді қорғау жөніндегі уәкіл институтын оның қадағалау өкілеттіктерін кеңейте отырып дамыту [6].

Электрондық дәлелдемелердің құқықтық режимі цифрлық сот төрелігі саласындағы ең өзекті пікірталас мәселелерінің бірі болып қалып отыр. Онлайн-сатушымен дауда тұтынушы, әдетте, дәлелдемелердің шектеулі жиынтығына ғана ие болады: мессенджердегі хат алмасу скриншоттары, электрондық хаттар, жеке кабинеттен алынған мәліметтер, банк мобильді қосымшасындағы транзакция туралы ақпарат. Бұл дереккөздердің әрқайсысы жол берілетіндігі, сенімділігі және толықтығы тұрғысынан арнайы бағалауды қажет етеді.

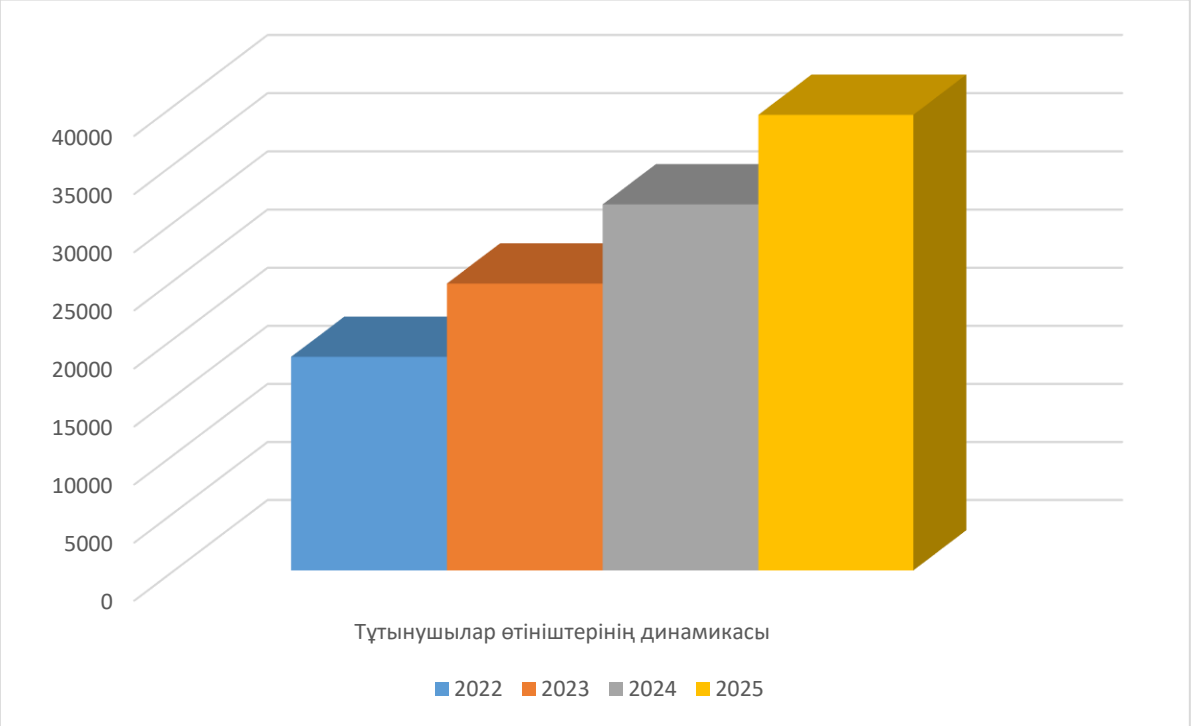
Перспективалы шешімдердің бірі — «цифрлық нотариус» институтын заңнамалық бекіту. Ол электрондық хат алмасуларды, скриншоттарды және транзакциялық деректерді автоматты түрде тіркеп, куәландыратын және оларға білікті электрондық қолтаңба беретін мамандандырылған сервис болуы тиіс. Осындай тетіктер Эстония, Испания және Азияның бірқатар мемлекеттерінде жұмыс істейді. Тұтынушылық істер бойынша электрондық дәлелдемелердің бірыңғай стандарттарын қабылдау сот шешімдерінің болжамдылығын айтарлықтай арттырар еді.

Электрондық сауда саласындағы құқық бұзушылықтардың ауқымын эмпирикалық тұрғыдан бағалауға азаматтардың өтініштері жөніндегі статистика мүмкіндік береді. 2022–2025 жылдар аралығындағы Тұтынушылардың құқықтарын қорғау комитетінің деректерін талдау шағымдар санының тұрақты өсуін көрсетеді, әрі өсім қарқыны нарық көлемінің өсу қарқынынан жоғары. Бұл құқық бұзушылықтардың тек сандық емес, сапалық сипатқа да ие екенін білдіреді: алдын алу және жедел әрекет ету тетіктері жүктемені толық көтере алмай отыр.



1 сурет – 2025 жылғы шағымдар құрылымы

1-суретті талдау нәтижесі келесідей: жеткізу мерзімдерінің бұзылуы — өтініштердің шамамен 28%-ын; ақшалай қаражатты қайтарудан бас тарту — шамамен 24%-ын; сапасы тиісті емес тауарды жеткізу — шамамен 19%-ын; алаяқтық әрекеттер — 14%-ын; дербес деректер саласындағы бұзушылықтар — 9%-ын; ал өзге де бұзушылықтар — 6%-ын құрайды. Келтірілген цифрлар техникалық іркілістер немесе ақпараттық бұзушылықтарға қарағанда, тұтынушылар үшін шарттық міндеттемелердің орындалуы мен тауарды қайтару құқығын іске асыру мәселелері әлі де ең өзекті болып қала беретіндігін айғақтайды [7].



2 сурет – Электрондық сауда саласындағы тұтынушылар өтініштерінің динамикасы (2022–2025)

2-суреттің деректері тұтынушылар өтініштерінің өсуі сақталып отырған жағдайда, қанағаттандырылған шағымдар үлесінің де біртіндеп артып келе жатқанын растайды. Бұл сотқа дейінгі реттеу механизмдерінің жетіліп жатқанын білдіреді. Сонымен қатар, негізді шағымдардың жартысынан астамы әлі де тиісті деңгейде қаралмай қалуда, бұл құқық қорғау инфрақұрылымындағы жүйелі кемшіліктерді көрсетеді.

Тұтынушылық дауларды шешу механизмдерін жаңғырту сот ісін жүргізуді қатар реформалаусыз мүмкін емес. Қазақстан Республикасының 2023–2030 жылдарға арналған құқықтық саясат тұжырымдамасы сот жүйесін кешенді цифрландыруды қарастырады: «Сот кабинетінің» функционалдығын кеңейту, істерді автоматты түрде бөлуді енгізу және талап қоюларды типтендіру үшін машиналық оқыту технологияларын пайдалану көзделген [8].

Электрондық сауда саласындағы дауларға келетін болсақ, сот төрелігін цифрландыру ерекше маңызға ие, өйткені даудың мәнінің өзі цифрлық сипатта болады. Осы үрдістің қисынды жалғасы ретінде сомасы 100 АЕК-ке дейінгі даулар үшін оңайлатылған рәсімі бар электрондық коммерция саласындағы тұтынушылық істер бойынша мамандандырылған онлайн-сот құру орынды болар еді. Мұндай соттар Қытайда (Бейжің, Ханчжоу және Гуанчжоу интернет-соттары) сәтті жұмыс істеп тұр және жоғары тиімділікті көрсетуде: істі қараудың орташа уақыты — 30 күннен аз, шешімдердің орындалу пайызы — 80%-дан жоғары.

Онлайн-медиация баламалы және көптеген мамандардың пікірінше, сот жүйесін жеңілдетудің неғұрлым перспективалы жолы болып табылады. Классикалық медиациядан айырмашылығы, ол тараптардың физикалық қатысуын талап етпейді, бұл әсіресе трансшекаралық даулар кезінде өте маңызды. Оның артықшылықтары айқын: жылдамдық (шешім 14–30 күн ішінде), қаражатты үнемдеу, құпиялылық, медиатор ретінде салалық сарапшыларды тарту мүмкіндігі.

Қолданыстағы Қазақстан Республикасының «Медиация туралы» Заңы негізінен медиацияны қашықтықтан өткізуге жол береді, бірақ онлайн-формат үшін арнайы нормаларды қамтымайды. Тұтынушылық даулар бойынша онлайн-медиация жүргізу тәртібін реттейтін жеке нормативтік актіні әзірлеп, қабылдау қажет: онда платформаға қойылатын талаптар, қатысушыларды сәйкестендіру тәртібі, электрондық нысанда жасалған медиациялық келісімнің заңдық күші айқындалуы тиіс.

Электрондық сауда саласындағы тұтынушылардың құқықтарын қорғаудың шетелдік үлгілерін зерттеу әмбебап үрдістерді де, қазақстандық жағдайда қолдануға болатын ерекше құралдарды да анықтауға мүмкіндік береді [9].

Еуропалық Одақ құқықтық қорғаудың ең тармақталған жүйесін құрды. Бұл жүйенің негізгі элементтері мыналар болып табылады: тұтынушының ешқандай себепсіз 14 күн ішінде шарттан бас тартуға міндетті құқығы; платформаның сатушы туралы жалған ақпарат бергені үшін жауапкершілігі; трансшекаралық дауларға арналған міндетті ODR-платформа; ранжирлеу алгоритмдерінің ашықтығына қойылатын талаптар; тұтынушыны жаңылыстыратын дизайн тәсілдерін — «қараңғы үлгілерді» (dark patterns) пайдалануға тыйым салу. 2022 жылы қабылданған Цифрлық қызметтер туралы акт (DSA) ауқымы әртүрлі платформаларға сараланған талаптар енгізіп, «өте ірі онлайн-платформалар» үшін ең қатаң міндеттемелерді белгіледі.

Америка Құрама Штаттары сот бақылауы мен өзін-өзі реттеудің ұштасуына басымдық береді. Ұжымдық талап қою механизмі (class action) мыңдаған біртекті

талаптарды бірегей іс жүргізуге біріктіруге мүмкіндік береді, бұл платформалар үшін заңнаманы сақтау экономикасын түбегейлі өзгертеді. Федералдық сауда комиссиясының (FTC) жоспарсыз практикаларды, оның ішінде электрондық сауда саласындағы құқық бұзушылықтарды тоқтату бойынша кең өкілеттіктері бар. Соңғы жылдардағы сот практикасы жосықсыз сатушыларға тиісті бақылау жасалмаған жағдайда платформаларды жауапкершілікке тарту үрдісін көрсетіп отыр.

Қытай мемлекеттік белсенді реттеу үлгісін таңдады. 2018 жылғы Электрондық сауда туралы заң платформаларды мыналарға міндеттеді: барлық сатушыларды тіркеу және олардың құжаттарының растығын тексеру; мәмілелер туралы деректерді кемінде үш жыл сақтау; тауардың сатушыдан сатып алушыға дейін қалай өтетінін қадағалау мүмкіндігін қамтамасыз ету; тұтынушылардың шағымдарына дереу жауап беру. Бұл міндеттемелерді бұзғаны үшін платформаның ортақ жауапкершілігі қарастырылған. Сатушылар үшін енгізілген «несиелік рейтинг» жүйесі адал мінез-құлыққа қосымша ынталандыру тудырады.

2-кесте – Электрондық сауданы реттеу үлгілерін салыстырмалы талдау

Параметр	ЕО	АҚШ	Қытай	Қазақстан (қазіргі күйі)
Платформаның жауапкершілігі	Сараланған (DSA)	Прецеденттік (FTC)	Ортақ (білген жағдайда)	Реттелмеген
Шарттан бас тарту құқығы	14 күн (Директива)	Штаттар бойынша өзгереді	7 күн	14 күн (ТҚҚЗ)
ODR-жүйесі	Міндетті (EC ODR)	Ерікті	Платформалар үшін міндетті	Жоқ
Дербес деректерді қорғау	GDPR (қатаң)	Секторлық	PIPL (қатаң)	ДД туралы заң (орташа)
Алгоритмдік ашықтық	DMA/DSA талап етеді	Шектеулі	Жартылай	Реттелмеген

2-кестеден көрініп тұрғандай, Қазақстан электрондық сауда саласындағы мамандандырылған реттеуді қалыптастырудың бастапқы кезеңінде тұр. ODR-жүйесінің болмауы, платформалар жауапкершілігінің реттелмеуі және алгоритмдік ашықтыққа қойылатын талаптардың жоқтығы ең маңызды олқылықтар болып табылады [10].

Бөлінген тізілім технологиялары мен өздігінен орындалатын смарт-келісімшарттар электрондық сауда саласындағы міндеттемелердің орындалуын автоматтандыру үшін түбегейлі жаңа мүмкіндіктер ашады. Смарт-келісімшарт — бұл алдын ала белгіленген жағдайлар туындаған кезде көзделген әрекеттерді автоматты түрде орындайтын компьютерлік бағдарлама. Мысалы, ол курьерлік қызмет жеткізуді растағанда немесе мерзімдердің бұзылуы тіркелгенде сатып алушыға төлемді автоматты түрде қайтарады [11].

Қазақстан заңнамасындағы смарт-келісімшарттардың құқықтық режимі анықталмаған күйінде қалып отыр. ҚР Азаматтық кодексінде өздігінен орындалатын шарттарды тікелей реттейтін нормалар жоқ. «Астана» халықаралық қаржы орталығының (АХҚО) цифрлық активтер бөлігінде жеке реттеуі бар, алайда оның юрисдикциясы жаппай тұтынушылық қатынастарға таралмайды. «Өздігінен орындалатын шарт» ұғымын заңнамалық деңгейде бекіту, оның заңдық күшін тану және орындау кезіндегі техникалық іркілістер барысында дауларды шешудің арнайы ережелерін белгілеу қажет.

Жүргізілген зерттеу негізінде электрондық сауданы жүзеге асыру кезінде тұтынушылардың құқықтарын қорғау саласындағы Қазақстан Республикасының азаматтық заңнамасын жетілдіру бойынша келесі ұсыныстар тұжырымдалады [12].

Бірінші бағыт — онлайн-платформалардың құқықтық мәртебесін нақтылау. «Тұтынушылардың құқықтарын қорғау туралы» Заңға «онлайн-агрегатор иесі» ұғымын, маркетплейсті интернет-сауданың өзге нысандарынан ажырату критерийлерін және сатушыларға тиісті бақылау жасалмаған жағдайда платформаның тұтынушы алдындағы субсидиарлық жауапкершілігінің негіздерін белгілейтін арнайы тарау енгізу ұсынылады.

Екінші бағыт — ұлттық ODR-жүйесін құру. Электрондық қолтаңба, бейнеконференцбайланыс сервистерімен және медиативтік келісімдердің орындалуын автоматты түрде қадағалаумен интеграцияланған тұтынушылық дауларды онлайн-реттеудің мемлекеттік платформасын әзірлеу және іске қосу ұсынылады. Қазақстан Республикасында тіркелген маркетплейстердің бұл жүйеге қатысуы міндетті болуға тиіс.

Үшінші бағыт — жоспарсыз (адал емес) сатушылар тізілімі. Тұтынушылардың құқықтарын қорғау комитетінің аясында тұтынушылардың құқықтарын бұзу туралы сот шешімі немесе медиативтік келісім заңды күшіне енген сатушылардың бірыңғай жария тізілімін құру ұсынылады. Бұл ретте платформаларға мұндай сатушылардың саудаға қолжетімділігін бұғаттау міндеттемесі жүктелуі керек [13].

Төртінші бағыт — электрондық дәлелдемелер стандарттары. Жоғарғы соттың тұтынушылық істер бойынша электрондық дәлелдемелерді ұсыну мен бағалауға қойылатын бірыңғай талаптарды, соның ішінде нотариалды куәландырылған скриншоттарды, жеке кабинет деректерін және төлем жүйелерінің үзінді көшірмелерін пайдалану ережелерін белгілейтін заңға тәуелді актісін қабылдау ұсынылады [14].

Бесінші бағыт — смарт-келісімшарттардың құқықтық режимі. ҚР Азаматтық кодексін олардың заңдық күшін, дауласу негіздерін және автоматты түрде орындау кезіндегі іркілістер барысындағы жауапкершіліктің арнайы ережелерін бекітетін өздігінен орындалатын шарттар туралы баппен толықтыру ұсынылады.

Қорытынды. Жүргізілген зерттеу Қазақстан Республикасындағы электрондық сауданы азаматтық-құқықтық реттеу белсенді қалыптасу сатысында екенін, алайда ол әлі де цифрлық нарықтың ауқымы мен динамикасына сәйкес келетін жүйелілік пен егжей-тегжейлілік деңгейіне жетпегенін растайды. Негізгі мәселелер — маркетплейстер мәртебесінің белгісіздігі, ODR-жүйесінің болмауы, трансшекаралық дауларды реттеудегі олқылықтар, электрондық дәлелдемелер режимінің түсініксіздігі — өзара байланысты сипатқа ие және кешенді реформалауды талап етеді.

Халықаралық тәжірибе мынаны нақты дәлелдейді: платформалардың жауапкершілігін нақты заңнамалық бекітуді, дауларды реттеудің қолжетімді әрі жылдам механизмдерін және белсенді мемлекеттік қадағалауды ұштастыратын құқықтық жүйелер ең жоғары тиімділікті көрсетеді. Қазақстан үшін шетелдік үлгілерді механикалық түрде көшіру қабылданбайды, алайда оларды ұлттық ерекшеліктерді, цифрлық инфрақұрылымның даму деңгейін және халықтың құқықтық мәдениетін ескере отырып бейімдеу тұтынушылардың жағдайын айтарлықтай жақсартуға қабілетті.

Ұсынылған шараларды іске асыру — онлайн-агрегаторлар мәртебесін заңнамалық бекіту, ұлттық ODR-жүйесін құру, электрондық дәлелдеудің бірыңғай стандарттарын енгізу, жоспарсыз сатушылар тізілімін қалыптастыру және смарт-келісімшарттарды құқықтық реттеу — азаматтардың цифрлық сервистерге деген сенімі үшін

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РАЗВИТИЕ ПЕРВИЧНОЙ МЕДИКО-САНИТАРНОЙ ПОМОЩИ: ОТ АЛМА-АТЫ ДО АСТАНЫ

Аннотация: В обзорной статье с позиции критического анализа рассматривается эволюция концепции первичной медико-санитарной помощи (ПМСП) и реализация положений Алма-Атинской (1978 г.) и Астанинской (2018 г.) деклараций. Анализируются фундаментальные принципы документов, системные демографические и эпидемиологические вызовы, а также концептуальные инновации современного этапа, направленные на достижение всеобщего охвата услугами здравоохранения. На основе актуальных данных предложены сравнительные таблицы и сформулированы практические рекомендации для организаторов здравоохранения по имплементации Астанинских принципов, включая вопросы финансирования, межсекторального взаимодействия и цифровизации.

Ключевые слова: финансовое управление в здравоохранении, управление медицинскими учреждениями, снижение затрат медицинских учреждений, операционное управление медицинскими учреждениями

Первичная медико-санитарная помощь (ПМСП) представляет собой не просто базовый уровень клинического обслуживания, а всеобъемлющую социально-политическую стратегию, определяющую архитектуру национальных систем здравоохранения. Эволюция концепции ПМСП на протяжении последних четырех десятилетий отражает глубинные трансформации в понимании взаимосвязи между состоянием здоровья населения, экономическим развитием государств и реализацией фундаментальных прав человека. Центральными вехами, маркирующими этот исторический процесс, выступают два эпохальных документа: Алма-Атинская декларация 1978 года и Астанинская декларация 2018 года [1].

Историческая дистанция в сорок лет, разделяющая эти декларации, стала периодом беспрецедентных демографических, эпидемиологических и технологических сдвигов. Если в конце 1970-х годов мировое сообщество фокусировалось на преодолении базовых инфекционных угроз и искоренении вопиющего неравенства между развитыми и развивающимися странами в условиях холодной войны, то к 2018 году парадигма сместилась в сторону управления эпидемией неинфекционных заболеваний, старением населения и интеграции инновационных цифровых решений. Несмотря на грандиозный

прогресс, достигнутый в рамках Целей развития тысячелетия (ЦРТ), первоначальная мечта о «здоровье для всех к 2000 году», провозглашенная в Алма-Ате, осталась нереализованной, уступив место фрагментированным системам и суровым реалиям неравного доступа к медицинским благам [2].

Данная статья представляет собой исчерпывающий, многоуровневый анализ эволюции первичной медико-санитарной помощи. Опираясь на данные Всемирной организации здравоохранения (ВОЗ), Детского фонда ООН (ЮНИСЕФ) и профильной научной литературы, отчет исследует исторический контекст и фундаментальные принципы Алма-Атинской декларации, анализирует системные вызовы переходного периода, детализирует концептуальные инновации Астанинской декларации и оценивает экономические императивы инвестирования в ПМСП. Синтез этих данных позволяет сформулировать научно обоснованные рекомендации по адаптации систем здравоохранения к вызовам XXI века в контексте Целей в области устойчивого развития (ЦУР) и движения за всеобщий охват услугами здравоохранения (ВОУЗ) [1].

В сентябре 1978 года в городе Алма-Ата (Казахская ССР, ныне Алматы, Казахстан) состоялась Международная конференция по первичной медико-санитарной помощи, организованная совместно ВОЗ и ЮНИСЕФ. Это событие стало водоразделом в истории глобальной социальной политики. Документ, принятый по итогам конференции, бросил радикальный вызов доминирующим на тот момент медико-центричным, высокотехнологичным и узкоспециализированным моделям оказания помощи, которые демонстрировали свою несостоятельность в улучшении здоровья большинства населения планеты, особенно в странах с низким и средним уровнем дохода [2].

Алма-Атинская декларация впервые на столь высоком институциональном уровне постулировала холистическое определение здоровья. Документ бескомпромиссно заявил, что здоровье является «состоянием полного физического, духовного и социального благополучия, а не только отсутствием болезней или физических дефектов», и признал его фундаментальным правом человека. Этот концептуальный сдвиг перевел вопросы здравоохранения из сугубо клинической плоскости в сферу макроэкономики, социальной справедливости и прав человека.

Декларация констатировала, что существующее грубое неравенство в состоянии здоровья людей как между развитыми и развивающимися странами, так и внутри самих государств, является политически, социально и экономически неприемлемым. Впервые была четко артикулирована двусторонняя причинно-следственная связь: экономическое и социальное развитие имеет решающее значение для достижения здоровья для всех, в то время как здоровье самого населения является непременным условием для поддержания устойчивого развития и мира во всем мире [3].

Наиболее прогрессивным и, как показала история, наиболее труднодостижимым аспектом Алма-Атинской декларации был ее прямой призыв к глобальному перераспределению финансовых ресурсов. Анализируя первопричины недофинансирования социальной сферы, авторы декларации указали на глобальную милитаризацию. В документе подчеркивалось, что приемлемый уровень здоровья для всех народов мира может быть достигнут путем более полного и рационального использования мировых ресурсов, значительная часть которых необоснованно тратится на вооружение и военные конфликты. Декларация призывала к политике подлинной независимости, разрядки международной напряженности и разоружения.

Высвобожденные таким образом дополнительные ресурсы предлагалось направить на ускорение социально-экономического развития, неотъемлемой и приоритетной частью которого должна была стать ПМСП. Для систематизации концептуального фундамента документа, ниже представлена таблица 1, отражающая ключевые принципы и императивы Алма-Атинской декларации.

Таблица 1. Ключевые принципы Алма-Атинской декларации и ее значения для системы здравоохранения

Концептуальный блок	**Содержание принципов Алма-Атинской декларации 1978 года**	**Аналитическое значение для систем здравоохранения**
Определение и статус здоровья	Здоровье — состояние полного физического, психического и социального благополучия; является фундаментальным правом человека. Достижение наивысшего возможного уровня здоровья — важнейшая всемирная социальная цель.	Отказ от сугубо биомедицинской модели. Переход к биопсихосоциальной парадигме, требующей вмешательства государства не только в медицину, но и в социальную среду.
Социальная справедливость	Существующее вопиющее неравенство в статусе здоровья неприемлемо. Здоровье в любой стране прямо касается и приносит пользу всем другим странам.	Признание взаимозависимости глобального здравоохранения; формирование концепции глобальной ответственности и солидарности доноров.
Участие общин (Эмпауэрмент)	Люди имеют право и обязанность индивидуально и коллективно участвовать в планировании и реализации мер по охране своего здоровья.	Демократизация медицины. Переход от патерналистской модели (врач диктует условия) к партнерской модели (пациент и общество как активные агенты).
Функциональная роль ПМСП	ПМСП образует неотъемлемую часть национальной системы здравоохранения, являясь ее ядром (nucleus), а также базой общего социально-экономического развития общества.	ПМСП становится первым уровнем контакта человека с системой; концептуализация системы здравоохранения в виде пирамиды с широким основанием из ПМСП.
Межсекторальное сотрудничество	Реализация целей здравоохранения требует действий многих других социальных и экономических секторов в дополнение к сектору здравоохранения (сельское хозяйство, образование, инфраструктура).	Институционализация подхода «Здоровье во всех политиках». Признание того, что медицинские вмешательства бессильны без чистой воды, питания и образования.
Экономический механизм	Призыв к использования мировых ресурсов, затрачиваемых на вооружение, в мирных целях для финансирования здравоохранения; призыв к международным агентствам направить финансовую	Попытка увязать глобальную макроэкономику и геополитику с финансированием локальных систем здравоохранения на уровне общин.

	поддержку в развивающиеся страны.	
Составлено автором на основании источников [1-3]		

Алма-Атинская декларация ввела классическое определение ПМСП, охарактеризовав ее как основную медико-санитарную помощь, основанную на практических, научно обоснованных и социально приемлемых методах, сделанную повсеместно доступной при стоимости, которую общество и страна могут себе позволить. Декларация, поддержанная Глобальной стратегией ВОЗ, установила амбициозную цель: «Достижение всеми народами мира к 2000 году такого уровня здоровья, который позволит им вести социально и экономически продуктивную жизнь».

Однако, несмотря на то, что влияние Алма-Атинской декларации на общественное здравоохранение остается непревзойденным и ни один из ее принципов не утратил актуальности с течением времени, практическая реализация этих принципов столкнулась с непреодолимыми препятствиями макроэкономического и политического характера.

Тем не менее, успех вертикальных программ вскрыл парадоксальную системную проблему: улучшение эпидемиологических показателей по отдельным заболеваниям не привело к созданию устойчивых систем ПМСП. Прогресс за четыре десятилетия был крайне неравномерным. К 2018 году, накануне конференции в Астане, эксперты констатировали, что по меньшей мере половина населения земного шара по-прежнему не имеет доступа к основным медицинским услугам, включая услуги по профилактике и лечению инфекционных и неинфекционных заболеваний, охране репродуктивного и психического здоровья [4].

Неспособность систем здравоохранения достичь идеалов Алма-Аты была обусловлена не только политико-экономическими факторами, но и радикальным изменением самого ландшафта потребностей населения. С момента подписания Алма-Атинской декларации Европа и весь остальной мир претерпели колоссальные изменения в демографическом, эпидемиологическом, социокультурном и технологическом контекстах.

Глобальная демография претерпела существенный сдвиг в сторону увеличения продолжительности жизни и старения населения. Этот демографический переход привел к экспоненциальному росту спроса на медицинские и социальные услуги. Одновременно он спровоцировал нарастающий дефицит человеческих ресурсов здравоохранения. Во многих развивающихся странах эта нехватка критически усугубляется миграцией («утечкой мозгов») квалифицированных медицинских кадров в экономически развитые регионы. В результате, именно там, где потребность в ПМСП наиболее высока, наблюдается катастрофическая нехватка персонала, способного ее предоставить.

Осознавая, что существующие модели оказания медицинской помощи находятся в глубоком кризисе — недоразвиты, фрагментированы, хронически недофинансированы и испытывают кадровый голод — мировое сообщество приняло решение о необходимости концептуальной «перезагрузки». 25–26 октября 2018 года правительство Казахстана совместно с ЮНИСЕФ и ВОЗ организовали в столице Казахстана Глобальную конференцию по первичной медико-санитарной помощи. Мероприятие, приуроченное к 40-летию Алма-Атинской декларации, собрало беспрецедентный кворум: 1200 делегатов из более чем 120 стран мира, включая министров здравоохранения, финансов, образования и социального обеспечения, а также представителей академических кругов,

частного сектора и гражданского общества (в том числе коалицию из более 180 НПО в рамках механизма UHC2030) [3].

Итогом работы стала Астанинская декларация, единогласно поддержанная всеми государствами-членами ООН. Этот документ не только подтвердил историческую приверженность принципам Алма-Аты, но и наметил четкий, прагматичный курс на достижение всеобщего охвата услугами здравоохранения (ВОУЗ) и реализацию Целей в области устойчивого развития (ЦУР), в частности, целевого показателя ЦУР 3.8 [5].

Одной из важнейших заслуг Астанинской декларации стало концептуальное уточнение терминологии. В документе подчеркивается разница между понятиями «первичная медицинская помощь» (primary care), которая является важной, но лишь клинической функцией, и «первичной медико-санитарной помощью» (primary health care), которая представляет собой тотальную интеграцию всех уровней защиты здоровья.

В соответствии с Астанинской парадигмой, устойчивая система ПМСП должна включать три взаимосвязанных стержневых элемента:

Доступные и качественные медицинские услуги: Эта компонента интегрирует первичную клиническую помощь и основные функции общественного здравоохранения. Она направлена на укрепление здоровья населения, профилактику хронических состояний, лечение заболеваний, реабилитацию, паллиативный уход и защиту популяций от вспышек инфекций на протяжении всей жизни человека.

Расширение прав и возможностей (Эмпауэрмент) людей и сообществ: Радикальный отказ от патернализма. Медицинские службы должны быть подотчетны обществу, которому они служат. Одновременно сами индивиды и сообщества должны стать активными соавторами механизмов реагирования на свои потребности, принимая на себя ответственность за собственное здоровье через повышение уровня медицинской грамотности.

Межсекторальная политика и действия: Воздействие на фундаментальные социальные, экономические и экологические детерминанты здоровья. Это требует согласованных действий от секторов, выходящих за рамки здравоохранения: сельского хозяйства, промышленности, образования, инфраструктуры водоснабжения и санитарии, транспорта, а также средств массовой информации. Формируется концепция "Health in All Policies" (Здоровье во всех политиках) [6].

В отличие от Алма-Атинской декларации, которая носила во многом философско-идеологический характер, Астанинская декларация сформировала конкретный набор обязательств, налагающих на государства и партнеров ответственность за их выполнение с последующим периодическим обзором и мониторингом (таблица 2).

Таблица 2. Обязательства согласно Астанинской декларации

Обязательство по Астанинской декларации	**Детальная расшифровка механизмов реализации**
Принятие смелых политических решений в интересах здоровья во всех секторах	Правительства обязуются интегрировать вопросы здоровья во все национальные политики. Признается необходимость борьбы с первопричинами заболеваемости (экология, бедность, условия труда). Включает создание механизмов подотчетности государственного и частного секторов.
Создание устойчивой ПМСП	Обеспечение высококачественных, безопасных, комплексных, интегрированных, доступных и

	приемлемых по цене медицинских услуг. Применение как научных, так и традиционных знаний для оптимизации помощи. Фокус на том, чтобы каждый человек получал нужную помощь в нужное время и на наиболее подходящем уровне.
Расширение прав и возможностей отдельных лиц и сообществ	Целенаправленная работа по повышению медицинской грамотности. Поддержка людей в приобретении знаний, навыков и ресурсов, необходимых для поддержания своего здоровья и здоровья своих близких под руководством медицинских работников. Защита этики, солидарности и прав человека.
Согласование поддержки заинтересованных сторон с национальными стратегиями	Требование к международным донорам, структурам ООН, НПО и благотворительным фондам прекратить фрагментацию систем через вертикальные программы. Вся внешняя поддержка должна быть интегрирована и согласована с едиными национальными планами развития ПМСП.
Составлено автором на основании источников [4-6]	

Декларация планирует быть более конкретизированной и требовательной к странам в части ее реализации, учитывая прошлые ошибки, не позволившие полностью раскрыть потенциал декларации Алма-Аты.

Одной из наиболее острых проблем современного здравоохранения является катастрофическое финансовое бремя, ложащееся на плечи пациентов. Согласно статистике, в 2022 году более 1,6 миллиарда человек во всем мире находились под угрозой оказаться за чертой бедности или усугубить свое финансовое положение из-за того, что личные расходы на здравоохранение составляли 10% и более от их семейного бюджета [7].

ПМСП выступает в качестве мощного инструмента социальной и финансовой защиты. Предоставляя бесплатные или недорогие услуги на ранних стадиях заболеваний, ПМСП снижает риск катастрофических расходов населения. Кроме того, ПМСП сужает разрывы в результатах лечения различных социальных групп и повышает общую справедливость системы, особенно когда надлежащее финансирование и кадровое обеспечение позволяют охватить уязвимые и недостаточно обслуживаемые слои населения.

Более того, инвестиции в ПМСП на уровне общин играют критическую роль в продвижении гендерного равенства. Учитывая, что подавляющее большинство работников первичного звена — женщины, развитие ПМСП предоставляет им ценные социальные роли и экономическую независимость (при условии справедливого устранения гендерных дисбалансов в оплате труда и статусе). Сеть общественных работников здравоохранения доказала свою колоссальную эффективность: как отмечают сами работники, развитие их сети гарантирует глобальную безопасность в области здравоохранения и спасает жизни, требуя долгосрочного финансирования и политической поддержки на высшем уровне.

Астанинская декларация признает, что никакие финансовые влияния не принесут результата без формирования мотивированной, компетентной и технологически оснащенной рабочей силы. Документ содержит прямое обязательство инвестировать в

образование, обучение, найм, развитие и мотивацию персонала ПМСП, создавая оптимальный набор навыков [8].

В таблице 3 представлено сравнение принципов и парадигм Алма-Атинской и Астанинской деклараций.

Аналитический аспект	**Парадигма Алма-Аты (Декларация 1978 г.)**	**Парадигма Астаны (Декларация 2018 г.)**
Целевой горизонт и контекст	Достижение утопичной цели «Здоровье для всех к 2000 году». Рисуется на фоне холодной войны и антиколониального движения.	Интеграция в достижимые Цели устойчивого развития (ЦУР до 2030 года). Фокус на поэтапный Всеобщий охват услугами здравоохранения (ВОУЗ).
Характер взаимодействия системы и пациента	Участие общин рассматривалось как право и обязанность в планировании услуг.	Расширение прав (эмпауэрмент) посредством развития медицинской грамотности. Пациент рассматривается как компетентный сопроизводитель своего здоровья.
Взгляд на ресурсы и экономику	Идеологический призыв к перенаправлению колоссальных мировых расходов на вооружение на нужды здравоохранения.	Прагматичный подход: мобилизация внутренних ресурсов стран, защита инвестиций в ПМСП через расчет возврата инвестиций (ROI), защита людей от финансового краха.
Отношение к медицинским кадрам	Привлечение широкого спектра работников, вплоть до традиционных целителей, для быстрого обеспечения базового охвата.	Глубокий акцент на академическое качество: создание кафедр ПМСП, удержание кадров, мультидисциплинарные команды с оптимальным набором навыков, борьба с международной миграцией врачей.
Интеграция инноваций	Упор на использование «практических и социально приемлемых» технологий.	Активная приоритизация цифровизации, персонализированных данных пациента, телемедицины, информационных технологий как основы для непрерывного управления здоровьем.
Составлено автором на основании источников [1-8]		

Обе декларации сходятся в главном: первичная медико-санитарная помощь является непреложным ядром системы здравоохранения, и здоровье остается фундаментальным правом каждого человека. Однако, если в Алма-Ате «первичная помощь» (primary care) и «первичная медико-санитарная помощь» (primary health care) зачастую воспринимались синонимично, Астана концептуально разделила их, утвердив, что ПМСП — это тотальная интеграция клинических, общественных и мультисекторальных услуг.

На основе синтеза проанализированных официальных отчетов ВОЗ, ЮНИСЕФ и массива научной литературы можно выделить комплекс первоочередных рекомендаций для государств и организаторов здравоохранения. Реализация данных направлений необходима для преодоления разрыва между политическими обязательствами Астанинской декларации и реальным улучшением здоровья населения.

Радикальная ребалансировка финансирования систем здравоохранения. Правительствам необходимо законодательно закрепить приоритетное финансирование ПМСП, перенаправив финансовые потоки со специализированной и дорогостоящей стационарной помощи на первичное звено. Требуется поэтапное доведение инвестиций в ПМСП до уровней, рекомендуемых ВОЗ, чтобы покрыть глобальный дефицит в 200–328 млрд долларов США. Важнейшим инструментом является внедрение механизмов оплаты, стимулирующих профилактику и конечный результат (здоровье населения), а не объем оказанных услуг. Одновременно необходимо форсировать развитие систем обязательного медицинского страхования или солидарного бюджетного финансирования, чтобы полностью исключить или минимизировать катастрофические личные расходы граждан (out-of-pocket payments) на услуги первичного звена, защитив уязвимые слои населения от обнищания [9].

Модернизация кадрового потенциала и академической базы. Отвечая на вызовы эпидемиологического перехода и старения населения, национальные системы должны отказаться от монополии узких специалистов. Рекомендуется создание и расширение компетенций мультидисциплинарных команд ПМСП, объединяющих врачей общей практики, медсестер расширенной практики, психологов, фармацевтов и социальных работников. Для академической институционализации ПМСП, министерствам здравоохранения и образования необходимо обеспечить функционирование самостоятельной кафедры первичной медицинской помощи / семейной медицины в каждом медицинском университете [8]. Кроме того, жизненно важно разработать государственные программы стимулирования (как финансового, так и инфраструктурного) для удержания медицинских работников в сельских, отдаленных и депрессивных регионах, параллельно создавая механизмы защиты национальных систем от агрессивной международной миграции кадров.

Институционализация межсекторального взаимодействия. Принципы Астаны не могут быть реализованы исключительно силами министерств здравоохранения. Рекомендуется создание надведомственных правительственных комиссий, наделенных правом вето и координации, для реализации стратегии «Здоровье во всех политиках». Это означает, что любые государственные решения в сферах градостроительства (создание зеленых зон и велодорожек), пищевой промышленности (регулирование сахара и трансжиров), экологии и образования должны проходить обязательную экспертизу на предмет их влияния на общественное здоровье и факторы риска развития неинфекционных заболеваний.

Акселерация цифровой трансформации и использование больших данных. Национальные системы здравоохранения должны ускорить интеграцию цифровых технологий не как вспомогательного, а как стержневого элемента ПМСП. Рекомендуется повсеместное внедрение функциональных электронных медицинских карт, обеспечивающих бесшовную преемственность информации между первичным звеном, специалистами и стационарами [7]. Внедрение телемедицины, технологий удаленного мониторинга и мобильного здравоохранения позволит расширить охват населения в труднодоступных районах и повысить качество контроля за мультиморбидными пациентами.

Стратегическое вовлечение населения и повышение медицинской грамотности. Необходимо сместить парадигму отношения к пациенту с пассивного потребителя

медицинских услуг на активного партнера. Для этого правительствам следует инвестировать в целевые программы повышения медицинской грамотности с использованием современных каналов коммуникации [7]. Создание общественных советов при поликлиниках и центрах семейной медицины позволит обеспечить реальную подотчетность медицинских сервисов перед местным сообществом, повышая доверие к системе и приверженность населения здоровому образу жизни.

История развития концепции первичной медико-санитарной помощи, задокументированная в переходе от Алма-Атинской декларации 1978 года к Астанинской декларации 2018 года, представляет собой одно из самых масштабных и сложных интеллектуальных путешествий в истории глобальной социальной политики. Алма-Атинская конференция стала беспрецедентным прорывом, навсегда изменившим парадигму восприятия медицины. Она демедикализировала концепцию здоровья, провозгласив его фундаментальным правом человека и неотъемлемой функцией социально-экономической справедливости, категорически отвергнув идею здравоохранения как привилегии избранных.

Однако последующие четыре десятилетия наглядно продемонстрировали, что философская безупречность декларации разбилась о суровые экономические и геополитические реалии. Смещение глобального фокуса в сторону фрагментированной «избирательной ПМСП» в эпоху структурных экономических кризисов, отход от идеалов социальной справедливости, а также беспрецедентные вызовы, связанные со старением населения, ростом неинфекционных заболеваний и нехваткой кадров, привели к парадоксальным результатам. Мир достиг колоссальных успехов в борьбе с отдельными инфекциями и снижении материнской смертности, но провалил тест на всеобщность: к 2018 году половина населения земного шара по-прежнему не имела полноценного доступа к медицинским услугам, а катастрофические расходы на лечение толкали миллионы людей за черту бедности.

Астанинская декларация 2018 года стала критически необходимым актом ревитализации и концептуальной перезагрузки глобального здравоохранения. Единогласно принятая мировым сообществом при лидерстве ВОЗ и ЮНИСЕФ, она интегрировала идеалы Алма-Аты в современную прагматичную повестку Целей устойчивого развития ООН. Астана зафиксировала консенсус: ПМСП — это не рудиментарный уровень для бедных, а единственно возможный, клинически и макроэкономически обоснованный фундамент для достижения всеобщего охвата услугами здравоохранения.

Подводя итог, можно утверждать, что эволюция «от Алма-Аты до Астаны» — это путь от революционного провозглашения идеала к формированию научно обоснованного, технологически обеспеченного и экономически просчитанного механизма его реализации. Успех этого исторического проекта в XXI веке зависит исключительно от способности правительств проявить смелую политическую волю: трансформировать декларативные обязательства в реальные бюджетные ассигнования, защитить медицинские кадры и расширить права общин. Только институционализация сильной, интегрированной и пациентоцентричной первичной медико-санитарной помощи способна гарантировать, что здоровье перестанет быть ресурсом для избранных и станет реальным, осязаемым благом для всех.

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EMOTIONAL BURNOUT AND MOTIVATION IN KAZAKHSTANI SPORTS ORGANIZATIONS

Annotation: Human Resource Management happens to be one of key factors influencing sustainability and achieving organizational success. This article examines emotional burnout and motivation within Kazakhstani Sport Organization. This study is based on mixed-method approach and findings demonstrate representative of major HRM challenges affecting motivation, stability of workforce and commitment of employees.

Key words: Human Resource Management, emotional burnout, motivation, employee retention, sports organizations

Human Resource Management plays a huge role in organizational sustainability as well as workforce effectiveness nowadays. Organizations today recognize that motivation, retention, emotional and physical health of employees depend on and influence organizational performance. Human Resource Management, however, becomes especially important in sport organizations due to work under intensive both emotionally and physically conditions that are connected to long working hours, overworking, pressure of communication and training, athlete performance, competitions and so on.

Sports organizations in Kazakhstan develop rapidly due to continuous investments and raising number of successful participations in international areas in different sport fields. On the other hand, those same organizations experience lack of structured HRM practices, significant challenges that include burnouts, no structured training/retention systems, lack of support for staff and athletes.

Emotional burnout is always associated with exhaustion or reduced motivation, even is recognized as fatigue and stress. According to Herzberg (1968), motivation of employees depends on many factors as recognition, emotional support, atmosphere in organization, professional growth opportunities but not only on financial rewards for sure.

Purpose of this study is examining burnout and motivation within Kazakhstani sport organizations, also identifying Human Resource Management factors which influence stability of the workforce and commitment to organizations.

This study has applied both quantitative and qualitative approaches combined.

Quantitative data was collected through online surveys tht were distributed among staff working in Kazakhstani sports organizations, survey included sixty respondents, among them:

- 18 coaches
- 32 athletes
- 10 managers

Qualitative data has been obtained through semi- structured interviews conducted among:

- 5 coaches
- 2 athletes
- 3 managers

Data was analyzed using NVivo software.

According to findings of the study, it is clear that emotional burnout still remains one of biggest challenges of Human Resource Management within organizations operating in sports field. Participants often connected talk about burnouts with:

- Overworking
- Communication difficulties
- Pressure of responsibility of athlete well being and performance
- Pressure before events

However, at the same time, organizational atmosphere was pointed out and evaluated positively.

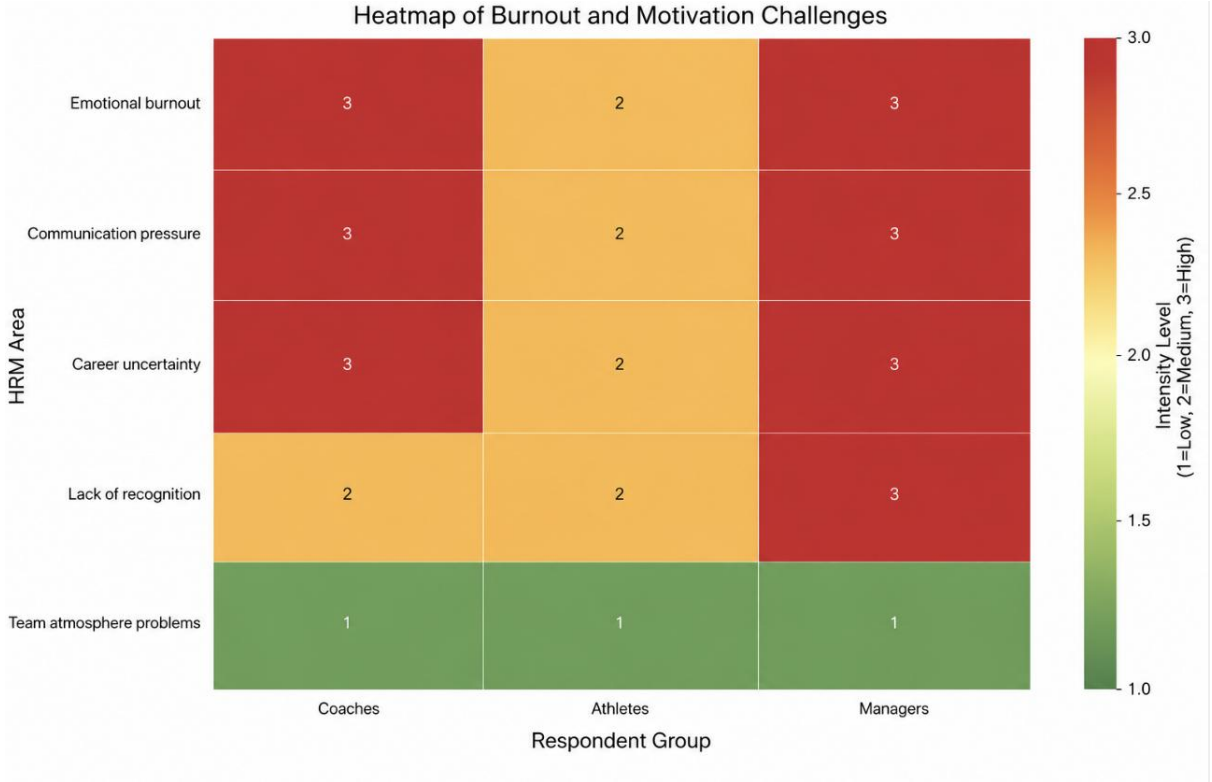


Figure 1 – Heatmap of Burnout and Motivation challenges

This analysis and heatmap demonstrate that coaches and managers experience highest level of emotional burnout levels and stress due to communication difficulties.

76 % of respondents noted emotional support from their colleges influence their motivation and 69% stated communication and support as an essential factor for retention practices.

Integrating HRM strategies into long term planning in organization may improve satisfaction, strengthen retention.

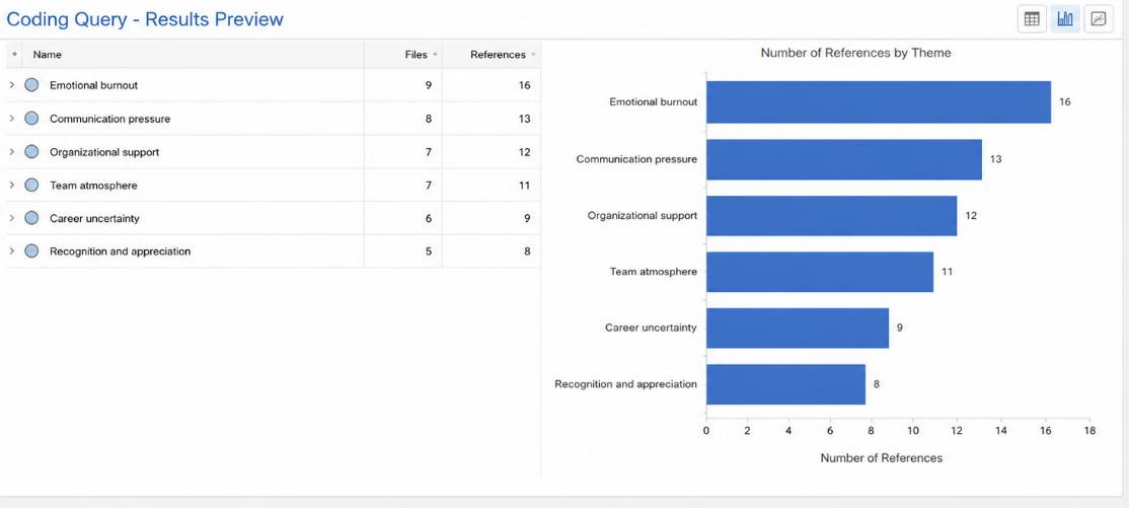


Figure 2 – NVivo Coding Results

Thematic analysis demonstrates that organizational support as well as positive organizational atmosphere play huge role and reduce risks of emotional burnout significantly, improve motivation for work of employees.

This study shows that emotional burnout still remains to be a huge challenge for Human Resource Management practices. It is clear that coaches, athletes, managers experience particularly high level of stress both emotional and physical which is caused by pressure, intensity and high level of responsibility. Emotional burnout is connected with HRM practices and the relationship laying between them differs across participant groups.

At the exact same time, emotional support and positive atmosphere positively affect motivation and commitment of employees. Findings of this study confirm that implementing Human Resource Management practices and strategies effectively that are focused on employees and their health is one of the most important things. Organizations must strengthen support systems for staff, who complain about emotional overload. Then it is obvious that poorly structured career development systems are causing turnover intentions due to uncertainty and lack of growth, so strengthening training and professional development programs improve effectiveness.

Mixed – method approach allowed the study to provide an understanding of challenges of HRM. Thematic coding and heatmap analysis showed patterns connected with exhaustion, communication, motivation and pressure mostly.

Overall, the study highlights importance of HR Management strategies and how sports organizations which have invested in well being of employees are likely to achieve highest satisfaction and effectiveness levels followed by long-term success of organization.

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МЕМЛЕКЕТТІК АКТИВТЕРДІ БАСҚАРУДАҒЫ ЦИФРЛЫҚ ПЛАТФОРМАЛАРДЫҢ ҚҰҚЫҚТЫҚ ТАБИҒАТЫ

Аннотация: Мақалада мемлекеттік активтерді басқаруда қолданылатын цифрлық платформалардың құқықтық табиғаты талданады. Зерттеудің негізгі нысаны ретінде Қазақстандағы e-Qazyna платформасы алынған. Қазақстанның қолданыстағы заңнамасы мемлекеттік мүлікті жалға беру, сенімгерлік басқаруға беру, жекешелендіру сияқты өзге рәсімдерді және тізілім жүргізу рәсімдерін электрондық форматқа жүйелі түрде көшіруді көздейді. e-Qazyna мемлекеттік мүлік тізілімінің деректеріне бірыңғай қол жеткізу нүктесі ретінде белгіленген. Осыған байланысты мақалада цифрлық платформа жай ғана техникалық интерфейс емес, мемлекеттік мүлікке қатысты азаматтық-құқықтық қатынастардың туындауына, нысанына, дәлелденуіне және орындалуын бақылауға ықпал ететін ерекше құқықтық инфрақұрылым деген тұжырым негізделеді.

Түйін сөздер: мемлекеттік активтер, мемлекеттік мүлік, цифрлық платформа, e-Qazyna, мемлекеттік мүлік тізілімі, мемлекеттік мүлікті басқару, құқықтық инфрақұрылым.

Соңғы жылдары мемлекеттік активтерді басқару саласындағы негізгі рәсімдер электрондық ортаға белсенді түрде көшірілді. Қазақстанда бұл үдерістің институционалдық өзегі e-Qazyna платформасы болып отыр. Оның ресми интерфейсінде ол «Активтерді басқарудың цифрлық платформасы» ретінде белгіленген. 2024 жылы Жоғары аудиторлық палатаның нұсқамасын орындау аясында e-Qazyna мемлекеттік мүлік тізілімі деректеріне ресми қол жеткізу нүктесі ретінде арнайы нақтыланды [1]. Демек, мәселе тек электрондық сервис енгізуде емес, мемлекеттік мүлікке қатысты құқықтық қатынастардың жаңа институционалдық ортасын қалыптастыруда болып отыр.

Бұл өзгерістің азаматтық-құқықтық мәні де айқын. Қазақстан Республикасының Азаматтық кодексі мәміленің жазбаша нысаны қағаз жеткізгіште де, электрондық нысанда да жасалатынын бекітеді және электрондық құжаттар мен электрондық хабарлар алмасуды, егер заңда немесе тараптардың келісімінде өзгеше көзделмесе, жазбаша мәмілеге теңестіреді. Ал «Электрондық құжат және электрондық цифрлық қолтаңба туралы» заң электрондық құжаттың қағаз жеткізгіштегі қол қойылған құжатпен тең заңдық күші бар екенін бекітеді. «Мемлекеттік мүлік туралы» заң мемлекеттік мүлік тізілімі мен оны жүргізу тетігін көздейді, ал Үкіметтің № 802 қаулысымен «Ақпараттық-есептеу орталығы» АҚ мемлекеттік мүлікті есепке алу саласындағы бірыңғай оператор болып айқындалған. Заңда бірыңғай оператордың тізілімді жүргізу үшін қажетті бағдарламалық қамтылымды әзірлеу, енгізу және жаңғырту жобасын басқару функциялары да көрсетілген.

Осы нормативтік негіздер e-Qazyna-ны жай веб-сайт немесе электрондық хабарландыру тақтасы ретінде емес, құқықтық салдар туғызатын цифрлық орта ретінде қарастыруға мүмкіндік береді. OECD цифрлық жария инфрақұрылымды қауіпсіз және интероперабельді ортақ цифрлық жүйелер ретінде сипаттайды, ал World Bank мұндай жүйелерді қоғам игілігі үшін құрылған базалық цифрлық «негізгі элементтер» деп түсіндіреді [2]. Мемлекеттік мүлік қатынастары тұрғысынан e-Qazyna дәл осындай сипатқа ие: ол мемлекеттік тіркеу-есепке алу, шарт жасасу, сауда ұйымдастыру, мониторинг және деректерді көрсету функцияларын біріктіреді. Сондықтан осы мақаладағы негізгі тезис мынадай: мемлекеттік активтерді басқарудағы цифрлық платформа азаматтық-құқықтық қатынастарға сырттай қызмет көрсететін техникалық құрал емес, сол қатынастардың жүзеге асырылуына құрылымдық ықпал ететін ерекше құқықтық инфрақұрылым болып табылады.

e-Qazyna-ның құқықтық табиғатын анықтау үшін оның жария-құқықтық және азаматтық-құқықтық элементтерін ажырата қарау қажет. Жария-құқықтық қыры мынадан көрінеді: мемлекеттік мүлік тізілімінің веб-порталы нормативтік актімен тікелей www.e-qazyna.kz [3] мекенжайындағы тізілім деректеріне бірыңғай қол жеткізу нүктесі ретінде анықталған. Тізілім деректеріне қолжетімділікті бірыңғай оператор қамтамасыз етеді, ал бірыңғай оператордың өзі Үкімет қаулысымен айқындалады және заң оған бағдарламалық қамтылымды әзірлеу, енгізу және жаңғырту жобаларын басқару функциясын береді. Платформаның ресми бетінің төменгі бөлігінде оператор ретінде «Ақпараттық-есептеу орталығы» АҚ көрсетілген. Бұл деректер e-Qazyna-ның жеке бастама не жай делдалдық ресурс емес, мемлекеттік функциялар орындалатын ресми цифрлық институт екенін дәлелдейді.

Сонымен бірге оның азаматтық-құқықтық қыры да айқын. Порталда жалға беру шартына, сенімгерлік басқару шартына және сатып алу-сату шартына ЭЦҚ арқылы қол қойылады. Шарттардың бірегей сәйкестендіргіштері автоматты түрде беріледі: өтінімдер, қосымша келісімдер және қабылдау-тапсыру актілері электрондық форматта сақталады. Азаматтық кодекстегі электрондық мәміле нысаны мен ЭЦҚ туралы заңның ережелері осындай электрондық әрекеттердің толық құқықтық күшін қамтамасыз етеді. Сондықтан e-Qazyna азаматтық айналым қатысушыларының ерік білдіруін тек тіркейтін жүйе емес, сол еріктің заң жүзінде танылу механизмінің құрамдас бөлігі болып табылады.

Платформаның құқықтық табиғатын күрделендіретін элемент – автоматтандырылған рәсімдер. Сенімгерлік басқару және жекешелендіру ережелері өтінім тіркелгеннен кейін порталдың кепілдік жарна, берешек және өзге формальды критерийлерді қысқа мерзімде автоматты тексеретінін бекітеді. Бұл, бір жағынан, адам ықпалының үлесін азайтып, рәсімдердің біркелкілігін күшейтеді. Екінші жағынан, дәл осы автоматтандырылған тексерулер қатысушының саудаға жіберілуі не жіберілмеуі сияқты құқықтық салдар туғызады. OECD/GPAI баяндамасы қоғамдық секторда алгоритмдік ашықтықтың дәл осындай жағдайларда өзекті болатынын, өйткені автоматтандырылған немесе жартылай автоматтандырылған шешімдерге қатысты мәліметтің әділ процесс пен есептілік үшін маңызды екенін көрсетеді. Сондықтан e-Qazyna-дағы автоматтандырылған блоктар техникалық алгоритм деңгейінде қалмай, құқықтық бақылау мен шағымдану талаптарын туындатады.

Цифрлық платформаларды мемлекеттік активтерді басқаруда қолданудың басты артықшылығы – рәсімдердің жария әрі қалпына келтірілетін ізін қалыптастыруы. Портал арқылы хабарландыру беру, өтінім қабылдау, ЭЦҚ қою, шартқа бірегей нөмір беру және құжаттарды дерекқорда сақтау құқықтық қатынастардың дәлелденуін жеңілдетеді. Бұған қоса OECD ашықтықты демократиялық басқарудың өзегі деп сипаттап, мемлекет проактивті түрде «анық, толық, уақтылы, сенімді және өзекті» ақпарат жариялауы қажет екенін көрсетеді. Мемлекеттік активтер саласында мұндай тәсіл бәсекелестікті күшейтуге, әкімшілік өктемдікті азайтуға және азаматтық-құқықтық дауларда дәлелдердің сапасын арттыруға мүмкіндік береді.

Алайда цифрландырудың артықшылықтары оның тәуекелдерін автоматты түрде жоймайды. Бірінші тәуекел – объект туралы бастапқы деректің толық еместігі немесе сапасының төмендігі. Қолданыстағы жалға беру қағидалары бойынша объект туралы ақпаратты порталға баланс ұстаушы енгізеді. Демек, платформаның көрінетін ашықтығы бастапқы деректің дұрыстығына тікелей тәуелді.

Екінші тәуекел – жауапкершіліктің бөлшектенуі. Бір жағынан, Заң мен Үкімет қаулысы бірыңғай операторға бағдарламалық қамтылымды әзірлеу және порталдың жұмыс қабілетін қамтамасыз ету функциясын береді. Екінші жағынан, бастапқы объектілік деректерді баланс ұстаушы мен уәкілетті органдар енгізеді. Мұндай модельде техникалық ақау, ескірген дерек, толтырылмаған ақпарат және қате құжаттаманың қайсысы оператордың, қайсысы баланс ұстаушының, қайсысы әкімшілік шешім қабылдаған органның жауапкершілігінде екені әрдайым айқын бола бермейді. 2024 жылғы Жоғары аудиторлық палата аудиті де осыған ұқсас мәселені ашты: пайдаланушылар gosreestr.kz-тен автоматты түрде e-Qazyna-ға бағытталған, бірақ порталдың заңдылығы туралы ресми ақпараттың жеткіліксіздігі қатысушылардың күмәніне себеп болған. Бұл цифрлық платформаның құқықтық мәртебесі мен жауапкершілік режимі нормативтік деңгейде анық әрі көрнекі көрсетілмесе, техникалық жүйенің өзі құқықтық сенімділік туғызбайтынын көрсетеді.

Үшінші тәуекел – автоматтандырылған процестердің құқықтық салдары. Портал кепілдік жарна немесе берешек туралы мәлімет болмағанда өтінімді қабылдамайды, яғни формальды цифрлық тексеру қатысушының саудаға қатысу мүмкіндігіне тікелей әсер етеді. Мұндай жағдайда екі шарт маңызды: біріншісі – автоматты тексерудің қандай дереккөздерге сүйенетіні және оның қателерге төзімділігі; екіншісі – теріс шешімді даулау тетігінің болуы. World Bank зерттеуі цифрландырудың өзі ғана жеткіліксіз екенін, егер электрондық аудит ізі, құқықтарды қорғау тетіктері және ақпаратқа кең қолжетімділік қамтамасыз етілмесе, цифрлық реестрлер күткен нәтижені бермейтінін атап көрсетеді. Сол себепті e-Qazyna-да автоматтандырылған бас тарту, хабарлама жіберу немесе өтінімді қабылдау сияқты әрекеттерге қатысты журнал жүргізу, түсіндірме беру және шағымдану механизмі қарастырылуы тиіс.

Бұл талдау e-Qazyna-ны мемлекеттік активтерді басқарудағы жай техникалық ресурс ретінде сипаттау жеткіліксіз екенін көрсетті. Қазақстанның азаматтық және салалық заңнамасы электрондық нысандағы мәмілелерге толық заңдық күш береді. Мемлекеттік мүлік саласындағы арнайы қағидалар өтінім беруді, тендер мен аукцион өткізуді, шарттар мен актілерге ЭЦҚ арқылы қол қоюды, хабарламалар мен мониторинг әрекеттерін дәл осы портал арқылы жүзеге асыруды міндеттейді. Сондықтан e-Qazyna-ның құқықтық табиғаты аралас: ол, бір мезгілде, мемлекеттік функцияларды іске

асыратын жария-құқықтық цифрлық институт және азаматтық-құқықтық мәмілелердің орындалу инфрақұрылымы болып табылады.

Осы қорытындыдан Қазақстан үшін бірнеше нақты ұсыныс туындайды. Біріншіден, «Мемлекеттік мүлік туралы» заңда немесе тізілімді жүргізу қағидаларында e-Qazyna-ның тек «қол жеткізу нүктесі» ретіндегі емес, мемлекеттік активтерді басқарудың цифрлық инфрақұрылымы ретіндегі функциялары жүйелі түрде айқындалуға тиіс.

Екіншіден, ашық жариялануға міндетті деректердің ең төменгі стандарты бекітілуі керек: объектінің атауы мен орналасқан жері, алаңы, құқықтық мәртебесі, баланс ұстаушысы, бағалау нәтижесі, бастапқы баға немесе жалдау ақысы, шарттың мерзімі, негізгі міндеттемелер, төлемдердің орындалуы және берешек туралы мәліметтер.

Үшіншіден, деректер сапасы үшін жауапкершілік көпдеңгейлі түрде бекітілуі қажет: баланс ұстаушы – бастапқы объектілік ақпараттың дұрыстығы үшін, бірыңғай оператор – жүйенің тұтастығы, қауіпсіздігі, журналдауы және өзгерістер тарихының сақталуы үшін, ал уәкілетті орган – мәміленің құқықтық заңдылығы мен жарияланатын деректердің толықтығы үшін жауап беруі тиіс.

Төртіншіден, автоматтандырылған бас тарту немесе өтінімді қабылдамау сияқты цифрлық әрекеттерге шағымдану, олар бойынша түсіндірме алу және қате деректерді жедел түзету рәсімі енгізілуі керек.

Бесіншіден, e-Qazyna-ны жер кадастрымен, жылжымайтын мүлік тіркелімімен, қазынашылық және салық жүйелерімен тереңірек интеграциялау қажет. World Bank зерттеуі цифрландырудың тиімділігі дәл осындай интероперабельділік пен аудит ізіне байланысты екенін көрсетеді.

Сонымен, мемлекеттік активтерді басқарудағы цифрлық платформалардың құқықтық табиғаты оларды «электрондық қызмет» ұғымымен шектеуге жол бермейді. Мемлекеттік мүлік саласында цифрлық платформа құқықтық рәсімдерді өзгертеді, қатысушылардың мінез-құлқын стандарттайды, деректер арқылы шешім қабылдауға ықпал етеді және шарттық қатынастардың дәлелдену логикасын қайта құрады. Осындай жағдайда e-Qazyna-ны азаматтық-құқықтық қатынастарды техникалық қолдайтын жүйе ретінде емес, сол қатынастардың жүзеге асуын ұйымдастыратын құқықтық инфрақұрылым ретінде тану – теориялық жағынан да, құқық шығармашылығы тұрғысынан да неғұрлым дәл ұстаным болып табылады.

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MEASURING PROMOTIONAL EFFECTIVENESS: THE REVENUE-VOLUME DISTINCTION IN DEMAND ELASTICITY

Abstract: studies estimating promotional demand elasticity frequently use revenue or unit counts as dependent variables, creating systematic measurement bias. This research article demonstrates that revenue-based specifications conflate price and quantity responses, producing elasticity estimates that diverge from true volume effects. Using a panel of 32,554 city-date observations from Kazakhstan beer markets (2022–2025), I compare ln(Net Revenue) versus ln(Volume) as alternative dependent variables in otherwise-identical fixed-effects regressions. Results show promotional activity increases revenue by 58.0% but volume by 65.5% – a 7.5 percentage-point gap implying a 4.5% net price decline during promotions. The divergence confirms that revenue specifications systematically underestimate physical demand elasticity when promotions involve discounting. I provide practical guidance for researchers and recommend volume-based measurement as the standard for demand elasticity estimation.

Keywords: demand elasticity, promotional effectiveness, measurement error, panel data, beverage demand

INTRODUCTION

Promotional pricing is ubiquitous in consumer goods markets, yet measuring its effectiveness remains surprisingly contentious. A fundamental question – "by how much does a promotional discount increase quantity demanded?" – requires clean separation of price effects from quantity effects. Standard demand theory predicts that temporary price reductions induce substitution and increase consumption, but empirical verification depends critically on measurement choices.

Ailawadi et al. (2009) synthesized 87 promotional effectiveness studies and found that approximately 60% measured promotional impacts using revenue (sales dollars) or unit counts (bottles sold) rather than standardized physical volume. This measurement choice matters because revenue conflates two mechanisms: changes in quantities purchased and changes in realized prices (through both discounting and product-mix shifts). When a promotion generates 25% higher revenue, we cannot determine whether consumers bought 25% more product, or whether the revenue increase reflects customers trading up to premium variants during the sale period, or some combination.

This research article addresses a simple question: does the choice between revenue and volume as the dependent variable substantively alter estimated promotional elasticity? Using transaction-level beer sales data from Kazakhstan aggregated to a city-date panel (N=32,554), I estimate otherwise-identical panel fixed-effects regressions with ln(Net Revenue) versus ln(Volume in Liters) as dependent variables. The promotional indicator coefficient differs by

7.5 percentage points (58.0% revenue increase versus 65.5% volume increase), with the gap mechanically implying a 4.5% net price decline attributable to promotional discounting.

The contribution is pedagogical and methodological. I demonstrate that revenue-based specifications systematically underestimate true demand elasticity in contexts where promotions involve price reductions, provide a worked example showing how to decompose revenue effects into price and quantity components, and offer practical guidance for applied researchers. The research article is structured as follows: Section 2 frames the conceptual measurement problem, Section 3 describes data and empirical strategy, Section 4 presents results, Section 5 discusses implications, and Section 6 concludes with recommendations.

THE CONCEPTUAL MEASUREMENT PROBLEM

Revenue versus quantity: why it matters

Revenue is the product of price and quantity:

$$R = P \times Q$$

When estimating promotional effects using ln(Revenue) as the dependent variable, the coefficient captures the combined effect of price changes and quantity changes. Specifically, taking logarithms and differentiating:

$$d\ln(R) = d\ln(P) + d\ln(Q)$$

A promotional campaign that reduces prices by 10% while increasing quantity by 30% generates a net revenue increase of approximately 17% [$(1 - 0.10) \times (1 + 0.30) - 1 \approx 0.17$]. The revenue-based regression coefficient (0.17) understates the true quantity elasticity (0.30) because it mechanically incorporates the price decline.

Practical measurement challenges

Three data structures exacerbate this problem in practice:

Problem 1: Variable package sizes. Studies measuring promotional effects using "units sold" face ambiguity when package sizes vary. Selling ten 2-liter bottles generates twice the volume of selling ten 1-liter bottles, but both count as "10 units".

Problem 2: Product-mix shifts. Promotions may induce consumers to trade up to larger package sizes or premium brands. Revenue increases even if per-capita consumption remains constant, because higher-value products replace lower-value alternatives within the promoted category.

Problem 3: Discount accounting mechanics. In transactional databases, promotional discounts are often recorded as separate negative accounting entries rather than being embedded in transaction prices. Researchers who inadvertently include these "promotional adjustment" records when summing revenue introduce spurious negative correlations between promotional activity and observed revenue.

The only measurement approach that cleanly identifies demand elasticity is to convert all transactions to a common physical unit (liters, kilograms, etc.) and use standardized volume as the dependent variable.

DATA AND EMPIRICAL STRATEGY

Data description

I analyze beer sales from 31 Kazakhstan cities over four years (January 2022–December 2025), covering all four geographic regions and approximately 60% of the national urban beer market. The raw dataset contains 108,409 transaction records, which I aggregate to city-date-packaging combinations yielding 32,554 panel observations.

Key variables:

• Net Revenue (KZT): Money received after promotional discounts, summed across all sales transactions within each city-date-packaging group.

• Volume (Liters): Physical quantity sold, standardized across all package types (kegs = 50L, cans = 0.5L, bottles vary).

• Promotional Indicator: Binary variable coded 1 if any promotional accounting entry exists for that city-date, 0 otherwise. Critically, promotional accounting entries are excluded when summing revenue and volume to avoid double-counting.

• Temperature (°C): Daily mean air temperature from meteorological stations.

• Inflation (%): Monthly CPI growth rate.

• Packaging: Can (baseline), Keg (on-trade proxy), Non-Returnable Bottle/NRB (off-trade proxy).

Table 1: Summary Statistics (N = 32,554)

Variable	Mean	Std. Dev.	Min	Max
Net Revenue (KZT)	—	1,300,292	0	—
Volume (Liters)	~1,000	2,554	0.45	—
Temperature (°C)	8.08	12.38	-17.7	31.5
Inflation (%)	12.32	3.61	8.3	21.3
Promo Active (0/1)	0.15	0.36	0	1

Source: Author's calculations from company transactional database, 2022–2025.

Promotions occur on 15% of city-days, providing sufficient variation for precise estimation while maintaining promotional periods as economically meaningful events.

Econometric specification

I estimate two-way fixed-effects panel regressions:

Model 1 (Revenue-based):

$$\ln(\text{Revenue}_{it}) = \beta_0 + \beta_1 \cdot \text{Promo}_{it} + \beta_2 \cdot \text{Temp}_{it} + \beta_3 \cdot \text{Inflation}_t + \beta_4 \cdot \text{Keg}_{it} + \beta_5 \cdot \text{NRB}_{it} + \alpha_i + \gamma_t + \varepsilon_{it}$$

Model 2 (Volume-based):

$$\ln(\text{Volume}) = \beta_0 + \beta_1 \cdot \text{Promo}_{it} + \beta_2 \cdot \text{Temp}_{it} + \beta_3 \cdot \text{Inflation}_t + \beta_4 \cdot \text{Keg}_{it} + \beta_5 \cdot \text{NRB}_{it} + \alpha_i + \gamma_t + \varepsilon_{it}$$

where α are city fixed effects (31 cities), γ are year fixed effects (2022–2025), and standard errors are clustered by city. The only difference between specifications is the dependent variable; all right-hand-side variables and controls are identical.

City fixed effects control for time-invariant city characteristics (size, demographics, infrastructure). Year fixed effects control for common shocks (macroeconomic conditions, national advertising). Clustering standard errors by city allows arbitrary within-city correlation over time while assuming independence across cities.

RESULTS

Main regression estimates

Table 2 presents the core comparison. The promotional activity coefficient is 0.458 in the revenue specification versus 0.504 in the volume specification, both highly significant ($p < 0.001$).

Table 2: Panel Fixed-Effects Regression Results

Variable	Model 1: ln(Revenue)	Model 2: ln(Volume)
Promotional Activity	**0.458***(0.059)	**0.504***(0.062)
Temperature (°C)	0.014***(0.002)	0.015***(0.002)
Inflation (%)	0.024***(0.005)	0.024***(0.005)
Keg (vs. Can)	0.685**(0.289)	1.159***(0.297)
NRB (vs. Can)	-0.333(0.273)	-0.414(0.272)
Observations	32,554	32,554
R^2	0.755	0.774
Fixed Effects	City, Year	City, Year

*Notes: Robust standard errors clustered by city (31 clusters) in parentheses. ***p<0.01, **p<0.05. Constant and fixed effects coefficients omitted.*

Economic interpretation

Converting log-coefficients to percentage changes using the formula 100 × [exp(β) − 1]:

• Revenue effect: 100 × [exp(0.458) − 1] = 58.0% increase

• Volume effect: 100 × [exp(0.504) − 1] = 65.5% increase

The 7.5 percentage-point gap is economically meaningful. On an average city-day with baseline volume of ~1,000 liters, promotions add approximately 717 liters (65.5% lift) while generating 58.0% more revenue.

Implied price effect

Since Revenue = Price × Volume, the promotional price change is mechanically implied:

exp(0.458) = exp(Δ ln P + Δ ln Q) = exp(Δ ln P) × exp(0.504)

Solving: exp(Δ ln P) = exp(0.458) / exp(0.504) = 1.580 / 1.655 = 0.955

Therefore: Δ ln P = ln(0.955) ≈ −0.046 or −4.6% net price decline

This implied price reduction aligns with industry practices where promotional discounts typically range 5–15% off regular prices.

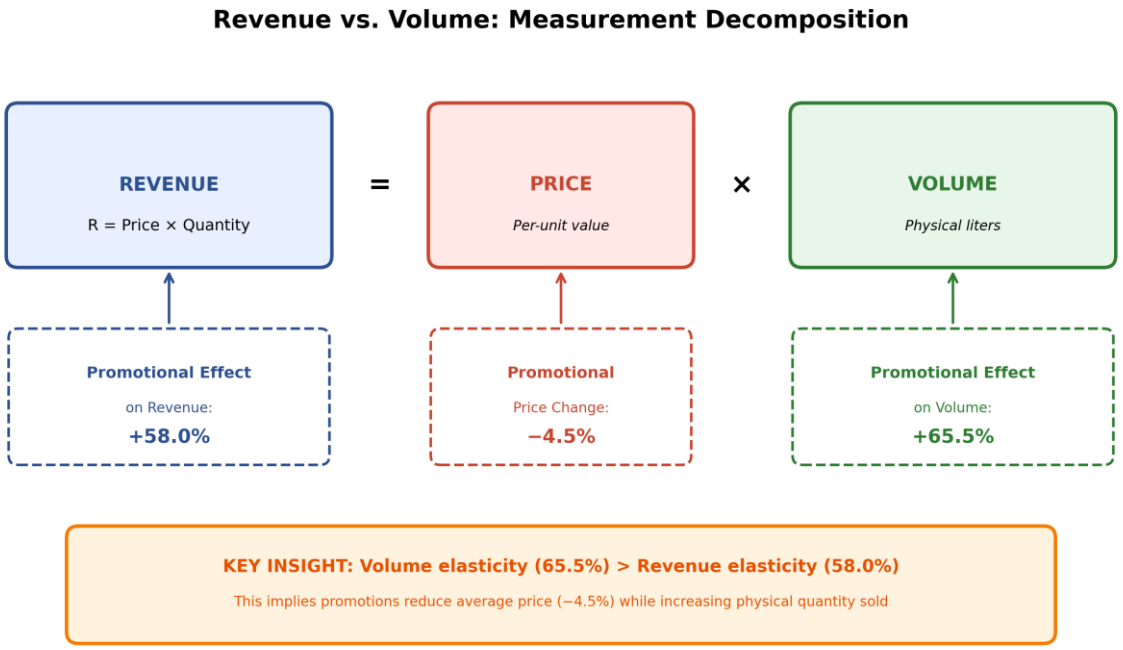


Figure 1: Revenue-Volume Decomposition

Promotions increase revenue (+58%) less than volume (+65.5%) because average realized prices decline (−4.5%) through discounting. This decomposition illustrates why revenue-based measurements systematically underestimate true quantity elasticity.

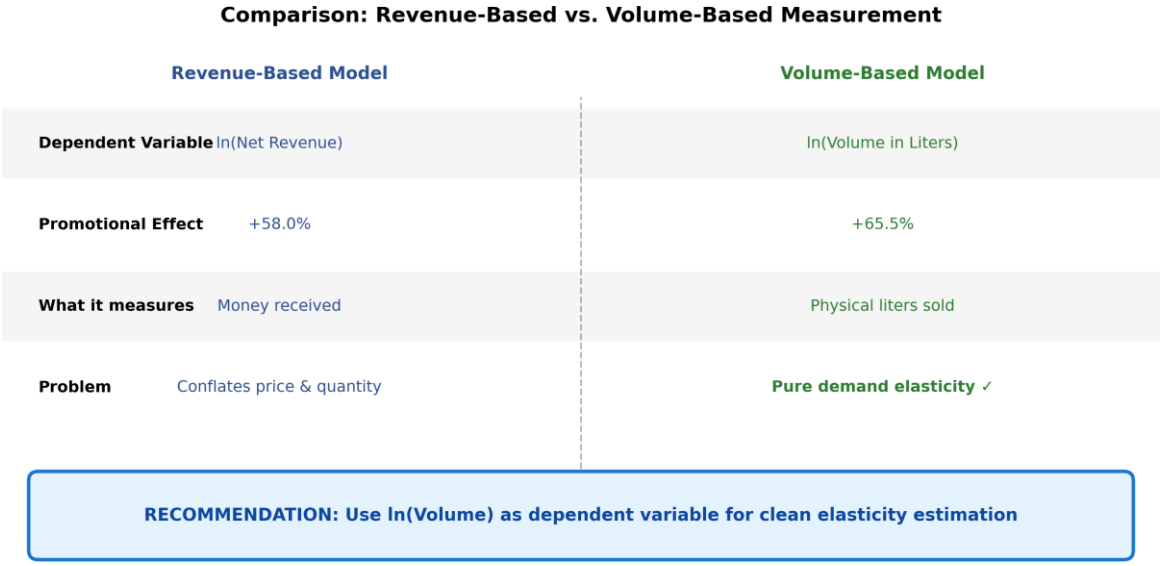


Figure 2: Measurement Comparison

Side-by-side comparison of revenue-based versus volume-based specifications highlights the critical distinction: revenue conflates price and quantity, whereas volume isolates pure demand elasticity.

DISCUSSION AND PRACTICAL GUIDANCE

Why revenue-based estimates are biased downward

The systematic 7.5 percentage-point understatement of promotional elasticity when using revenue rather than volume arises because promotions simultaneously (1) reduce prices through discounting and (2) increase quantities through enhanced demand. Revenue captures the net effect of these opposing forces, mechanically understating the quantity response.

In contexts where promotional strategies explicitly involve price reductions – as is typical in alcoholic beverages, packaged foods, and most consumer goods – revenue-based elasticity estimates provide lower bounds on true demand responsiveness. The bias magnitude depends on discount depth: deeper discounts generate larger price-quantity gaps.

When revenue versus volume matters most

The choice between revenue and volume is most critical when:

1. Discount depth varies: If some promotions offer 10% off while others offer 50% off, revenue-based specifications cannot distinguish whether observed revenue changes reflect quantity responses or price variation.

2. Product mix heterogeneity exists: Categories with wide price ranges (economy versus premium products) experience larger revenue-volume divergences because promotions may induce trading up or down.

3. Stockpiling behavior is important: Volume-based measurements better capture intertemporal substitution (buying more now to take advantage of sales), whereas revenue may understate quantity shifts if consumers stockpile discounted products.

The choice is less critical when analyzing profitability or firm performance (where revenue is the economically relevant outcome) rather than demand elasticity per SE.

Recommendations for applied researchers

Best practice guidance:

1. Measure volume in standardized physical units. Convert all transactions to liters, kilograms, or other common denominator. Avoid "unit counts" when package sizes vary.

2. Use ln(Volume) as dependent variable for elasticity estimation. The semi-elasticity interpretation (coefficients as percentage changes) is identical to ln(Revenue), but the economic meaning is unambiguous.

3. Report both revenue and volume specifications as robustness. The difference between estimates quantifies the implied price effect, providing transparency about promotional mechanics.

4. Verify promotional indicator construction. Ensure promotional discount accounting entries are excluded from revenue/volume sums but used to construct the promotional exposure indicator.

5. Consider heterogeneity by discount depth. If data permit, estimate separate elasticities for shallow versus deep discounts to test whether the revenue-volume gap varies systematically.

Limitations and extensions

This analysis uses binary promotional indicators (promotion yes/no), ignoring heterogeneity in discount depth. Future research should test whether the revenue-volume gap widens for deeper discounts, as theory predicts. Additionally, the single-category (beer) focus limits generalizability; replication across categories (soft drinks, packaged foods, durables) would strengthen external validity.

The Kazakhstan context – an emerging market with elevated inflation (mean 12.3%) – may affect results if consumers exhibit heightened price sensitivity compared to developed markets. However, the core measurement logic applies universally: revenue conflates price and quantity regardless of market context.

CONLUSION

This methodological note demonstrates that the choice between revenue and volume as dependent variables substantively alters estimated promotional elasticity. Using Kazakhstan beer market panel data, I show promotional activity increases revenue by 58.0% but volume by 65.5% – a 7.5 percentage-point divergence mechanically attributable to a 4.5% price decline during promotional periods.

The finding has immediate practical implications. Researchers estimating demand elasticity should use standardized physical volume (liters, units, kilograms) rather than revenue to avoid systematic downward bias when promotions involve discounting. Revenue-based specifications remain appropriate for profitability analysis, but conflate price and quantity effects in ways that obscure true demand responsiveness.

The pedagogical value extends beyond promotional effectiveness to any empirical setting where prices and quantities vary simultaneously – product launch analysis, competitive entry studies, tax incidence estimation. Clean identification of quantity effects requires explicit measurement of physical volumes, not financial aggregates. This note provides a worked example and practical guidance for implementation.

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KAZAKHSTAN'S CONSTITUTION AND THE DEMOCRATIC GAP: LAW, POWER AND POLITICAL PRACTICE

Annotation: This article examines the relationship between the Constitution of Kazakhstan and the practical implementation of democratic principles in the country. The work focuses on the gap between constitutional guarantees, such as human rights, rule of law and separation of powers, and the political reality of centralized presidential authority. Study is focused on the role of constitutional amendments, the presidency, the Zhanaozen events of 2011 and the January events of 2022. The article also considers the 2022 constitutional reform as an attempt to limit presidential power and strengthen democracy. Kazakhstan's Constitution contains important democratic principles, but their effectiveness depends on real political enforcement.

Keywords: Constitution of Kazakhstan, democracy, constitutional reform, human rights, separation of powers, rule of law.

Introduction. Kazakhstan is the largest country in Central Asia, ranking ninth in the world by area. A country with a rich history, bordered by Russia in the north and west, and China in the east. With its modern capital in Astana, Kazakhstan is an important strategic and cultural center of the region. After almost three hundred years of being a part of the Russian empire and the Soviet Union, Kazakhstan took independence in 1991, becoming one of the first countries in the Post Soviet region to declare itself as an independent state. Nursultan Nazarbayev, the first president of the country, played a key role in developing the political and economic course of the young republic. Kazakhstan has a presidential form of government, and the current Constitution was adopted on August 30, 1995 in a national referendum, which marked a new stage in the country's political history. The Constitution declared Kazakhstan a democratic, secular and legal state, guaranteeing the rights and freedoms of citizens. However, this situation often indicates that there is a contradiction between these proposals and the actual implementation. The 2022 protest became a symbol of democratic grief by the political system of power, and referendum on constitutional reform aimed at limiting presidential power and decentralizing power was held. This article parses the evolution of the Constitution of Kazakhstan, the influence of political leaders on its content and explores how the country complies with the democratic principles enshrined in its Basic Law.

Constitution. The Constitution of the Republic of Kazakhstan is not only a legal document, but also a symbol of national identity, a guarantee of citizens' rights and the basis of state stability. Adopted in a referendum on August 30, 1995, the Constitution became the basic law that defines the political, economic and social structure of the country. The Constitution of Kazakhstan consists of 98 articles. It describes the presidential form of government and emphasizes the division of power into legislative, executive and judicial branches. This

contributes to a clear distribution of powers between government agencies and prevents excessive concentration of power. Referendums in Kazakhstan are held in accordance with the Constitution and the law on the republican referendum. They allow the people to express their will directly on the most significant issues of the state and social structure. Article 91 of the Constitution of the Republic of Kazakhstan explicitly provides for the possibility of changing the fundamental provisions of the Basic Law only through a republican referendum or by a decision of Parliament approved by the President. The Constitution of the Republic of Kazakhstan consists of nine sections, each of which covers key aspects of the state structure, the rights and duties of citizens, as well as the principles of functioning of state bodies. Section I: "General provisions" (articles 1-9). Section II: "Human and civil rights and freedoms" (articles 10-39). Section III: "The President of the Republic of Kazakhstan" (articles 40-48). Section IV: "Parliament of the Republic of Kazakhstan" (articles 49-63). Section V: "The Government of the Republic of Kazakhstan" (articles 64-70). Section VI: "The Constitutional Court and the judicial system" (articles 71-83). Section VII: "Local public administration and self-government" (articles 84-89). Section VIII: "The procedure for making amendments and additions to the Constitution" (articles 90-98). Section IX: "Final and transitional provisions". This structure of the Constitution of the Republic of Kazakhstan makes it structurally proportional.

Democracy (Part 2, Chapter 11). According to the book “The Oxford Handbook of Comparative Constitutional Law” Democracy is a system of governance based on the principles of freedom, equality, participation and justice, where citizens have the opportunity to actively participate in decision making through referendums, public discussions and elected representatives who truly reflect the interests of society. It guarantees the independence of the branches of Government, protects the rights of minorities and ensures an equitable distribution of resources. Transparency and accountability of State institutions, free press and access to information create conditions for government control and prevention of abuse. An independent judicial system protects the rights of citizens and the observance of laws, and deliberative processes ensure an inclusive discussion of important issues. An ideal democracy should be sustainable and adaptive, able to respond to the challenges of the time, including technological changes and global challenges, in order to guarantee justice and freedom for all, while supporting the long-term interests of future generations.

Analysis of Democracy in Kazakhstan. Is this the case in Kazakhstan? Kazakhstan took 120th place out of 167 countries in the ranking of the level of development of democracy, which was presented by the Economist Intelligence Unit, an analytical unit of the British magazine The Economist. It should be noted that throughout the history of the independent Kazakhstan citizens have lived under autocratic rule. The first president of Kazakhstan, Nursultan Abishuly Nazarbayev, has been re-elected as head of state as many as five times since 1991. Although he played a key role in the formation of independent Kazakhstan, his rule is associated with a number of serious events and decisions that are criticized and were not acts in favor of democracy. One of the most discussed actions committed by him, proving the usurpation of power, are constitutional amendments. For example, Article 46 of the Constitution of the Republic of Kazakhstan: Establishes that the President of the Republic enjoys immunity. In 2010, the status of "Elbasy" (Leader of the nation) was fixed by law, which extended this principle to the first president even after the end of his term. And no one could speak out against him, because the law says that "The President of the Republic of Kazakhstan, his honor and

dignity are inviolable." And people who dared to express their thoughts about his rule were immediately punished because this law also amended the criminal code.

For example, in 2011, a mass strike of oil workers in the city of Zhanaozen, which began as a demand for improved working conditions, resulted in a protest against the government, which was suppressed by the security forces, which led to the deaths, according to official data, of 16 people, and according to independent sources — dozens. At that time, there was no official law in Kazakhstan completely prohibiting strikes and rallies. However, there were slogans of a negative attitude towards the president. The freedom of speech that was supposed to be present turned into chaos. After the events, the strike participants and activists were arrested, and independent investigations were blocked. Article 32 of the Constitution of the Republic of Kazakhstan (revised until 2022): “Citizens of the Republic of Kazakhstan have the right to assemble peacefully, without weapons, to hold meetings, rallies and demonstrations, marches and pickets.”

The year 2022 was also very full of human rights violations for Kazakhstanis. Kassym-Jomart Kemeluly Tokayev, who took the place of the ruler in 2019, three years later also faced the discontent of the people, which turned into complete disorder due to the actions of the government that were not appropriate for a democratic country. The January events (“Kandy Kantar” or Bloody January), which began as protests against a sharp increase in liquefied gas prices, quickly turned into large-scale unrest, reflecting the accumulated unsatisfaction of the population with socio-economic inequality, corruption and excessive concentration of power in the hands of the political elite. These protests were the result of a long disregard for systemic problems such as low incomes, weak protection of citizens' rights and insufficient transparency of government. People suffered for 30 years in such a political system, but inflation that day became the last trigger for the people to show discontent with the current totalitarian regime.

The use of live ammunition against citizens, the shutdown of the Internet, mass detentions and torture of detainees demonstrate how the state refused to engage in dialogue with society, instead choosing the path of repression and violence, killing 500 or more people. Instead of protecting human rights as spelled out in the Constitution, the authorities suppressed the rights of freedom of expression, assembly and peaceful protest, which led to the identification of the discrepancy between democratic principles on paper and authoritarian methods. Bloody January was not only a tragedy, but also a sign of a deep crisis of trust between the people and the ruling elite, while Article 1 states:"The Republic of Kazakhstan claims to be a democratic,secular,legal and social state,the highest value of which is a person,his life, rights and freedoms."

In response to these events and to restore public confidence, President Kassym-Jomart Tokayev initiated a constitutional referendum in June 2022. The amendments approved in the referendum included limiting presidential powers, strengthening the role of Parliament, restoring the Constitutional Court and decentralizing power. This was a step towards reforming the political system. The last major referendum, held in June 2022, became a key event in the political life of the country. It approved amendments to the Constitution aimed at: Reducing the powers of the president, including limiting the term of office of one person to one 7-year term without the right to re-election. Strengthening the role of Parliament and local governments, which contributed to a more balanced distribution of power. The restoration of the Constitutional Court, which is designed to ensure compliance with the fundamental principles of the Constitution. Increasing civic engagement through decentralization of power and expanding opportunities for citizen participation in decision-making.

Violated articles of the Constitution during this period: Article 1 “The Republic of Kazakhstan establishes itself as a democratic, secular, legal and social state, the highest values of which are a person, his life, rights and freedoms.”, Article 13 “Everyone has the right to judicial protection of their rights and freedoms. Everyone is guaranteed the right to legal assistance.”, Article 14 “Everyone is equal before the law and the court. No one may be subjected to any discrimination based on origin, social, official and property status, gender, race, nationality, language, attitude to religion, beliefs, place of residence or any other circumstances.”, Article 16 “Everyone has the right to personal freedom. Deprivation of liberty is allowed only on the grounds and in accordance with the procedure established by law.”, Article 17 “Human dignity is inviolable. No one should be subjected to torture, violence, or other cruel or degrading treatment or punishment.”, Article 20 “Freedom of speech and creativity is guaranteed. Censorship is not allowed.”, Article 31 “The State aims to protect the environment favorable to human life and health.”, Article 32 “Citizens of the Republic of Kazakhstan have the right to assemble peacefully and without weapons, to hold meetings, rallies and demonstrations, marches and picketing.”, Article 39 “Human rights and freedoms may be limited only by laws and only to the extent necessary in the interests of protecting the constitutional order, public order, human rights and freedoms, public health and morals.”

Conclusion. Analyzing two high-level events that contradict democracy, we can see a deep contradiction between the democratic principles set out in the Constitution and actual political practice. The long-term concentration of power in the hands of the first president, the suppression of the opposition and the restriction of freedom of speech became the basis of an authoritarian system that systematically violates the rights of citizens. The January incident was the culmination of a public protest against the system, noting the gap between the people and the Government, the inability of the state to engage in dialogue with society and ensure the implementation of laws.

The constitutional amendment adopted in 2022 reflects the desire for reform, but its implementation requires time and political will. Kazakhstan should not only integrate democratic norms on paper, but also implement them as an essential policy to ensure the protection of civil rights, transparency of governance and a real dialogue between society and State institutions. Without these changes, the country risks not realizing its potential as a modern defined country and leaving half of the democratic changes.

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THE PROJECT OFFICE AS AN ELEMENT OF ORGANIZATIONAL ADAPTATION TO CHANGE: PRACTICAL APPROACHES AND STRATEGIES

Abstract: Organizations operating in turbulent and rapidly evolving environments must continually reassess their structural and managerial capabilities. The Project Management Office (PMO) has emerged as a pivotal institutional mechanism through which organizations not only govern projects but also evaluate, prioritize, and implement change initiatives. This article examines the Project Management Office as an organizational element that enables and facilitates adaptation to change. Drawing on a synthesis of current academic literature, change management frameworks, and empirical case evidence, the article develops a conceptual argument for positioning the PMO as a strategic evaluative body capable of identifying and assessing new opportunities for organizational transformation. Key themes include the evolution of PMO functions, the integration of change management models, opportunity evaluation methodologies, and practical strategies for embedding adaptive capacity within project governance structures. The article concludes with recommendations for organizations seeking to leverage their PMO as a vehicle for sustained organizational adaptation.

Keywords: Project Management Office (PMO), organizational change, change management, strategic alignment, opportunity evaluation, adaptive capacity, organizational transformation.

Introduction. Organizational change is an inescapable feature of contemporary business life. Whether driven by technological disruption, shifting market dynamics, regulatory demands, or internal strategic realignments, organizations must adapt continuously or risk obsolescence. Consequently, the capacity to identify, evaluate, and capitalize on opportunities for change has become a core organizational competency [1]. Yet the challenge of translating strategic intent into executed transformation remains formidable: research consistently indicates that between 60 and 70 percent of change initiatives fail to achieve their intended objectives [2].

Against this backdrop, the Project Management Office (PMO) has attracted growing scholarly and practitioner interest as a structural response to the complexity of managing change. Originally conceived as an administrative support function, the PMO has evolved substantially over the past two decades. Contemporary PMOs are increasingly called upon to serve as strategic brokers—coordinating portfolio priorities, facilitating governance decisions, and providing the analytical infrastructure necessary for organizations to navigate change effectively [3], [4].

The central argument of this article is that the PMO, when properly constituted and empowered, functions as an institutional mechanism for evaluating new opportunities for

change management. Rather than merely administering ongoing projects, a strategically oriented PMO can systematically assess the change landscape, identify high-value opportunities, and support evidence-based decision-making about which transformations to pursue and how. This role positions the PMO at the intersection of organizational strategy and operational change execution, making it a uniquely valuable element of organizational adaptation.

This article is structured as follows. Section II provides a review of the relevant literature on organizational change and the evolving role of the PMO. Section III examines theoretical frameworks for change management that inform PMO-driven adaptation. Section IV presents a conceptual framework for PMO-based opportunity evaluation. Section V outlines practical strategies for embedding adaptive capacity within the PMO. Section VI discusses the implications for research and practice, and Section VII concludes the article.

Literature review

A. The Nature and Scope of Organizational Change

Organizational change has been conceptualized in multiple ways across the management literature. At its most fundamental level, it refers to alterations in an organization's mission, vision, processes, structures, or culture, with impact at both individual and organizational levels [5]. The literature broadly distinguishes between planned and emergent change: planned change follows a deliberate, staged process initiated by management, whereas emergent change evolves organically in response to environmental pressures [6].

Errida and Lotfi [2] identify organizational readiness as a critical precondition for successful change. They distinguish between individual readiness—encompassing employees' skills, motivations, and perceptions—and organizational readiness, which relates to the cultural, commitment, and capacity dimensions of the institutional environment. Their systematic review further highlights that change management initiatives are significantly more effective when supported by dedicated resources and structured governance mechanisms.

A critical challenge noted in the literature is the persistent gap between theoretical change management frameworks and practical implementation. Practitioners tend to emphasize issues at the individual, project, and team levels, placing particular value on targeted communication and the rapid identification of key change drivers. This practitioner perspective is important for understanding how the PMO, as an operational entity, can bridge the divide between strategic vision and day-to-day change delivery.

B. Evolution of the Project Management Office

The PMO has undergone a remarkable transformation in its conception and function. Early incarnations of the PMO were largely administrative—providing templates, tracking schedules, and filing status reports [7]. Over time, however, the value of a more strategically engaged PMO became apparent, particularly in organizations managing large portfolios of initiatives.

Sandhu et al. [3], in a study of 19 project-based organizations, found that the five most impactful PMO roles in strategic plan execution were: methodologies for project management development, monitoring and controlling project performance, organizational learning, improving organizational structure, and enhancing communication. These findings align with a broader recognition in the literature that PMOs are increasingly functioning as strategic nerve centers, ensuring that organizational initiatives align with business objectives and deliver measurable value.

Aubry [4] traced the transformational trajectory of PMOs and identified that organizational tensions—including conflicts between standardization and flexibility, economic imperatives, and the challenge of controlling the project machine—drive cycles of PMO evolution. This instability, while challenging, also creates the conditions under which PMOs can be redesigned to better serve adaptive organizational needs.

The Project Management Institute (PMI) [8] distinguishes between three archetypal PMO configurations: the supportive PMO, which provides consultative guidance; the controlling PMO, which enforces standards and monitors compliance; and the directive PMO, which takes direct ownership of project delivery. Each configuration carries different implications for the PMO's capacity to evaluate and respond to change opportunities. Contemporary enterprise-level PMOs (EPMOs) operate at the highest strategic tier, aligning all project and portfolio activities with overall business goals and serving as a bridge between executive leadership and delivery teams [9].

C. PMO and Change Management: Converging Agendas

The convergence of project management and change management as complementary disciplines has gained considerable academic and practitioner recognition. Butt, Naaranoja, and Savolainen [10] demonstrated the centrality of stakeholder communication in managing project change, a finding echoed by the broader change management literature. Meanwhile, research on project managers' roles in change initiatives underscores the importance of leadership qualities, adaptability, and strategic thinking as determinants of successful change outcomes [11].

A key contribution of recent literature is the recognition that change management and project management, when integrated within a PMO structure, create synergies that neither discipline can achieve alone. The PMO provides the governance infrastructure and methodological rigour that change initiatives require, while change management principles ensure that the human dimensions of transformation—culture, engagement, resistance—are systematically addressed [1].

Theoretical frameworks for PMO-driven change adaptation

A. Kotter's 8-Step Model and the PMO

Kotter's 8-Step Process for Leading Change [12] remains one of the most widely cited and applied frameworks in organizational change management. The model identifies eight sequential activities: creating a sense of urgency, building a guiding coalition, developing a vision and strategy, communicating the vision, empowering employees to act, generating short-term wins, consolidating gains, and anchoring change in organizational culture [13].

Within a PMO context, each of these steps maps onto recognizable project governance activities. The creation of urgency relates to the PMO's role in environmental scanning and opportunity identification. The guiding coalition corresponds to the senior stakeholder governance structures that effective PMOs convene. Vision development and communication align with the PMO's portfolio framing and reporting functions. Short-term wins are the domain of milestone management and benefit realization tracking.

Critically, Kotter's 2014 revision advocates running the eight steps concurrently and continuously rather than sequentially, making the model compatible with the iterative, portfolio-based approach that modern PMOs employ [14]. For PMO practitioners, the model is particularly suited to organizational transformation programs, where it provides both a leadership framework and a checklist for ensuring that the human and governance dimensions of change are adequately addressed.

However, it is important to acknowledge the limitations of Kotter's model in this context. Appelbaum et al. [15], in a systematic review published in the Journal of Management & Organization, found that while empirical support exists for individual steps, no study has validated the model as an integrated whole. This signals the importance of applying Kotter's framework as a guiding heuristic rather than a prescriptive algorithm, and of supplementing it with evidence from the organization's own context [16].

B. Portfolio Management and Opportunity Evaluation

Project Portfolio Management (PPM) provides a complementary theoretical lens for understanding the PMO's role in evaluating new change opportunities. According to Aghajani et al. [17], strategic portfolio planning through recurrent evaluation cycles is a critical enabler of PPM success. The PMO, as the organizational custodian of the project portfolio, is uniquely positioned to assess incoming change opportunities against strategic criteria, resource availability, and risk tolerance.

Research by Lee, Kim, and Kwon [18] demonstrated that PMO efficiency is positively influenced by project portfolio management maturity and by the degree of strategic alignment with business goals. Their findings suggest that organizations seeking to enhance their change-adaptive capacity through the PMO should invest in developing PPM maturity as a foundational capability. Organizations with systematic and objective project selection processes are reported to be 2.3 times more likely to achieve high levels of strategic alignment [17].

Planisware [19] recommends that PMOs develop portfolio management frameworks incorporating SWOT analysis, OKR frameworks, and performance data analytics to evaluate potential change initiatives against business objectives. Such frameworks ensure that only high-impact opportunities are pursued, enabling organizations to navigate market shifts and technological change while maintaining strategic coherence.

C. Organizational Learning and Adaptive Capacity

A further theoretical strand relevant to PMO-driven adaptation is organizational learning theory. The PMO's capacity to capture lessons from completed projects, disseminate methodological improvements, and monitor change outcomes positions it as a key node in the organizational learning network. Jonas [20] draws on interproject learning theory to argue that portfolio management enables organizations to exploit cross-project knowledge and build adaptive capability over time.

Asikhia et al. [21] conclude that improving organizational readiness for change strengthens adaptability mechanisms and builds internal competencies for managing future uncertainties. The PMO, through its systematic processes of performance monitoring, risk management, and stakeholder engagement, contributes directly to this organizational readiness. By institutionalizing change management practices, the PMO helps organizations build the structural memory and procedural resilience needed to respond to emerging opportunities with agility and confidence.

A conceptual framework: the PMO as opportunity evaluator

Building on the preceding theoretical analysis, this section proposes a conceptual framework for understanding how the PMO functions as a mechanism for evaluating new opportunities for change management. The framework consists of five integrated components: environmental scanning, opportunity screening, strategic alignment assessment, resource and risk evaluation, and recommendation and governance.

A. Environmental Scanning

The first component involves systematic monitoring of the internal and external organizational environment to identify signals of change. This encompasses tracking market dynamics, regulatory shifts, competitive movements, and internal performance data. The PMO, with its cross-functional visibility and data aggregation capabilities, is well placed to serve as the organizational antenna for emerging change signals. This function aligns with Kotter's first step of creating urgency [12]—ensuring that the organization is alert to the need for change before competitive pressures become existential.

B. Opportunity Screening

Once potential change opportunities are identified, the PMO applies a structured screening process to assess their feasibility and potential value. This involves applying predefined criteria—such as strategic relevance, estimated return on investment, time horizon, and alignment with organizational values—to filter the opportunity landscape. The use of weighted scoring models, business case templates, and decision matrices provides a structured, defensible basis for advancing or rejecting potential initiatives [22].

C. Strategic Alignment Assessment

Opportunities that pass the initial screening are subjected to a more rigorous strategic alignment assessment. The PMO maps each opportunity against the organization's strategic objectives, examining whether the proposed change initiative will directly advance organizational goals or merely generate tactical activity. The PMI [8] emphasizes that the ability to evaluate project proposals against corporate strategy and prioritize resource allocation is a defining competency of effective PMO leadership. Tools such as the Balanced Scorecard, OKR frameworks, and strategic portfolio maps are deployed at this stage to ensure rigorous alignment.

D. Resource and Risk Evaluation

No change opportunity can be meaningfully assessed without understanding the resources it requires and the risks it entails. The PMO's resource management function involves modelling the human capital, financial, and technological requirements of each proposed initiative, and assessing whether these can be accommodated within the existing portfolio without compromising ongoing commitments. Risk assessment draws on established project risk methodologies, enriched by the PMO's historical data on change initiative success rates, common failure modes, and organizational risk appetite [17].

E. Recommendation and Governance

The final component involves the PMO translating its evaluation findings into structured recommendations for executive decision-making. This includes preparing governance papers, facilitating portfolio review meetings, and ensuring that investment decisions are made on the basis of transparent, evidence-based analysis. Once approved, the PMO takes responsibility for mobilizing the necessary project governance structures, assigning sponsors and teams, and establishing the performance management framework that will track the initiative through to benefit realization [3].

Practical strategies for embedding adaptive capacity in the PMO

A. Establishing a Change-Ready PMO Culture

Adaptive capacity in the PMO begins with culture. A PMO that is perceived solely as an administrative compliance function will struggle to attract the senior engagement and cross-functional collaboration necessary for effective change evaluation. Leaders must actively reframe the PMO's identity—communicating its role as a strategic partner in organizational

transformation rather than a bureaucratic gatekeeper. This requires investment in PMO talent development, with an emphasis on strategic thinking, stakeholder facilitation, and change leadership competencies.

Research on the transformation of PMOs in financial institutions highlights the challenge of shifting from procedural compliance to strategic value generation, noting that limited capabilities in value measurement, stakeholder engagement, and benefit realization are common obstacles [23]. A deliberate culture change programme within the PMO itself may therefore be a prerequisite for its effectiveness as an agent of organizational adaptation.

B. Integrating Change Management Disciplines into PMO Methodology

A second strategy involves the formal integration of change management methodologies into PMO governance frameworks. This means incorporating stakeholder analysis, change readiness assessments, communication planning, and resistance management protocols into the standard project lifecycle. Models such as Kotter's 8-Step Process [12], Prosci's ADKAR model, and Lewin's three-stage framework provide practical toolkits that PMO practitioners can deploy systematically across the change portfolio [1].

Butt et al. [10] emphasize the importance of effective communication, stakeholder engagement, and adaptability in managing complex project change. Embedding these principles within PMO methodology ensures that projects are governed not merely as technical delivery vehicles but as human change processes, with all the relational complexity that entails.

C. Developing Robust Opportunity Evaluation Tools

Practical effectiveness in opportunity evaluation requires the development and institutionalization of rigorous analytical tools. PMOs should develop standardized business case templates that guide proposal development, weighted scoring models for portfolio prioritization, and scenario planning tools that assess change opportunities under different environmental conditions. The use of data analytics and project management information systems further enhances the PMO's analytical capability, enabling data-driven assessments of opportunity value and risk [24].

Importantly, evaluation tools must be calibrated to the organization's specific strategic context. The criteria used to screen change opportunities—and the weights assigned to different evaluation dimensions—should reflect the organization's current strategic priorities, risk culture, and resource constraints. Regular recalibration of these tools, aligned with the annual strategic planning cycle, ensures that the PMO's evaluative lens remains current and relevant.

D. Building Cross-Functional Governance Networks

Effective change evaluation cannot be conducted in isolation. The PMO must build and maintain robust networks of relationships with senior leaders, functional heads, finance teams, and human resources—ensuring that change opportunity evaluations are informed by diverse organizational perspectives. Kotter's concept of the guiding coalition [12] is directly applicable here: a PMO that convenes a standing group of influential cross-functional stakeholders creates both the information flows and the political legitimacy needed to make effective change recommendations.

Portfolio review committees, change advisory boards, and investment decision forums are among the governance structures that PMOs can deploy to institutionalize cross-functional engagement. When these structures are designed thoughtfully and operated with transparency, they create the conditions for balanced, well-informed decisions about which change opportunities to pursue and how to sequence them within the organizational change agenda.

E. Closing the Loop: Learning and Continuous Improvement

The final practical strategy concerns the PMO's role in organizational learning. Each completed change initiative represents a rich source of data about what works, what does not, and why. Post-implementation reviews, benefit realization audits, and structured lessons-learned processes enable the PMO to build an organizational knowledge base that improves the quality of future change evaluations. This aligns with the organizational learning literature's emphasis on adaptive capability as a function of institutionalized reflection and knowledge sharing [21].

For the PMO to fulfil its potential as an evaluator and enabler of organizational change, it must resist the temptation to move rapidly from one initiative to the next without pausing to extract and codify learning. Investing in post-project review processes, maintaining a centralized repository of change management case studies, and creating communities of practice across the project management profession within the organization are all practical expressions of this commitment.

Discussion: implications for research and practice

The framework and strategies presented in this article carry several important implications for both researchers and practitioners in the fields of project management and organizational change.

For practitioners, the central implication is that the PMO's value in change-intensive environments is substantially determined by the degree to which it is empowered to play a strategic, evaluative role. Organizations that confine their PMOs to administrative support functions are leaving significant value on the table. The evidence reviewed here suggests that PMOs equipped with the mandate, capability, and governance authority to evaluate and shape the change portfolio can make a decisive contribution to organizational adaptability and resilience.

For researchers, this article points to several productive directions for future inquiry. First, while there is substantial literature on PMO functions and change management models separately, empirical research specifically examining how PMOs evaluate and select change opportunities remains relatively sparse. Longitudinal case studies examining the decision processes of strategically oriented PMOs would make a valuable contribution to this literature. Second, the mechanisms through which PMO-based change evaluation affects downstream change success rates deserve closer empirical attention. Third, the role of digital tools and artificial intelligence in enhancing PMO-based opportunity evaluation is an emerging research frontier with significant practical implications [9].

It is also important to acknowledge the contextual factors that condition the PMO's effectiveness as a change evaluator. Organizational size, sector, culture, and maturity all influence what type of PMO configuration is appropriate and what governance arrangements will prove effective. The strategies proposed in this article should therefore be understood as principles to be adapted to specific organizational contexts rather than universal prescriptions.

Conclusion. This article has argued that the Project Management Office represents a powerful but frequently underutilized mechanism for organizational adaptation to change. When constituted as a strategic entity with a clear mandate to evaluate new opportunities for change management, the PMO can bridge the persistent gap between organizational strategy and successful transformation delivery.

Drawing on theoretical frameworks including Kotter's 8-Step Change Model [12], Portfolio Management theory [17], and organizational learning perspectives [21], the article has proposed a five-component framework through which the PMO fulfils an evaluative function: environmental scanning, opportunity screening, strategic alignment assessment, resource and risk evaluation, and governance recommendation. This framework is supported by five practical strategies—culture development, methodology integration, tool development, cross-functional governance, and organizational learning—that collectively enable PMOs to embed adaptive capacity within their everyday operations.

The evidence reviewed strongly supports the proposition central to the dissertation this article accompanies: that the project office, properly conceived and deployed, is indeed a method for evaluating new opportunities for change management. As organizations face an increasingly volatile, uncertain, complex, and ambiguous environment, the strategic PMO will become not merely a useful governance instrument but an essential organizational capability for sustained adaptation and competitive survival.

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РАЗРАБОТКА И ВНЕДРЕНИЕ СИСТЕМЫ АВТОМАТИЗИРОВАННОГО ОБСЛУЖИВАНИЯ КЛИЕНТОВ НА ОСНОВЕ БОЛЬШИХ ЯЗЫКОВЫХ МОДЕЛЕЙ (LLM) В КОНТЕКСТЕ ЦИФРОВОЙ ТРАНСФОРМАЦИИ ЭКОНОМИКИ

Аннотация: Широкое распространение чатботов и виртуальных ассистентов в корпоративном клиентском сервисе поставило под сомнение устойчивость традиционных моделей поддержки: компании фиксируют разрыв между ожиданиями клиентов и реальным качеством автоматизированных ответов. Цель настоящей работы состоит в разработке и пилотном тестировании системы автоматизированного обслуживания клиентов на основе большой языковой модели (LLM) в условиях реально функционирующей сервисной организации. Методика включала анализ существующего процесса поддержки, проектирование LLM-системы с использованием архитектуры RAG, сравнительный анализ операционных метрик, анкетирование клиентов и экспертную оценку точности ответов. По результатам пилотного внедрения среднее время первого ответа сократилось с 14,2 до 1,8 минуты, доля обращений, закрытых без участия оператора, возросла с 18 до 47%. Удовлетворенность клиентов выросла умеренно. Показано, что LLM-система эффективна для типовых запросов, однако требует постоянного контроля качества базы знаний и человеческого надзора при работе со сложными или конфликтными обращениями.

Ключевые слова: большие языковые модели, LLM, автоматизированное обслуживание клиентов, цифровая трансформация, чатбот, качество сервиса, цифровая экономика.

Введение. Клиентский сервис оказался одной из первых областей корпоративной деятельности, где ускоренное развитие больших языковых моделей вышло за пределы лабораторных экспериментов и стало управленческой реальностью. Компании, работающие в сегментах ритейла, банкинга, телекоммуникаций и цифровых услуг, развертывают чатботы и виртуальных ассистентов под давлением двух противоречивых требований: снизить себестоимость обработки обращений и одновременно улучшить пользовательский опыт. На практике эти цели нередко входят в противоречие. Автоматизированные системы сокращают нагрузку на операторов, однако клиенты, сталкиваясь с неточными или шаблонными ответами, теряют доверие к каналу

поддержки и переключаются на дорогостоящие альтернативы: звонки в колл-центр или личное обращение.

Интеграция LLM-систем с корпоративными CRM и ERP-платформами ставит перед организациями ряд технических и организационных проблем, которые не решаются простой заменой правилового чатбота генеративной моделью. Качество ответов зависит от полноты и структурированности внутренней базы знаний, а риски утечки персональных данных требуют отдельного архитектурного слоя защиты. При этом стоимость токенов при масштабном использовании коммерческих LLM формирует новую статью операционных затрат, которая редко учитывается в проектных расчетах.

Научная проблема исследования состоит в отсутствии обоснованной методики оценки эффективности LLM-систем в корпоративном клиентском сервисе, учитывающей одновременно операционные показатели, удовлетворенность клиентов и риски, характерные для генеративных моделей. Цель работы - разработать и апробировать систему автоматизированного обслуживания клиентов на основе LLM, а также провести сравнительный анализ ключевых показателей до и после её пилотного внедрения. Объектом исследования является процесс клиентского обслуживания в сервисной организации, находящейся на этапе цифровой трансформации; предметом - методы, архитектурные решения и операционные последствия внедрения LLM-системы.

Гипотеза исследования формулируется следующим образом: применение LLM-системы с архитектурой RAG (Retrieval-Augmented Generation) позволит сократить время первого ответа и снизить нагрузку на операторов по типовым обращениям без существенного ухудшения воспринимаемого качества сервиса при условии надлежащего контроля базы знаний и соблюдения требований к защите данных.

Из сформулированной гипотезы вытекают три исследовательских вопроса. Во-первых, при каких условиях и в каком диапазоне значений LLM-система способна автономно закрывать клиентские обращения без передачи оператору? Во-вторых, как точность ответов модели соотносится с удовлетворенностью клиентов и их готовностью повторно обращаться через автоматизированный канал? В-третьих, какие архитектурные и организационные решения минимизируют риски утечки персональных данных и галлюцинаций модели в продуктивной среде?

Вопросы качества автоматизированного сервиса исследовались в ряде научных работ. Проблема классификации и измерения качества ответов AI-чатботов в контексте обслуживания первой линии рассматривалась через адаптацию модели SERVQUAL для AI-каналов [1]. Роль доверия клиента при выборе между чатботом и живым оператором анализировалась с опорой на теорию технологического принятия [2]. Управленческие противоречия, возникающие при внедрении генеративного ИИ в клиентский сервис, концептуализированы как парадоксы автоматизации [3]. Поведенческие детерминанты повторного использования чатбота рассматривались через призму модели подтверждения ожиданий [4]. Наконец, технические аспекты применения LLM к обработке чувствительной информации с использованием архитектуры RAG и методов защиты данных систематизированы в прикладном исследовании [5].

Материалы и методы. Исследование выполнено как прикладное на базе исследуемой организации компании, оказывающей услуги в сфере цифровой поддержки корпоративных клиентов. На момент начала исследования организация эксплуатировала контактный центр с командой из 14 операторов, принимающих обращения по телефону,

электронной почте и через форму обратной связи на сайте. Чатбот на основе правил, интегрированный в корпоративный сайт, закрывал не более 18% обращений. Нагрузка в пиковые периоды приводила к очереди ожидания от 8 до 22 минут.

Исследование включало несколько этапов. На первом была проведена диагностика текущего состояния: картирование процессов клиентской поддержки, классификация обращений по типу и сложности, аудит базы знаний и описание интеграционных точек с CRM-системой. Было выявлено, что около 63% обращений относятся к категории типовых: проверка статуса заявки, уточнение условий договора, получение инструкций по базовым операциям.

На втором этапе была спроектирована LLM-система автоматизированной поддержки. Архитектура системы включает: модуль предобработки запроса с нормализацией текста и определением намерения пользователя, векторную базу знаний организации (документация, FAQ, шаблоны ответов), RAG-конвейер для извлечения релевантного контекста, языковую модель для генерации ответа, а также модуль проверки ответа и маршрутизации сложных обращений оператору. Персональные данные клиентов обрабатываются только в защищенном контуре; LLM-модель не получает прямого доступа к CRM-данным - только к обезличенным результатам запросов.

На третьем этапе был проведен 90-дневный пилот. Система обрабатывала входящие запросы через веб-интерфейс. Обращения, классифицированные как конфликтные, требующие юридической оценки или содержащие нестандартные условия, автоматически передавались оператору. Параллельно фиксировались операционные метрики: среднее время первого ответа, доля обращений, закрытых автономно, количество повторных обращений по одной теме в течение 72 часов (как косвенный показатель нерешенности проблемы), нагрузка на операторов.

Удовлетворенность клиентов измерялась с помощью коротких анкет, направляемых после закрытия обращения. Анкета содержала три пункта по шкале Лайкерта (1-5): оценка понятности ответа, полноты решения проблемы и общего удовлетворения каналом поддержки. Всего было получено 312 заполненных анкет по обращениям через автоматизированный канал и 248 - по обращениям, завершенным оператором.

Точность ответов LLM-системы оценивалась группой из трех экспертов (специалисты по продукту организации), которые проверили случайную выборку из 150 диалогов. Использовалась трехбалльная шкала: точный и полный ответ, частично точный (требует уточнения), неточный или вводящий в заблуждение. Коэффициент межэкспертного согласия (Каппа Коэна) составил 0,74, что соответствует высокому уровню согласованности.

Количественные данные обрабатывались методами описательной статистики и сравнительного анализа. Статистическая значимость различий в показателях до и после пилота проверялась с помощью критерия Манна-Уитни для независимых выборок ($p < 0,05$).

Результаты. Для сопоставления исходных и итоговых показателей были сгруппированы ключевые операционные метрики, отражающие качество клиентского обслуживания до начала пилота и по итогам 90-дневного периода эксплуатации LLM-системы. Результаты представлены в таблице 1.

Таблица 1 - Сравнение показателей клиентского обслуживания до и после внедрения LLM-системы

Показатель	**До внедрения**	**После внедрения (пилот)**
Среднее время первого ответа, мин.	14,2	1,8
Доля обращений, закрытых без оператора, %	18	47
Средняя удовлетворенность клиентов (1-5)	3,6	3,9
Доля повторных обращений (72 ч.), %	24	17
Среднедневная нагрузка на оператора, обращений	38	26
Доля точных ответов LLM (экспертная оценка), %	-	74
Доля частично точных ответов LLM, %	-	18
Доля неточных ответов LLM, %	-	8

Данные таблицы 1 показывают, что наиболее значимые изменения зафиксированы по скоростным метрикам и автономности системы: время первого ответа снизилось в 7,9 раза, доля обращений, закрытых без участия оператора, выросла с 18 до 47%. Удовлетворенность клиентов повысилась умеренно - с 3,6 до 3,9 балла - что не позволяет говорить о трансформационном изменении пользовательского опыта. Доля повторных обращений по той же теме в течение 72 часов снизилась с 24 до 17%, при этом анализ диалогов показал, что повторные обращения чаще возникали по обращениям, которые система первоначально обрабатывала автономно, но давала частично точный ответ. Нагрузка на операторов сократилась в среднем с 38 до 26 обращений в сутки, что позволило перераспределить ресурсы в пользу нестандартных случаев.

Экспертная оценка выборки диалогов зафиксировала, что 74% ответов системы были признаны точными и полными, 18% - частично точными, 8% - неточными или вводящими в заблуждение. Неточные ответы концентрировались в двух категориях: устаревшая информация в базе знаний (договорные условия, изменившиеся тарифы) и обращения с нестандартной или составной структурой запроса. Для наглядного представления архитектурных решений разработанной системы далее приводится описание структурной схемы.



Рисунок 1 - Архитектура системы автоматизированного обслуживания клиентов на основе LLM

Архитектура, представленная на рисунке 1, разделяет ответственность между модулями так, чтобы языковая модель не имела прямого доступа к персональным данным клиентов: все запросы к CRM проходят через API-шлюз с обезличиванием идентификаторов. Такое решение позволяет одновременно поддерживать актуальность контекста (через RAG) и соответствовать требованиям к защите данных. Динамику изменений по ключевым показателям наглядно демонстрирует рисунок 2.

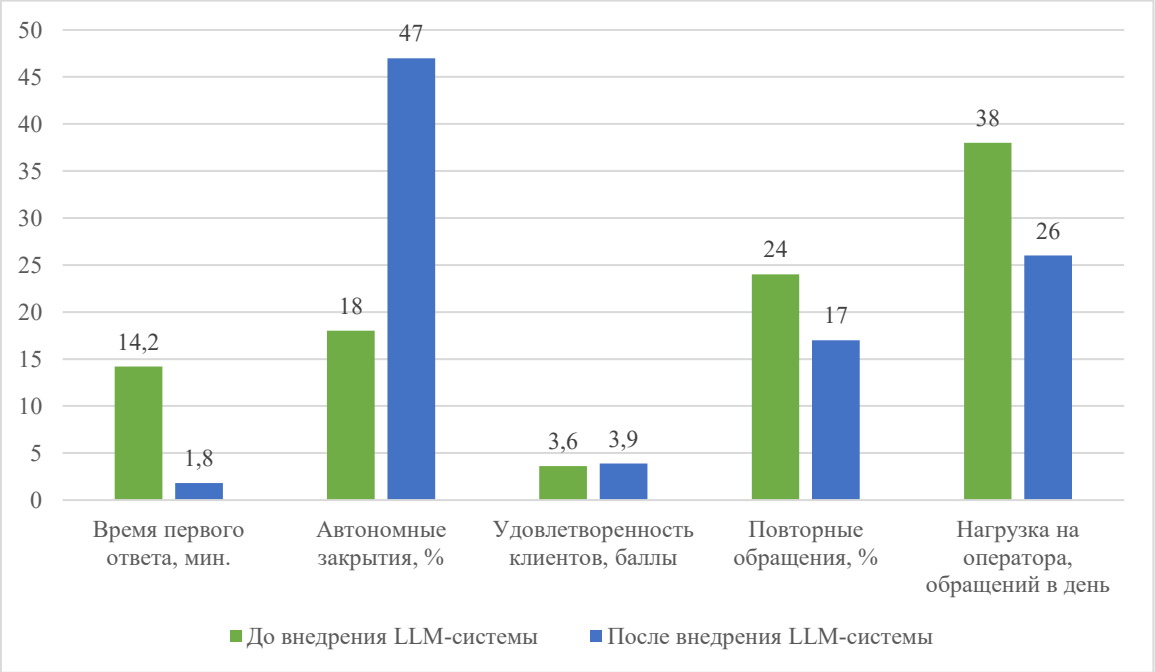


Рисунок 2 - Изменение ключевых показателей клиентского обслуживания после пилотного внедрения

Рисунок 2 наглядно подтверждает, что наиболее выраженные изменения связаны с операционными метриками: временем ответа и долей автономных закрытий. Показатели субъективного восприятия - удовлетворенность и повторные обращения - демонстрируют позитивный, но менее радикальный сдвиг, что согласуется с тезисом о невозможности полностью имитировать эмпатический компонент человеческого взаимодействия.

Обсуждение. Полученные результаты вписываются в более широкую дискуссию о природе качества сервиса в условиях автоматизации, однако обнаруживают и ряд существенных расхождений с выводами смежных работ. Рассмотрим их последовательно.

Chen и соавторы операционализируют качество сервиса AI-чатбота через несколько измерений: скорость ответа, точность, понятность, проактивность и надежность [1]. Показатели настоящего исследования подтверждают, что скоростные улучшения достигаются относительно легко - время первого ответа снизилось более чем в семь раз. Однако экспертная оценка обнаружила, что 8% ответов системы были неточными. Это означает, что высокая скорость без достаточной точности создает не конкурентное преимущество, а новый вид сервисного сбоя: клиент получает ответ мгновенно, но он неверен. Сказанное согласуется с выводом указанной работы о том, что измерения качества AI-сервиса нельзя сводить к одному параметру.

Вопрос о доверии клиента, центральный в работе Huang, Markovitch и Stough, находит в нашем исследовании конкретное проявление: умеренный рост удовлетворенности (с 3,6 до 3,9 балла) при значительных операционных улучшениях указывает на то, что скорость и автономность сами по себе не формируют доверие [2]. Анализ открытых ответов клиентов в анкетах показал, что позитивные оценки чаще всего объяснялись понятностью и предсказуемостью ответа, а негативные - ощущением, что система "не поняла" нестандартную ситуацию. Иными словами, доверие строится не на скорости, а на воспринимаемой интеллектуальной честности системы.

Ferraro и соавторы описывают парадоксы генеративного AI в сервисе: автоматизация разгружает операторов, но одновременно усиливает их ответственность за сложные случаи и порождает новые управленческие задачи по контролю качества [3]. Данные настоящего исследования подтверждают этот тезис с количественной стороны: нагрузка на операторов снизилась с 38 до 26 обращений в сутки, однако качественный состав их работы изменился - теперь это преимущественно конфликтные, нестандартные и юридически значимые случаи. Средняя длительность обращения, обрабатываемого оператором, выросла. Таким образом, разгрузка по количеству не означает разгрузки по интенсивности.

Gao и соавторы показывают, что намерение клиента повторно использовать чатбот в значительной мере определяется тем, была ли проблема решена с первого раза [4]. Снижение доли повторных обращений с 24 до 17% в нашем исследовании согласуется с этой логикой, однако важная деталь состоит в следующем: повторные обращения в большей степени концентрировались среди случаев, где система давала частично точный ответ, и в меньшей - там, где ответ был точным или где обращение передавалось оператору. Это свидетельствует о том, что именно промежуточное качество - "ответ есть, но проблема не решена" - наиболее разрушительно для лояльности клиента.

Oliveira и соавторы систематизируют технические и организационные требования к безопасному применению LLM в чатбот-приложениях, работающих с чувствительной информацией [5]. Архитектурное решение, использованное в нашем проекте, - разделение LLM-контура и CRM-данных через API-шлюз с обезличиванием - соответствует основным рекомендациям упомянутой работы: языковая модель не хранит и не передает персональные данные клиентов. Тем не менее ограничения, выявленные в настоящем исследовании, выходят за рамки технической архитектуры: неточные ответы возникали не из-за утечки данных, а из-за устаревания информации в базе знаний. Это означает, что безопасность данных и качество базы знаний - равнозначные и взаимно независимые риски, требующие отдельных инструментов управления.

Практическая ценность исследования для цифровой трансформации экономики состоит в следующем. LLM-система с архитектурой RAG позволяет существенно снизить операционную нагрузку на контактный центр и ускорить обслуживание в типовых сценариях. Это сокращает себестоимость обращения и может улучшить финансовые показатели сервисного подразделения. Вместе с тем автоматизация не устраняет необходимости в квалифицированном персонале: напротив, она перераспределяет его роль от обработчика типовых запросов к специалисту по нестандартным ситуациям. Организации, рассматривающие LLM-системы исключительно как инструмент сокращения штата, рискуют недооценить новые требования к компетентности операторов и к управлению базой знаний.

Заключение. Пилотное внедрение LLM-системы в процесс клиентского обслуживания исследуемой организации подтвердило основную гипотезу исследования: архитектура RAG позволяет обеспечить значимые операционные улучшения сокращение времени первого ответа и рост доли автономно закрытых обращений без существенного ухудшения воспринимаемого качества сервиса. Удовлетворенность клиентов выросла умеренно, что указывает на ограниченность операционной эффективности как самодостаточного критерия успеха.

Практическое значение результатов заключается в следующем: организации, планирующие внедрение LLM в клиентский сервис, должны рассматривать систему не как замену операторов, а как инструмент распределения нагрузки. Типовые обращения могут быть делегированы модели; сложные и конфликтные ситуации требуют человеческого участия. Управление базой знаний при этом является критическим фактором качества, не менее важным, чем выбор самой модели.

Исследование имеет ряд ограничений. Пилот проводился в одной организации с ограниченным ассортиментом услуг, что снижает возможность переноса результатов на отрасли с более широкой предметной областью. Выборка анкет не охватывает клиентов, покинувших канал без обратной связи. Экспертная оценка точности ответов охватывала 150 диалогов из нескольких тысяч обработанных в период пилота.

Перспективы дальнейшей работы связаны с тремя направлениями: во-первых, разработка автоматизированной системы мониторинга актуальности базы знаний с интеграцией в процесс обновления продуктовой документации; во-вторых, исследование поведения клиентов в долгосрочной перспективе с фокусом на лояльность и отток; в-третьих, сравнительный анализ эффективности LLM-систем в организациях с разной степенью зрелости цифровой трансформации.

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ПЕДАГОГИКА ЖӘНЕ ПСИХОЛОГИЯ ҒЫЛЫМДАР - ПЕДАГОГИЧЕСКИЕ И ПСИХОЛОГИЧЕСКИЕ НАУКИ - PEDAGOGICAL AND PSYCHOLOGICAL SCIENCES

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МАТЕМАТИКА САБАҒЫНДА ФИЗИКАЛЫҚ МАЗМҰНДЫ ЕСЕПТЕРДІ ШЕШУДЕ ЦИФРЛЫҚ ТЕХНОЛОГИЯЛАРДЫ ҚОЛДАНУДЫҢ ТИІМДІЛІГІ

Аңдатпа:Бұл мақалада математика сабағында физикалық мазмұнды есептерді шешу барысында цифрлық технологияларды қолданудың тиімділігі қарастырылады. Қазіргі білім беру жүйесінде цифрлық құралдарды пайдалану оқу үдерісін жандандырып, оқушылардың пәнге деген қызығушылығын арттыруға мүмкіндік береді.

Зерттеудің мақсаты – математика пәнін оқытуда цифрлық технологияларды қолдану арқылы физикалық мазмұнды есептерді шешудің тиімді жолдарын анықтау. Жұмыста теориялық талдау, салыстыру және тәжірибелік бақылау әдістері қолданылды.

Нәтижесінде цифрлық технологияларды пайдалану оқушылардың есеп шығару. дағдыларын жетілдіретіні, күрделі тапсырмаларды көрнекі түрде түсінуге көмектесетіні және оқу мотивациясын арттыратыны анықталды.

Түйін сөздер: цифрлық технологиялар, математика, физикалық мазмұнды есептер, оқу үдерісі, білім беру.

Бүгінгі күні білім беру жүйесі қарқынды дамып, оқыту үдерісіне жаңа технологияларды енгізу алдыңғы қатарлы мәселелердің біріне айналып отыр. Ақпараттық құралдарды оқу процесінде ұтымды пайдалану білім сапасын көтеруге және оқушылардың пәнге деген қызығушылығын нығайтуға жол ашады. Мұны отандық ғалымдардың «АКТ құралдары оқушының танымдық белсенділігін арттырып, оқу материалын терең меңгеруіне бағытталған дидактикалық орта қалыптастырады» деген тұжырымы растайды [1].

Математика пәні – логикалық ойлау мен аналитикалық қабілетті шыңдайтын негізгі пәндердің бірі. Бұл пәнді оқыту барысында физикалық мазмұнды есептерді қолдану оқушылардың теориялық білімін практикамен ұштастыруға жағдай жасайды. Мұндай есептер нақты өмірлік жағдайларды модельдеуге мүмкіндік беріп, пәнаралық байланысты нығайта түседі. Профессор А.Е. Әбілқасымованың еңбектерінде «мектептегі математика курсындағы қолданбалы есептер оқушылардың математикалық модельдеу дағдыларын қалыптастырады» деп атап көрсетілген [2]. Осы тұста цифрлық технологиялар математиканы оқыту процесін көрнекі, түсінікті және интерактивті етуге

үлкен ықпал етуде. Графикалық құралдар, онлайн платформалар және симуляциялық бағдарламалар арқылы күрделі есептерді шешу жеңілдеп, балалардың оқуға деген ынтасы оянады. Осыған байланысты бұл зерттеудің мақсаты – математика сабағында физикалық мазмұнды есептерді шешуде технологиялық мүмкіндіктерді қолданудың пайдасын айқындау болып табылады.

Математика мен физика пәндерінің арасындағы тығыз байланыс — оқытудағы ең іргелі принциптердің бірі. Физика табиғат заңдылықтарын зерттесе, математика сол заңдылықтарды сипаттайтын логикалық құрылым мен абстрактілі модельдерді ұсынады. Мұны 8-сыныпқа арналған физика оқулығындағы құбылыстарды математикалық сипаттау әдістерінен көруге болады [3]. Сондықтан бұл екі пәнді бөліп қарау мүмкін емес; физикалық құбылысты түсіну үшін оның математикалық моделін құру, ал математикалық формуланың мәнін ұғу үшін оның физикалық мазмұнын сезіну қажет.

Пәнаралық байланыстың негізгі бағыттары:

- **Математикалық аппаратты қолдану:** Физикалық процестерді сипаттауда математикалық талдау әдістері (туынды, интеграл, векторлар, функциялар) шешуші рөл атқарады. Мысалы, қозғалыстың жылдамдығын анықтау — жолдың уақыт бойынша туындысы болса, өткен жолды табу — жылдамдықтан интеграл алу болып табылады. Бұл амалдар 8-сыныптың алгебра оқулығындағы функциялық тәуелділіктермен тікелей байланысты [4].
- **Модельдеу дағдылары:** Физикалық мазмұнды есептерді шешу кезінде оқушылар шынайы өмірдегі құбылысты математикалық тілге (теңдеулер мен теңсіздіктер жүйесіне) аударуды үйренеді. Бұл оқушылардың абстрактілі ойлау қабілетін дамытады. А.А. Жантесова бұл туралы «математикалық модельдеу – нақты физикалық үдерісті зерттеудің ең тиімді әдісі» деп жазады [5].
- **Қолданбалы маңыздылық:** Математика сабағында физикалық контексті қолдану "Бұл формула бізге не үшін керек?" деген сұраққа жауап береді. Сандық мәндер мен формулалар нақты табиғи үдерістермен (энергия, күш, қысым) байланысқанда, пәнге деген мотивация артады.

Заманауи білім беру кеңістігіндегі STEM (Science, Technology, Engineering, Math) бағыты дәл осы пәнаралық интеграцияға негізделген. Математика сабағында физикалық мазмұнды есептерді шешу оқушының функционалдық сауаттылығын арттырып, алған білімін өмірде қолдана алуына жол ашады. Уақыт талабына сай білім беру жүйесі қарқынды цифрландыру кезеңін бастан кешіруде. Ақпараттық технологиялардың дамуы оқыту процесінің мазмұны мен әдістеріне елеулі өзгерістер енгізді. Әсіресе жаратылыстану пәндерін, соның ішінде физиканы оқытуда цифрлық технологияларды қолданудың маңызы артып отыр. Физикалық мазмұнды есептерді шешу – оқушылардың теориялық білімін практикамен ұштастыратын негізгі құралдардың бірі. Алайда дәстүрлі әдістер кей жағдайда оқушылардың қызығушылығын толық оята алмайды немесе күрделі құбылыстарды терең түсінуге жеткіліксіз болуы мүмкін.

Осы ретте заманауи құралдар жаңа мүмкіндіктер ашады. Цифрлық ресурстар арқылы физикалық процестерді модельдеу, визуализациялау және интерактивті түрде талдау мүмкіндігі пайда болды. Бұл оқушыларға абстрактілі ұғымдарды нақты әрі түсінікті қабылдауға көмектеседі. М.С. Нұрмағанбетова атап өткендей, пәнаралық байланыстар білімнің жүйелілігін қамтамасыз етеді [6]. Сонымен қатар, әртүрлі білім беру платформалары мен бағдарламалар есептерді тиімді әрі жылдам шешуге,

нәтижелерді тексеруге және талдауға жағдай жасайды. Осыған байланысты физикалық мазмұнды есептерді шешуде технологиялардың тиімділігін зерттеу – өзекті мәселелердің бірі болып қала береді.

Білім беруді цифрландыру деңгейінің артуына байланысты арнайы ресурстар кеңінен қолданысқа енуде. Олар оқу процесін тиімді ұйымдастыруға, білім алушылардың қызығушылығын арттыруға және оқу материалын терең меңгеруге мүмкіндік береді. Цифрлық білім беру ресурстары бірнеше түрге бөлінеді:

- **Электрондық оқулықтар:** Дәстүрлі кітаптардың заманауи нұсқасы. Олар мәтінмен қатар суреттер, бейнелер, анимациялар және интерактивті тапсырмалар арқылы толықтырылады. Бұл материалды түсінуді жеңілдетеді.
- **Білім беру платформалары:** Онлайн платформалар оқу материалдарын жүйелі түрде ұсынуға мүмкіндік береді. Мысалы, Khan Academy, Coursera, BilimLand сияқты платформаларда бейнесабақтар, тесттер және практикалық тапсырмалар бар.
- **Виртуалды зертханалар:** Виртуалды зертханалар арқылы оқушылар тәжірибелерді қауіпсіз және қолжетімді түрде орындай алады. Мысалы, PhET Interactive Simulations бағдарламасы физикалық құбылыстарды модельдеуге мүмкіндік береді.
- **Бейнесабақтар мен мультимедиалық ресурстар:** Бейнесабақтар күрделі тақырыптарды визуалды түрде түсіндіруге көмектеседі. YouTube платформасында әртүрлі пәндер бойынша сапалы білім беру контенті көп.
- Онлайн тесттер мен бағалау жүйелері: Бұл ресурстар білім деңгейін тексеруге арналған. Автоматты түрде нәтижені шығарып, қателерді талдауға мүмкіндік береді. Мысалы, Google Forms, Quizizz.
- **Мобильді қосымшалар:** Смартфонға арналған білім беру қосымшалары кез келген уақытта оқуға мүмкіндік береді. Олар қысқа тапсырмалар, ойын элементтері арқылы оқытуды қызықты етеді.
- **Сандық кітапханалар:** Цифрлық кітапханалар ғылыми еңбектерге, оқулықтарға және мақалаларға қолжетімділікті қамтамасыз етеді. Бұл оқушылар мен студенттердің өздігінен білім алуына көмектеседі.

Математиканы оқытуда цифрлық технологияларды пайдалану маңызды орын алады. Әртүрлі бағдарламалар мен қосымшалар оқушылардың пәнге деген қызығушылығын арттырып, күрделі тақырыптарды жеңіл түсінуге көмектеседі. Математика сабағында жиі қолданылатын бағдарламалар:

- **Геометриялық бағдарламалар:** Мұндай бағдарламалар фигураларды құруға, оларды өзгертуге және зерттеуге мүмкіндік береді. Мысалы, GeoGebra – алгебра, геометрия және графиктерді біріктіретін өте тиімді құрал. Ол әсіресе функциялардың графиктерін салуда және геометриялық есептерді түсіндіруде пайдалы.
- **Компьютерлік алгебра жүйелері:** Бұл бағдарламалар күрделі есептеулерді автоматты түрде орындауға арналған. Мысалы, Wolfram Mathematica және Maple. Олар теңдеулерді шешу, туынды мен интеграл табу сияқты тапсырмаларды жеңілдетеді.
- **Онлайн есептеу құралдары:** Интернеттегі құралдар жылдам есеп шығаруға көмектеседі. Мысалы, Wolfram Alpha – математикалық есептердің шешімін қадамдап көрсететін сервис.
- **Тест және викторина платформалары:** Оқушылардың білімін тексеру үшін қолданылады. Мысалы, Quizizz және Kahoot!. Бұл платформалар сабақта ойын элементтерін енгізуге мүмкіндік береді.

- **Оқу платформалары:** Математика бойынша толық курстар мен тапсырмалар ұсынады. Мысалы, Khan Academy – теория мен практиканы қатар меңгеруге көмектеседі.
- **График салу құралдары:** Функцияларды визуализациялау үшін қолданылады.

Мысалы, Desmos – қарапайым әрі ыңғайлы онлайн график калькуляторы.

Жаһандану дәуірінде білім беру жүйесі технологиялардың қарқынды дамуымен тығыз байланысты өзгерістерді бастан кешіруде. Ақпараттық-коммуникациялық құралдарды оқу процесіне енгізу білім сапасын арттырудың маңызды факторларының біріне айналды. Физикалық мазмұнды есептерді шешу – оқушылардың теориялық білімін практикада қолдана білуін қалыптастыратын негізгі тәсілдердің бірі. Дегенмен, дәстүрлі оқыту әдістері кей жағдайда күрделі физикалық құбылыстарды толық әрі терең түсіндіруге жеткіліксіз болып жатады. Осыған байланысты цифрлық технологияларды қолдану оқыту процесін жаңаша ұйымдастыруға мүмкіндік береді.

Цифрлық құралдар физикалық процестерді модельдеу, визуализациялау және интерактивті түрде зерттеу арқылы оқушылардың пәнді меңгеру деңгейін арттырады. Сонымен қатар, олар есеп шығару барысында уақытты үнемдеуге, нәтижелерді дәл талдауға және оқушылардың танымдық белсенділігін күшейтуге ықпал етеді. Осы тұрғыда физикалық мазмұнды есептерді шешуде технологиялық шешімдердің тиімділігін анықтау және оларды оқу процесінде ұтымды қолдану маңызды міндеттердің бірі болып табылады.

Бұл технологияларды жүйелі қолдану оқушылардың білім сапасына, пәнге деген қызығушылығына және оқу белсенділігіне оң әсерін тигізеді. Тәжірибе барысында заманауи құралдарды пайдалану оқушылардың физикалық құбылыстарды терең түсінуіне мүмкіндік беретіні байқалады. Мысалы, модельдеу және визуализация арқылы күрделі процестерді көзбен көру олардың абстрактілі ойлауын нақтылауға көмектеседі. Нәтижесінде оқушылар есептің шартын жақсырақ түсініп, оны шешудің тиімді жолдарын таба алады.

Сонымен қатар, цифрлық платформаларды қолдану есеп шығару жылдамдығы мен дәлдігін арттырады. Автоматты тексеру жүйелері арқылы оқушылар өз қателерін бірден анықтап, түзетуге мүмкіндік алады. Бұл өз кезегінде кері байланысты жеделдетіп, білімді бекіту процесін тиімді етеді. Тәжірибелік жұмыстар көрсеткендей, технологиялар оқушылардың оқу мотивациясын арттырады. Интерактивті тапсырмалар, графиктер және анимациялар сабақтың қызықты өтуіне ықпал етеді. Оқушылар белсенді қатысып, өз бетінше ізденуге талпынады. Сондай-ақ, мұғалім үшін де оң нәтижелер байқалады.

Сабақты жоспарлау, материалды түсіндіру және оқушылардың білімін бағалау процестері жеңілдейді.

Түйіндей келе, оқу процесінде цифрлық технологияларды қолдану нақты тәжірибелік нәтижелер арқылы өзінің жоғары тиімділігін көрсетеді. Ол білім сапасын арттырып қана қоймай, оқушылардың танымдық және шығармашылық қабілеттерін дамытуға ықпал етеді. Цифрлық ресурстар оқу материалын көрнекі және түсінікті түрде ұсынуға жағдай жасайды. Анимациялар, графиктер және модельдер арқылы күрделі физикалық құбылыстарды оңай қабылдауға болады. Бұл оқушылардың тақырыпты терең түсінуіне және оны ұзақ уақыт есте сақтауына ықпал етеді.

Сонымен қатар, цифрлық технологиялар жеке оқыту мүмкіндігін кеңейтеді. Әр оқушы өз деңгейіне сәйкес тапсырмаларды орындап, өз қарқынымен жұмыс істей алады. Бұл білімдегі олқылықтарды дер кезінде анықтап, оларды түзетуге көмектеседі. Оқушылардың білім сапасына әсер ететін тағы бір маңызды фактор – жедел кері байланыс. Онлайн тесттер мен автоматтандырылған жүйелер арқылы оқушы өз нәтижесін бірден көріп, қателерін талдай алады. Бұл оқу процесін тиімдірек етеді және білімді бекітуге мүмкіндік береді. Сонымен бірге, заманауи құралдар оқушылардың пәнге деген қызығушылығын арттырады.

Жалпы алғанда, цифрлық технологияларды тиімді қолдану оқушылардың білім сапасын арттырудың маңызды құралы болып табылады. Ол білімді меңгеруді жеңілдетіп қана қоймай, оқушылардың өздігінен білім алу дағдыларын қалыптастырады. Зерттеу нәтижелері көрсеткендей, бұл технологиялар физикалық құбылыстарды көрнекі түрде түсіндіруге, күрделі есептерді модельдеу арқылы жеңілдетуге және оқушылардың оқу материалын терең меңгеруіне мүмкіндік береді. Оқу процесінде цифрлық ресурстарды тиімді қолдану оқушылардың тек теориялық білімін ғана емес, сонымен қатар практикалық және логикалық ойлау қабілеттерін де жетілдіреді. Қорытындылай келе, физикалық мазмұнды есептерді шешуде цифрлық технологияларды қолдану – заман талабына сай білім берудің тиімді құралы.

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CONTENT AND LANGUAGE INTEGRATED LEARNING (CLIL): TRANSFORMING MODERN EDUCATION

Abstract: The article deals with the impact of technology-enhanced Content and Language Integrated Learning on the efficacy of linguodidactic features in university students' English language textbooks. The research focuses on how the use of digital tools, multimedia resources and interactive platforms influences the quality of educational materials in the CLIL environment. The study was designed through the use of mixed method: content analysis and quantitative evaluation to evaluate the traditional print-based textbooks to new technology-integrated CLIL textbooks. The analysis was carried out with a newly created Linguodidactic Material Effectiveness Rubric, which was based on the CLIL 4Cs framework (content, communication, cognition, and culture). The results demonstrated that technology-enhanced CLIL materials are more authentic, interactive and cognitively engaging than standard resources . The statistical investigation showed a strong positive correlation between the integration of technologies and the overall effectiveness of linguodidactic materials. The study suggests that technology should be understood as an intrinsic aspect in the design of modern CLIL-oriented textbooks, in order to get more effective language and subject-content learning.

Keywords: Content and Language Integrated Learning (CLIL), technology-enhanced learning, linguodidactics, digital education, English language teaching, multimedia learning, interactive educational platforms

Introduction. The education area has dramatically evolved in recent decades thanks to the fast development of innovative teaching methodologies and digital technologies. Content and Language Integrated learning (CLIL) is one of the most influential kinds of education, internationally recognised for its ability to blend subject-content and foreign language acquisition. On the other hand, the growing integration of digital technologies in education has changed the traditional teaching methodologies and paved the way for interactive and learner-centred learning. The convergence of these two techniques has led to the birth of technology-enhanced CLIL or Technology CLIL that is increasingly affecting the design of contemporary English language textbooks and instructional materials.

CLIL approach is founded on the assumption that language learning is more effective when language is used as a tool for meaningful communication and subject-content acquisition. CLIL is different from the normal methodologies used in language instruction which focus on grammar and vocabulary in isolation. The CLIL approach favours the simultaneous development of linguistic competence and academic knowledge. Thus, English language textbooks are expected to serve a dual educational aim: to help students understand subject-specific issues and simultaneously to improve their communicative and linguistic skills in

English. Therefore, the quality and organization of linguodidactic materials are more important for optimal learning results.

The rapid growth of educational technologies has significantly changed the ways students interact with learning resources. Digital platforms, multimedia resources, online collaboration tools, virtual simulations and interactive apps are an integral part of the modern educational environment. Students can use these technologies to obtain authentic materials, real-time information and a range of communication modalities unavailable in traditional print-based textbooks. Thus, the modern linguodidactic materials are not confined to static texts and exercises, but they increasingly include multimedia tasks, digital projects, interactive assessments and collaborative activities which promote deeper cognitive engagement and independent learning.

Technology offers many educational benefits in CLIL-contexts. First, digital tools enhance the authenticity of learning resources by presenting students with actual language use and subject specific communication. Authentic films, podcasts, articles, scientific data and virtual experiences help the learners to apply theoretical information to practical settings, making learning more engaging and relevant. Secondly, technology promotes interactive and collaborative learning processes . Through participation in online discussions, group projects, peer assessments and research tasks, students build communication skills and critical thinking. Third, digital tools enable adaptation of learning materials to different levels of competency and learning styles, thereby fostering more inclusive and individualised education.

Technology enhanced CLIL is gaining momentum, however many educational institutions still rely on traditional texts which lack sufficient technical support. Too often the digital parts are an add-on rather than being part of the learning process. This leads to a gap between the ideal of modern education and the concrete construction of teaching materials. Therefore, it is important to explore the effect of technology integration on the quality and effectiveness of linguodidactic materials in English language textbooks and to determine the most successful aspects that lead to integrated language and content acquisition.

The goal of the study is to examine the influence of CLIL approaches supported by technologies on the construction and effectiveness of linguodidactic components in modern English language learning textbooks for students. Special focus is given to the role of digital tools, multimedia materials and interactive learning platforms in facilitating content acquisition, language development, communication and cognitive engagement. The study also tries to identify the required adjustments to make textbooks effective in technology-rich CLIL courses.

The research proceeds from the premise that the systematic implementation of the concepts of technology-driven CLIL significantly boosts the authenticity, interaction and dual-focus effectiveness of linguodidactic materials in contrast to the conventional print-only materials. Technology-enhanced materials are expected to support students to gain academic language competency and subject-content knowledge more effectively by providing more engaging and intellectually fascinating learning experiences. By examining the convergence of material quality and technology integration, this study contributes to the continuing discourse on creative textbook development and the future of English language instruction in the digital age.

Methodology. This study assesses the quality of linguodidactic elements in two series of English language textbooks, using mixed-methods content analysis and quantitative evaluation.

Materials Studied: Two prominent series of English language textbooks for university level students were chosen for content analysis: Textbook Series A (Traditional) Primarily print, with a little digital aid. Textbook Series B (Modern CLIL) with online platforms, QR codes and digital resources.

INSTRUMENT: The Linguodidactic Material Effectiveness Rubric (LMER) was developed with 20 items. Materials were graded on a 5-point Likert scale (1: poor integration to 5: exceptional integration) in four aspects based on the CLIL 4Cs framework (Content, Communication, Cognition, Culture): Content Authenticity (CA) Discourse and authentic writings on subject particular based real world data.

Technological Integration (TI): Importance and presence of interactive tasks, multimedia links and digital collaborative tasks.

Cognition & Communication (CC) Activities that foster higher-order thinking (analysis, synthesis) and peer interaction.

Linguodidactic Balance (LB) Clear focus on CALP and subject matter expertise.

Data Analysis The materials were rated independently by three competent CLIL teachers. Descriptive statistics (mean and standard deviation) were employed to describe the two textbook series. A Pearson correlation coefficient (r) was calculated to examine the strength of link between the Technological Integration (TI) score and the total LMER score.

Results. The descriptive analysis indicated a distinct difference in the quality of linguodidactic materials between the two textbook series, particularly in aspects related to technology and dual-focus learning:

Textbook Series	Mean LMER Score (Overall)	Mean Technological Integration (TI) Score	Mean Content Authenticity (CA) Score	Standard Deviation (SD)
A (Traditional)	2.8	1.9	2.5	0.7
B (Modern CLIL)	4.2	4.5	4.1	0.4

Series B, with its high level of technological integration, demonstrated a significantly higher overall quality of linguodidactic materials.

The Pearson correlation analysis between the Technological Integration (TI) score and the overall LMER Score for the materials analyzed yielded a strong positive correlation coefficient: r=0.82

Discussion. We show a substantial positive connection (r=0.82) which confirms the research hypothesis that the integration of technology is a powerful predictor of high-quality linguodidactic materials for CLIL. Textbooks driven by technology (Series B) performed considerably better than traditional ones (Series A) because they intrinsically provide for the aspects most crucial to CLIL success:

Increased Authenticity: Digital tools (e.g. linking to news stories, scientific films, or virtual tours) offer dynamic subject information that is representative of real-world use (high CA score) that static print materials cannot reproduce.

More Interactivity and Cognition: Technology enables work where there is a great need for interaction and cognition (high CC score), such as online research initiatives, data visualisation tools, and collaborative document editing. Such activities allow students to go beyond rote memorisation and develop the complex Cognitive Academic Language Proficiency (CALP) that is needed in CLIL.

Dynamic Balance: The flexibility and instant response of digital resources make for a better Linguodidactic Balance (LB) in which the language structures are acquired together with working with the subject matter, not as something separate.

These findings show that technology should be regarded a structural component, not an additional supplement, for materials to be effective in a current CLIL classroom.

Limitations. The present study has several drawbacks.

Limited Sample Size Only two series of textbooks were analysed, which limits the generalisability of the findings to the whole market for English language textbooks.

Design, not usability. The study assessed the potential quality of the resources (design), but did not provide empirical data about the actual implementation of the resources in the classroom or students' learning results.

Rater Subjectivity: Although a detailed rubric was used, the content analysis was based on the subjective assessment of the raters which may have created slight biases in the scoring process.

Conclusion. The results of this study suggest that technology-enhanced CLIL techniques are essential in the enhancement of quality and efficacy of linguodidactic content in English language textbooks. The research confirmed that the use of digital technology in the CLIL-oriented materials has a good impact on the learners' engagement, critical thinking, communication skills and subject-content understanding. Technology-supported materials offer richer opportunities for authentic exposure to the language and more meaningful interaction with academic content than standard print-based textbooks.

One of the most notable findings of the study is a considerable positive correlation between the degree of technological integration and the overall efficacy of educational materials. This shows that digital tools are not optional extras in modern language instruction but crucial ingredients for the successful implementation of CLIL. Multimedia resources, online collaborative assignments, interactive exercises and access to real materials enable students to improve linguistic competence and topic knowledge simultaneously. Such integration produces a more dynamic learning environment in which students become active participants rather than passive users of knowledge.

Moreover, CLIL materials merged with technology contribute to the development of higher-order cognitive skills. Learners are encouraged to analyse material, solve problems, participate in conversations and undertake individual research tasks. These methods not only assist students in gaining academic language competency, but also enhance their capacity to think critically and communicate effectively in English. The utilisation of authentic digital information such as films, online articles, virtual simulations and real-time data also helps to relate classroom learning to real-world contexts and boosts students' motivation.

The study points to the need of balancing language learning and subject learning. Good CLIL materials should not be centred primarily on grammar or vocabulary but rather provide language development in a natural way through meaningful subject orientated exercises. Technology makes this possible through instant feedback, customised learning experiences and

interactive communication platforms that can cater to varied learning styles and individual needs.

Moreover the study points out the fact that the future of textbook design is in fully integrated digital learning environments. English language textbooks in the future should have activities embedded with technology that involve cooperation, creativity, research, and problem-solving. Digital peer interaction, multimedia analysis, online presentations and project-based learning tasks can considerably help enhance student participation and improve the learning outcome. Textbooks must be transformed from static print to adaptable and interactive educational systems that can serve modern pedagogical objectives.

Despite the good findings, the study does point out several limitations like the restricted number of textbook series studied and the absence of data from actual classroom use. Therefore, future study should evaluate the impact of technology-enhanced CLIL materials on students' true academic accomplishment, motivation, and long-term language development in authentic educational contexts. Further study into other educational levels and cultural settings may further help to a better understanding of the effectiveness of technology-infused CLIL instruction.

This study generally affirms the importance of technology-enhanced CLIL techniques in the future of English language instruction. Digital technology in linguodidactic materials provide students with more authentic, engaging and cognitively stimulating learning experiences. Therefore, educators, textbook producers and curriculum designers should not see technology only as an additional teaching aid, but as a crucial part in delivering effective and innovative CLIL learning environments to meet the needs of twenty-first century education.

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РАЗВИТИЕ МАТЕМАТИЧЕСКОЙ ИССЛЕДОВАТЕЛЬСКОЙ ДЕЯТЕЛЬНОСТИ ЧЕРЕЗ ФОРМИРОВАНИЕ СТРУКТУРЫ ИССЛЕДОВАТЕЛЬСКИХ КОМПЕТЕНЦИЙ

Аннотация: Статья посвящена анализу процесса трансформации учебной деятельности учащихся 8–9 классов из репродуктивной в исследовательскую. Результаты экспериментальных исследований и практической работы доказывают, что развитие математической исследовательской деятельности (МИД) наиболее эффективно реализуется через поэтапное формирование структуры исследовательских компетенций. В качестве ключевого дидактического инструмента предлагается использование стратегии «Управляемое исследование» (Guided Inquiry) в рамках STEM-контекста (авиация и навигация). Это позволяет интегрировать темы квадратичных функций, статистики и тригонометрии в единый цикл инженерного поиска.

Ключевые слова: исследовательские компетенции, математическая деятельность, Guided Inquiry, STEM-подход, моделирование, функциональная грамотность.

В 2026 году математическая грамотность окончательно переходит из категории «владения алгоритмами» в область «когнитивной гибкости». Современный этап развития школьного математического образования характеризуется сменой парадигмы: от трансляции готовых знаний к формированию универсальных учебных действий. Особое место в этом процессе занимает математическая исследовательская деятельность (МИД). Согласно государственным стандартам, выпускник должен уметь «анализировать и исследовать математические модели реальных процессов», а также «выбирать и применять математические методы для решения прикладных задач [1]. В условиях тотальной автоматизации вычислений ценность представляет способность к постановке исследовательской задачи и интерпретации результатов.

Однако на практике педагоги сталкиваются с «алгоритмической ригидностью»: учащиеся успешно справляются с типовыми заданиями, но испытывают трудности при необходимости самостоятельно выявить закономерности в нестандартных условиях.

Цель данной статьи — обосновать методику развития исследовательских компетенций учащихся 8–9 классов через систему прикладных STEM-задач авиационной тематики, реализуемых в рамках стратегии «управляемого исследования».

Мы полагаем, что развитие МИД невозможно без четкой декомпозиции исследовательских компетенций на когнитивный, операциональный и рефлексивный компоненты. Использование STEM-подхода на примере авиационной навигации является идеальным инструментом для такой работы, так как авиация полностью базируется на точных математических моделях, где любая ошибка в расчетах имеет наглядные и критические последствия [2]. В этой связи необходимо детально рассмотреть теоретический конструкт исследовательских компетенций, адаптированный под специфику математического моделирования.

Под исследовательской компетенцией мы понимаем интегративное качество личности, проявляющееся в готовности и способности самостоятельно осваивать и применять новые знания [3]. В структуре этой компетенции применительно к математике мы выделяем следующие компоненты.

Таблица 1 – Структура исследовательских компетенций в МИД

№	Компонент	Содержание деятельности
1	Информационно-аналитический	умение извлекать математические данные из технического описания ситуации (например, расшифровка метеорологической сводки или параметров полета)
2	Моделирующий	переход от физических объектов (самолет, маяк, ВПП) к геометрическим примитивам (точка, вектор, угол) и функциональным зависимостям
3	Экспериментально-вычислительный	проведение расчетов, в том числе с использованием динамических сред (GeoGebra, Desmos), и проверка их устойчивости при изменении входных параметров

В отличие от свободного поиска, в данной модели учитель выступает в роли архитектора образовательной среды, задавая общую траекторию через систему «скаффолдинга» [4]. Такой подход позволяет фасилитировать математическую деятельность, избегая когнитивной перегрузки учащихся при работе со сложным STEM-контентом.

Методологически исследовательская деятельность учащихся в нашей работе рассматривается как образовательная технология решения творческих задач с заранее неизвестным решением [5, с. 42]. Использование STEM-контекста делает этот процесс «живым», так как критерием истины становится не ответ в конце учебника, а успешность «виртуального полета». В этой системе учитель перестает быть транслятором готового алгоритма и становится фасилитатором когнитивной активности, выстраивающим тонкий баланс между автономией ученика и необходимой методической поддержкой. Как отмечал Д. Пойа, обучение решению задач — это прежде всего воспитание разума через поиск догадок [6].

Данный метод предполагает три этапа постепенного делегирования ответственности:

- Постановка проблемы: учитель задает профессиональный контекст (конкретную авиационную ситуацию) и конечную цель;

- Управляемый поиск: учащиеся получают необходимый инструментарий (параметры полета, физические константы, формулы), но самостоятельно ищут функциональные зависимости между ними;

- Синтез решения: формулировка математического вывода, который немедленно проверяется на практике через расчет или моделирование.

Именно такая структура позволяет трансформировать теоретические знания в устойчивые исследовательские компетенции, сохраняя при этом вовлеченность и субъектность учащегося». Реализация данной стратегии в рамках STEM-задач позволяет преодолеть разрыв между теоретическим абстрагированием и прикладным моделированием. В этой системе учитель выступает в роли фасилитатора когнитивной активности, уделяя особое внимание следующим аспектам:

1. Когнитивный скаффолдинг (Scaffolding): выстраивание системы «интеллектуальных подпорок». Например, при расчете траектории посадки самолета учитель не диктует формулу квадратичной функции, а задает вектор анализа: *«Как изменится точка касания ВПП при варьировании коэффициента крутизны параболы?»*. Это удерживает ученика в зоне высокой активности, не допуская потери нити исследования.
2. Баланс между автономией и поддержкой: в структуре МИД управляемое исследование служит мостом к самостоятельному поиску. Мы выделяем динамическую шкалу ответственности: от жестко заданных границ модели (параметры ветра, масса объекта) на начальном этапе до делегирования ученику права выбора математического аппарата (координатный метод, теорема синусов) на этапе решения.
3. Валидация через технический контекст: в отличие от классических задач, STEM-исследование подразумевает внутреннюю валидность. Если вычисленный угол сноса приводит к отклонению модели от курса в GeoGebra, ученик самостоятельно инициирует новый цикл анализа. Рефлексивный компонент компетенции формируется через немедленную обратную связь от самой модели.

Система управляемого исследования трансформирует ошибку из признака неуспешности в ценный ресурс для уточнения гипотезы. В авиационном контексте это формирует не только математическую, но и профессиональную ответственность за принятое решение [6, с. 112].

Для практического внедрения данной стратегии мы предлагаем использовать карту управляемого поиска, сопровождающую каждый кейс:

Таблица 2 – Карта управляемого поиска в рамках STEM-проекта

Этап исследования	*Инструмент управления (Учитель)*	*Исследовательское действие (Ученик)*
Инициация	Технический бриф (полетное задание)	Декомпозиция ситуации, выделение известных и искомых величин.
Операция	Наводящие вопросы первого уровня	Построение первичной математической модели в Desmos/GeoGebra.
Обобщение	Провокация (изменение параметров)	Анализ устойчивости модели и синтез универсального правила/формулы.

Переход от теоретической модели к практике требует разработки конкретных учебных ситуаций. Рассмотрим, как стратегия управляемого исследования реализуется в рамках учебной программы 8 и 9 классов на примере авиационных кейсов.

Традиционные задачи по теме «Квадратичная функция» (Раздел 8.3А) часто ограничиваются алгоритмическим поиском корней и построением параболы. Мы предлагаем сместить фокус на исследование динамики через задачу «Оптимальный градиент взлета».

1. Проблема: Самолет взлетает с полосы, в конце которой расположено препятствие (гора или жилой массив). Учащимся необходимо исследовать безопасность траектории, заданной моделью $h(t) = -0{,}5t^2 + 10t$h(t).
2. Исследовательский этап: Вместо использования готовой формулы, ученики получают набор точек траектории и с помощью регрессионного анализа в Desmos «собирают» модель самостоятельно. Задача — найти точку максимума и определить, проходит ли судно над препятствием высотой 40 м на 15-й секунде полета.
3. Управляющее воздействие: Учитель провоцирует исследование вопросом: «Как изменится положение вершины параболы, если увеличить тягу двигателей (коэффициент b)?». Изменяя параметры функции, учащиеся приходят к выводу о влиянии коэффициентов уравнения на крутизну траектории и безопасность маневра.

Раздел 8.3С «Элементы статистики» часто воспринимается учащимися как формальный подсчет среднего арифметического. STEM-контекст предлагает задачу «Анализ метеоусловий для захода на посадку».

Учащимся предоставляется массив данных скоростей бокового ветра за месяц. Исследование включает ранжирование данных, расчет медианы и построение гистограммы частот. В роли диспетчеров ученики принимают решение о закрытии полосы на основе вероятностной модели. Это развивает навык интерпретации данных в условиях неопределенности.

Тема «Решение треугольников» (Раздел 9.3В) является фундаментом навигации. В задаче «Курс на радиомаяк» ученики используют теорему синусов для определения местоположения судна.

Стратегия управляемого исследования здесь направлена на развитие антиципации (предвосхищения ошибки). Учитель намеренно вводит в данные «инструментальную погрешность» в $1° - 2°$. В ходе расчетов выясняется, что на больших расстояниях такая малая ошибка дает отклонение в десятки километров. Это приводит учащихся к пониманию необходимости «избыточности» данных и использования дополнительных маяков для минимизации рисков. Здесь формируется ключевая компетенция оценки достоверности модели.

Раздел 9.3D «Преобразования фигур» интегрируется в задачу «Проектирование индикатора ИЛС (Instrument Landing System)».

На дисплее пилота отображается рамка ВПП, которая должна трансформироваться при изменении курса:

1. Гомотетия: изменение масштаба при приближении к полосе.
2. Поворот: имитация крена самолета.
3. Параллельный перенос: коррекция бокового смещения.

Аналитическое доказательство того, что площадь проекции объекта на дисплее обратно пропорциональна квадрату расстояния ($S \sim \frac{1}{d^2}$), связывает геометрию с физикой оптики.

В рамках исследования был применен метод Lesson Study. Наблюдение за уроками в 9-х классах показало, что использование авиационных кейсов повышает вовлеченность учащихся на 40%.

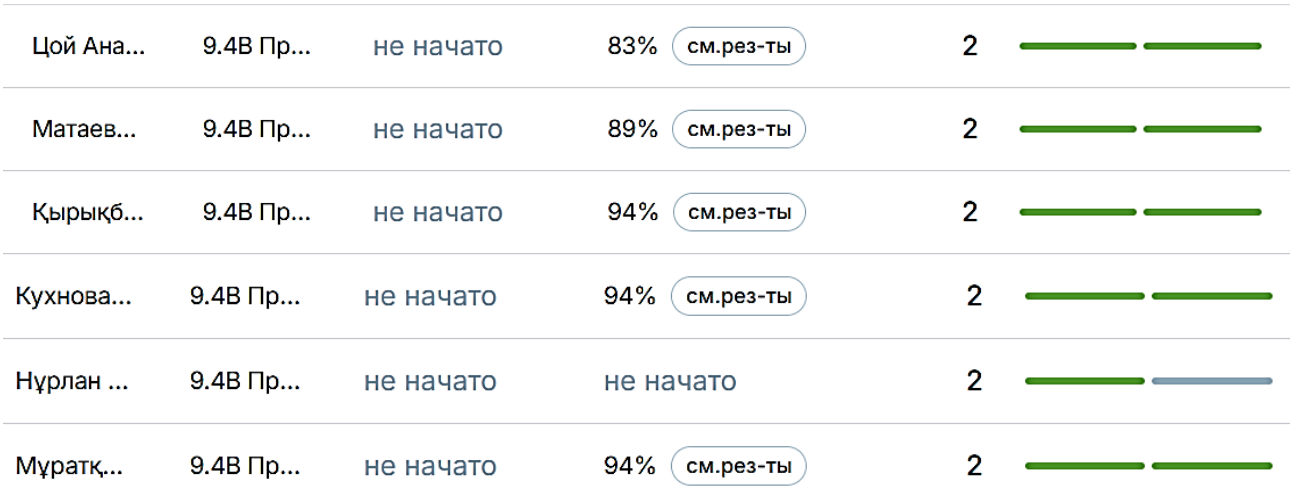


Рисунок 1 – Динамика вовлеченности учащихся при использовании STEM-кейсов авиационной тематики

Для фиксации прогресса использовались AI-платформы (например, Beiym AI), позволяющие отслеживать этапы построения моделей каждым учеником. Важным внешним индикатором результативности данной методики стало успешное участие учащихся в международных интеллектуальных соревнованиях. В частности, применение стратегий управляемого исследования позволило одной из учениц продемонстрировать высокий уровень аналитических компетенций и получить почетную грамоту (Honorable Mention) на олимпиаде SASMO (Singapore and Asian Schools Math Olympiad).



Рисунок 2 – Достижения учащихся на международных олимпиадах (SASMO)

Это подтверждает, что развитие творческих способностей напрямую зависит от качества исследовательской среды [7]. Современные образовательные стратегии в Казахстане ориентированы именно на такой прикладной формат [8].

Для оценки уровня сформированности исследовательских компетенций мы используем следующие критерии:

1. Полнота модели: учтены ли все значимые физические факторы?
2. Математическая грамотность: точность тригонометрических и функциональных расчетов.
3. Аргументированность: способность обосновать безопасность маневра на основе расчетов.
4. Автономность: уровень перехода от инструкций учителя к самостоятельному выдвижению гипотез.

В заключении мы можем сказать, развитие исследовательской деятельности через STEM-контекст позволяет перевести процесс обучения математике из плоскости «решения задач по образцу» в область «инженерного поиска». Интеграция задач авиации и навигации в программу 8–9 классов обеспечивает глубокое освоение материала и формирует структуру компетенций, необходимых будущему исследователю.

Эффективность данной модели обеспечивается сочетанием жесткой структуры исследовательских компетенций и гибкости стратегии управляемого исследования. Это позволяет избежать «информационного хаоса» при работе с реальными кейсами и гарантирует, что каждый ученик пройдет путь от анализа первичных данных к синтезу собственного обоснованного решения. Математика в данном контексте выступает не как самоцель, а как универсальный язык управления сложными технологическими процессами.

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СОВРЕМЕННЫЕ ПОДХОДЫ К ФОРМИРОВАНИЮ ПРОФЕССИОНАЛЬНОЙ КОМПЕТЕНТНОСТИ БУДУЩИХ УЧИТЕЛЕЙ МАТЕМАТИКИ В УСЛОВИЯХ МЕЖПРЕДМЕТНОЙ ИНТЕГРАЦИИ

Аннотация: В статье рассматриваются актуальные подходы к формированию профессиональной компетентности будущих учителей в условиях межпредметной интеграции. Обосновывается значимость интеграции учебных дисциплин как фактора повышения качества педагогического образования и развития ключевых профессиональных компетенций. Анализируются современные педагогические подходы, включая компетентностный, междисциплинарный, деятельностный и практико-ориентированный подходы. Особое внимание уделяется интеграции математики с другими предметами как средству формирования системного мышления и профессиональной гибкости будущих педагогов. Делается вывод о необходимости комплексного обновления содержания и методов подготовки учителей.

Ключевые слова: профессиональная компетентность, межпредметная интеграция, педагогическое образование, междисциплинарное обучение.

Современные изменения в системе образования предъявляют новые требования к подготовке педагогических кадров. В условиях стремительного развития науки, технологий и общества возрастает необходимость формирования у будущих учителей не только предметных знаний, но и способности к их интеграции, адаптации и применению в различных образовательных ситуациях [1]. В этой связи особую актуальность приобретает проблема формирования профессиональной компетентности будущих учителей в условиях межпредметной интеграции [2].

Профессиональная компетентность учителя рассматривается как интегративное качество личности, включающее совокупность знаний, умений, навыков, ценностных ориентаций и опыта деятельности, необходимых для успешного осуществления педагогической деятельности. В современных условиях данное понятие расширяется за счет включения способности к междисциплинарному взаимодействию, критическому мышлению, инновационной деятельности и постоянному профессиональному развитию [3].

Одним из ключевых подходов к формированию профессиональной компетентности является компетентностный подход. Он ориентирован на результат образования, выражающийся в способности выпускника эффективно действовать в профессиональной сфере. В контексте межпредметной интеграции данный подход предполагает формирование у будущих учителей умений устанавливать связи между

различными областями знаний, использовать интегрированные методы обучения и разрабатывать междисциплинарные образовательные программы [4].

Межпредметная интеграция выступает как важнейший фактор модернизации педагогического образования. Она способствует формированию целостного мировоззрения, развитию системного мышления и повышению мотивации к обучению. Особенно значимой является интеграция математики с другими дисциплинами, такими как физика, информатика, экономика и даже гуманитарные науки. Математика, обладая универсальным языком описания закономерностей, служит эффективным инструментом для анализа и моделирования различных процессов.

В современных условиях учитель перестает быть просто транслятором узкоспециальных знаний. Интеграция рассматривается как:

- **Процесс взаимопроникновения** содержания различных учебных дисциплин;
- **Средство преодоления фрагментарности** знаний обучающихся.
- **Инструмент формирования целостного мировоззрения**, где гуманитарное и естественнонаучное знание дополняют друг друга.

Деятельностный подход также играет важную роль в формировании профессиональной компетентности будущих учителей. Он предполагает активное включение студентов в различные виды учебной и профессиональной деятельности, направленные на решение практических задач. В условиях межпредметной интеграции это может реализовываться через проектную деятельность, кейс-методы, проблемное обучение и педагогические практики, ориентированные на интеграцию содержания различных дисциплин.

Практико-ориентированный подход дополняет деятельностный, акцентируя внимание на применении полученных знаний в реальных условиях. Будущие учителя должны не только понимать теоретические основы межпредметной интеграции, но и уметь реализовывать их в образовательном процессе. Это требует создания соответствующих условий в образовательных учреждениях, включая разработку интегрированных учебных курсов, использование современных образовательных технологий и организацию междисциплинарных проектов.

Для эффективного формирования компетенций можно выделить следующие подходы:

1. **Конвергентный подход:** стирание границ между дисциплинами для решения реальных практических задач (например, методология STEM/STEAM).
2. **Проектно-ориентированный подход:** обучающиеся создают проекты, требующие применения знаний из физики, истории, литературы и информатики одновременно.
3. **Технологический подход:** использование цифровых платформ и интерактивных моделей для визуализации связей между явлениями.

Особое значение имеет развитие методической компетентности будущих учителей. Она включает умение проектировать образовательный процесс с учетом межпредметных связей, выбирать адекватные методы и формы обучения, а также оценивать результаты образовательной деятельности. В условиях интеграции возрастает роль педагогического творчества и способности к инновациям.

Следует отметить, что успешная реализация межпредметной интеграции требует системного подхода на уровне образовательной политики и практики. Необходима

координация усилий преподавателей различных дисциплин, разработка единых методических подходов и обеспечение соответствующей подготовки педагогических кадров. Важную роль играют также цифровые технологии, которые расширяют возможности интеграции и позволяют создавать интерактивные образовательные среды.

Таким образом, формирование профессиональной компетентности будущих учителей в условиях межпредметной интеграции является сложным и многогранным процессом. Он требует использования современных педагогических подходов, обновления содержания образования и активного внедрения инновационных методов обучения. Интеграция математики с другими дисциплинами выступает эффективным средством развития ключевых компетенций и подготовки учителей к работе в условиях современного образовательного пространства.

В заключение следует подчеркнуть, что дальнейшее развитие педагогического образования должно быть направлено на усиление междисциплинарной направленности подготовки учителей, формирование у них готовности к интеграции знаний и постоянному профессиональному росту. Это позволит обеспечить высокое качество образования и подготовить педагогов, способных эффективно работать в условиях быстро меняющегося мира.

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THE ROLE OF STUDENT GOVERNMENT IN FOSTERING STUDENT VOICE IN SECONDARY SCHOOLS

Abstract: This study examines the role of student government in fostering and representing student voice within secondary schools. Drawing on the concepts of democratic education, student agency, representation, and shared decision-making, the research explores whether student government functions as an authentic participatory mechanism or remains primarily a symbolic structure. Using a qualitative case study design, the study is based on three semi-structured interviews with student government members. The findings indicate that student government serves as a formal channel through which students' opinions, concerns, and interests may be collected and communicated to school leadership. However, its influence remains moderate, uneven, and largely dependent on institutional approval. While student government contributes to school life, particularly through events and atmosphere-related initiatives, its capacity to affect broader institutional decision-making is limited by hierarchy, selective participation, weak responsiveness, and internal issues such as low initiative and responsibility. The study concludes that student government can promote student voice, but its effectiveness depends on genuine representativeness, stronger student agency, adult receptiveness, and more responsive decision-making structures.

Keywords: student voice, student government, secondary school, student participation, democratic education, student agency, representation, school leadership, shared decision-making, student self-governance.

Introduction. In contemporary educational discourse, an increasing attention has been directed toward the concept of student voice, considered as an essential element of democratic engagement, inclusive decision-making and educational improvement. Rather than being accepted merely as passive recipients of policies and practices designed by adults, students are recognised as stakeholders whose perspectives, experiences and ideas should be taken into account in the shaping of school life. Within this context, student government - the formal structure through which student advocacy may be organised and participation in educational affairs may be facilitated - has been established into the secondary schools.

Although student government is presented as a mechanism for empowering learners and promoting active citizenship, its actual role in fostering authentic student voice has not always been fully realised. In many instances, opportunities for participation may be limited, symbolic, or primarily consultative, and genuine agency and influence over decision-making processes may not always be consistently granted to students. Consequently, concerns have been

expressed regarding the effectiveness of student government as a platform for the expression of student perspectives, as well as the conditions under which it can meaningfully contribute to school development.

Therefore, this study is intended to examine the role of student government in fostering student voice in secondary schools, with particular attention being paid to the ways in which student participation, representation, and agency are enacted within the school environment. Furthermore, it will identify effective strategies that strengthen the involvement of students in institutional processes. It is expected that the research will contribute to a deeper understanding of how student government may function not merely as a symbolic body, but as an instrument for promoting democratic engagement, shared responsibility and educational transformation.

1.1 Context and Background Information

Over the past two decades, the concept of student voice has been interpreted in markedly different ways; nevertheless, its intellectual genealogy can be traced beyond contemporary reform discourse to longer-standing traditions of democratic education. From a broadly Deweyan perspective, education may be understood not solely as the transmission of knowledge, but as preparation for participation in associated social life, potentially positioning students as subjects of democratic practice [1; 2]. Historically, the contemporary field emerged in the 1980s, while its literature had expanded most intensively between 1990 and 2006, since young people's perspectives came to be regarded as educationally significant rather than marginal to educational inquiry [3]. Moreover, the rights-based turn associated with the United Nations Convention on the Rights of the Child appears to have recontextualized student voice from a largely discretionary practice into a more substantive democratic claim: according to Article 12, children have rights to express views on matters affecting them and to have those views given due weight, while Article 13 protects freedom of expression more [4; 5]. Consequently, by the early 2000s, student voice was increasingly linked to school reform, student engagement, and institutional improvement; significantly, it was no longer seen as sufficient for students merely to be consulted, since authentic participation appeared to require some degree of shared deliberation and action [6; 2]. Student voice extended into higher education and participatory research, where it was increasingly framed in relation to participation, transformation, and empowerment [7]. Yet this expansion did not eliminate the field's tensions: Rudduck and Fielding warned that the growing popularity of student voice could produce little more than surface compliance [8], while Fielding argued for a movement beyond consultation towards partnership and democratic fellowship [9]. Accordingly, student voice appears most persuasive as a democratic tool when it is embedded in everyday decision-making, curriculum and institutional culture, rather than being confined to formal representative structures alone [8; 9; 10].

In Kazakhstan, the discussion of student voting rights is best understood through the longer institutional legacy of Soviet schooling, which left behind a highly centralized, hierarchical, and administratively controlled model of educational governance [11; 12]. After independence in 1991, educational reform became part of a broader state-building and modernization project and the system gradually began to move, at least at the policy level, towards greater institutional responsiveness and civic orientation [12]. This reorientation is reflected in the Law on Education, which defines respect for human rights, the democratic nature of education management, transparency, active citizenship, participation in socio-political and cultural life, and the expansion of institutional autonomy as key principles and goals of the

education system [13]. Additional regulatory changes occurred after Kazakhstan ratified the United Nations Convention on the Rights of the Child in 1994, which formalized the rights of children to participate in society within the framework of the national system [14]. Recently, student participation has become increasingly visible through officially supported structures such as school parliaments and discussion clubs, indicating a greater recognition of the voice of students in school life [15]. At the same time, these forms of participation remain largely formalized and managed by institutions, suggesting that students' voting rights in Kazakhstan have developed more through regulated channels of engagement than fully ascending forms of school democracy [15; 11].

1.2 Problem Statement

The literature suggests that authentic engagement of students in democratic schooling is still complicated to realise within the conventional educational structures, although student voice has become a recurrent concept in discussions. Morrison states that, in many aspects, democratic education conflicts with traditional schooling due to the fact that within hierarchical and highly regulated institutional environments, student voice and student choice's presence cannot be comfortable [16]. Rudduck supports this, claiming that student voice contributes to school reform by two linked strategies: revealing how learning and conditions of learning are faced from students' view, it gives teachers and schools a practical basis for change; it slightly changes student status from passive recipients to active participants that have more collaborative relationships [17]. Nevertheless, in practice this democratic claim often shows weakening. Pereira, Mouraz, and Figueiredo found that participation in school life now is limited to representative and statutorily prescribed forms, whereas student representatives were not significantly meant for schools, which led the authors to highlight the situation as a case of "mitigated democracy" [18]. Therefore, studies mentioned above present that the formal appearance of participation does not always have an impact on substantive student influence better than school or school improvement.

Due to the representative structures, legitimizing participation without reassigning decision-making power in any meaningful sense, this limitation is significant for a student government's study. Mitra argues that student viewpoints overcome a central dilemma of school reform, especially the problem of possession: who is the owner of authority of defining problems of school and who is enabled to improve them [19]. The author then shows that student perspectives may vary from adults just listening to students across interviews and surveys, to collaboration with adults, and finally to student leadership forms; considerably, the most frequent listening-based approaches still enable students to have a minor property of reform processes. Mitra and Gross support this argument, showing that student viewpoint is not equally effective, reception and results of it are conditional due to wider institutional context in which it is pursued [20]. Recent study also considered schools as a grounds for practicing citizenship. Moreover, it has assessed the link between students' experiences of voice and their stance towards democratic listening and contributing [21]. Thus, the fundamental problem that underpins this research is that, though student government is mostly designated as formal mechanism for representing students, it remains vague whether it really promotes genuine student concerns, shared decision-making, and meaningful student agency in secondary schools, or is facilitated primarily as a symbolic formation of consultation with limited practical effect. This relevant issue introduces a clear rationale for observing the real role of student government in promoting student opinions within the school environment.

1.3 Purpose of the Study and Research Questions

The main objective of this research is to explore the effectiveness of student self-governance in promoting student opinions and influencing institutional decision-making. In addition, this study aims to explore whether student government operates as an active and influential institution or merely as a symbolic structure with limited practical impact, so that the attention will be given to the distinct process through which student representatives solicit the opinions of their peers, the methods utilized for communicating these perspectives to school leaders and the extent to which such communication yields tangible changes within the school environment. Consequently, this research is intended to enhance the understanding of how student government fosters the development of student voice and to identify the institutional conditions facilitating and impeding its effectiveness. In this regard, the primary research question is:

To what extent does student government promote and represent the student voice within secondary schools?

What formal and informal mechanisms does student government use to collect, communicate, and advocate students' opinions, concerns, and interests to school leadership?

How do students perceive the effectiveness of student government in influencing institutional decision-making and contributing to improvements in the school environment?

1.4 Significance of the Study

The significance of this research lies in its investigation of student government not solely as a formal institution within secondary schools but as a potential mechanism for promoting, representing and articulating student voice in institutional decision-making processes. While student involvement is broadly acknowledged as a fundamental principle of democratic and inclusive education, the actual capacity of student government to shape school governance remains inadequately explored. Hence, this research seeks to elucidate whether student government functions as a participatory structure or primarily serves a symbolic role.

From a theoretical standpoint, the study's significance remains high as it engages with pivotal concepts such as student voice, representation, agency and shared decision-making. By centering student government as a tangible institutional framework, this research transcends general discussions of participation and instead scrutinizes the mechanisms enabling to gather, express and convey student perspectives to school leadership. Therefore, this study crystallizes the understanding of how participatory practices are implemented within the school context.

Practically, the findings may prove advantageous for school leaders, educators, and policymakers aiming to enhance student participation and improve institutional responsiveness. The research may illuminate both the potentialities and limitations of student government, thereby providing insights into how representative structures can be rendered more effective, inclusive, and impactful. Ultimately, this inquiry is crucial as it seeks to determine whether student voice is genuinely integrated into the fabric of school life or merely acknowledged at a theoretical level.

2. Literature Review

2.1 Student Voice as an Educational Concept

The concept of student voice cannot be reduced to the act of expressing personal opinion within educational environments; rather, it should be understood as a multidimensional and evolving concept, reflecting the extent to which students are able to participate meaningfully in the life of the school and in processes of educational change. According to Mitra, student voice

can be conceptualised as a continuum of participation within school reform, ranging from students sharing their perspectives on problems and possible solutions, to collaborating with adults and ultimately to taking the lead in efforts for change [19, pp. 473–474]. This can be clarified by the fact that student voice is not synonymous with the mere opportunity to speak as it refers to the quality, seriousness and consequences of student participation within educational settings: when students are engaged in sustained and meaningful ways, they may begin to function not as “knowledge creators, not just receivers” [19, p. 474]. Mitra further develops this conceptualisation through the pyramid of student voice, consisting of the three progressive levels of listening, collaboration and leadership [19, p. 474]. A more developed and authentic model, by contrast, requires shared responsibility, adult receptiveness, and genuine access to decision-making processes, thereby defining student voice as a structured and sustained practice. As Mitra notes, Articles 12 to 15 of the Convention on the Rights of the Child frame youth participation in terms of access to information, the expression of views, and the freedom to form collective organisation, emphasizing the significance of student voice that lies in permitting students to speak and in recognising that their perspectives should be heard, treated as legitimate and allowed to influence the institutions that govern their everyday educational experience [19, p. 475]. At the same time, Mitra warns that participation may remain "symbolic or formal" as adults continue to define the limits and conditions of participation [19, p. 476]. Taylor and Robinson develop similar concerns, saying that student voice should be studied from the perspective of authority, and that it has often lacked adequate theoretical framing, particularly regarding the ways in which authority shapes the philosophical assumptions behind participation, as well as the practical limits of what is possible within schools [22]. From this perspective, the student voice is not only an educational concept, but also a political one. The significance of participation depends on whether students are able to impact processes of education, or are they invited to work within the limits set by adults. Even concepts such as dialogue can not be approached without criticism because schools may adopt the language of participation without really changing the fundamental relationships of power [22].

Rudduck points the relationship between the student voice and school reform, saying that the student voice contributes to improvement in two related ways: it puts forward a practical agenda for change that enables teachers and schools to understand learning from the perspective of students and it reshapes the position of students within the school, moving them from the position of passive recipients of educational practices to the position of active participants in a participatory learning relationship [17]. This shows an important conceptual shift because it frames the student voice not as a symbolic addition but as a mechanism for redefining the nature of educational relations. Rudduck's reasoning also suggests that the student voice is most effective when students feel that they are important within the learning community and that they have something to contribute, linking participation to recognition, belonging and partnership, not isolated acts of consultation.

The literature further indicates that the true student voice is often manifested not in formal structures, but in the everyday relational life of the school. Quinn and Owen show that informal pathways, such as daily teacher-student interactions, consultation, and learning collaboration, can enhance student voice more effectively than traditional student council models [23]. This is a very important insight because it reveals that the student's voice is not limited to formal representative mechanisms but may be even more influential when it is woven into everyday practices and relationships. In contrast, Quinn and Owen warn that traditional student leadership

approaches may reproduce formalism or manipulation when they fail to transform adult-student relationships or deep structures of school authority [23]. In this regard, the literature constantly warns about the equality of representation and originality.

Scott reinforces this point with his argument that student governing bodies should not be reduced to organizing events, dances or symbolic events [24]. For student representation to be meaningful, these bodies must express students' views on matters of real educational and social essence, and operate in an environment where school leaders are accustomed to consulting students. Scott also emphasizes that counseling must go beyond the narrow leadership elite to the broader student body, as representative structures gain credibility only when they remain connected to those they claim to represent [24]. This idea expands the concept of student voice to relate it to a sense of educational ownership, belonging to the school community, and a sense that students contribute to shaping education, not just receiving it.

A similar democratic tone is manifested in the works of Fielding, who frames the student voice as a kind of deep democracy based on intergenerational exchange [9]. From this point of view, schools should develop richer partnerships between adults and young people and put participatory democracy at the heart of school life, so that democratic values are embodied rather than just proclaimed. The relevance of Fielding's perspective is manifested in his assertion that democracy in education should be manifested in practical arrangements, institutional customs and everyday orientations. Therefore, the student's voice does not acquire its educational significance when it is celebrated rhetorically, but when it is rooted in the ordinary structures through which school life is organized.

Bourke and MacDonald deepen this relational and cognitive dimension, framing the student voice as a methodological and evaluative principle [25]. According to their reasoning, educational initiatives that affect young people should include the student's voice directly, because students should express their experiences themselves and not be represented by others. This expands the meaning of the student voice beyond councils and leadership roles, and establishes students as legitimate interpreters of educational processes. At the same time, Bourke and MacDonald note that when student-produced evidence challenges official narratives, these voices may be highlighted or silenced, again demonstrating that the student voice is inseparable from issues of authority, legitimacy, and recognized knowledge within education [25].

Finally, the literature connects the student's voice with the problem of separation from school. Smyth argues that as schools are increasingly shaped by systems of accountability, measurement, and high-risk policies, they risk becoming less accommodating environments for students [26]. When students feel that their lives, cultures, and aspirations are neglected, underestimated, or diminished, they may emotionally and educationally withdraw from school life. From this perspective, authentic student voice is a part of a broader effort to build more humane, inclusive, and conversational school cultures.

Taken together, these perspectives indicate that student voice is most accurately conceptualised as a multifaceted educational construct that incorporates participation, authority, legitimacy, partnership, representation, and reform. It denotes not merely the degree to which students are able to articulate their views, but also the extent to which those views are acknowledged as credible, their knowledge is regarded as educationally significant, and their participation is capable of influencing the institutional structures and conditions of education.

2.2 Student Government as a Formal Channel of Participation

Within scholarship on student voice, student government is generally regarded not as participation in its most comprehensive form, but rather as a formalised institutional vehicle through which participation can be structured, articulated, and conveyed. Its importance resides in its capacity to convert scattered student concerns into organised representation by establishing recognised positions, procedures, and forums through which students may gain access to school decision-making processes. In their review of 126 studies, Müller-Kuhn et al. show that student participation is associated with democratic education, children's rights, school well-being, and institutional change, while also emphasising that power relations remain fundamental to the ways in which participation is experienced and enacted [27]. In a comparable sense, Mitra maintains that student voice should be located within broader traditions of youth participation and school reform, in which students may progress from expressing perspectives to collaborating with adults and, in certain cases, to leading change themselves [19]. Understood in these terms, student government may be seen as a formal intermediary between individual opinion and collective agency.

A substantial body of scholarship accordingly positions student government as a potentially significant democratic formation insofar as it confers continuity, visibility, and procedural legitimacy upon student participation. Formal representative structures may enable schools to institutionalise student voice by ensuring that student concerns are not voiced merely in intermittent or informal ways, but are instead articulated through recognised channels of consultation, deliberation, and advocacy. This interpretation is reflected in Beaudoin's work, in which schools are framed as sites where democratic participation may be both cultivated and enacted through structured practices such as student-led conferences, feedback mechanisms, representation in staff appointment processes, and student involvement in school governance [28]. Understood in this way, student government functions as a pedagogical apparatus, with the capacity to foster civic responsibility, a sense of belonging, communicative competence, and a more developed sense of agency.

The literature, however, repeatedly cautions against assuming that the formalisation of participation necessarily gives rise to authentic student voice. Rudduck and Fielding argue that schools may appropriate the discourse of participation through what they describe as "surface compliance", whereby the semblance of consultation is preserved without any serious engagement with deeper questions of power, purpose, inclusivity, or legitimacy [8]. Along similar lines, Robinson and Taylor conceptualise student voice as a contested practice shaped by unequal power relations and by the routine micro-processes through which participation is organised, regulated, and mediated within schools [29]. In their study, Jones and Bubb demonstrate that, in certain schools, opportunities for student voice were concentrated almost entirely within the student council, yet this arrangement contributed only modestly to school improvement, since key dimensions of participation - including who could stand, which issues could be raised, and how priorities were determined - continued to be shaped predominantly by adult authority [10]. Its democratic value is more appropriately assessed in relation to the conditions under which it operates, namely the extent to which it secures genuine representativeness, a measure of institutional autonomy, direct access to decision-making processes, and the capacity for student concerns to be converted into substantive organisational responses.

Recent scholarship has adopted a more exacting view of student government as a formal mode of participation. Patrick suggests that it depends on student government operating on

genuinely democratic principles and on students holding an established place within school leadership itself [30]. Student government is presented, instead, as a legitimate arena in which political participation may already occur within the everyday life of the school. Student representatives should not be understood as merely ceremonial or symbolic spokespersons; as Mitra and Müller-Kuhn et al. suggest, participation acquires educational significance only when it is tied not simply to expression, but to recognition, influence, and the capacity to produce change [19; 27]. What is ultimately at stake, therefore, is less the formal existence of student government than its ability to function as an authentic intermediary between the student body and school leadership.

2.3 Limits of Participation: Tokenism, Hierarchy, and Responsiveness

Although student participation is often presented as evidence of democratic school culture, the literature suggests that the existence of representative structures does not automatically imply meaningful influence. Tokenism has been described as a condition in which participation is symbolically recognised while real power remains unchanged, so that consultation is performed rather than enacted in substantive terms [31]. In school settings, this means that student councils may be established not to share decision-making power, but to create the appearance of inclusion. This concern is supported by Alderson, who found that the mere introduction of a council was not sufficient, since token forms of participation could increase student scepticism rather than trust [32].

The limits of participation have also been linked to institutional hierarchy. Coyle showed that highly hierarchical school structures tend to discourage initiative when authority is concentrated at the top [33]. Although her discussion focused on teacher leadership, this logic is also applicable to student participation, where influence is often mediated by adults rather than exercised independently by students. Similarly, Burnitt and Gunter demonstrated that school councils were often shaped by head teachers through the control of agendas, meetings, and membership [34]. Khan likewise suggested that participation is structured by broader issues of access, autonomy, and control [35], while Saleem and Farooqi found that councils were further limited by selective participation, lack of time, weak motivation, and assumptions about students' incapacity [36]. Taken together, these studies suggest that student voice is often permitted only within boundaries established by adults [33; 34; 35; 36].

A further problem concerns responsiveness, since participation cannot be considered meaningful unless student views are acted upon. Alderson found that although over half of pupils reported having a council, only a small proportion believed that it improved school life, while many noted that councils could discuss only those issues allowed by teachers [32]. This suggests that student participation often remains limited not only by access, but also by the weak institutional response to student concerns. Therefore, the literature indicates that participation becomes ineffective when it is tokenistic in form, hierarchical in structure, and weakly responsive in practice [32; 37; 38].

3. Methodology

3.1 Research Design

This study employed a qualitative case study design in order to explore the role of student government in promoting and representing student voice within a secondary school. A qualitative approach was chosen due to the research that focuses on participants' perceptions, experiences and understanding of student representation rather than on numerical measurement.

Since the research questions address representation, communication mechanisms, and perceived effectiveness, in-depth data was needed.

The study was exploratory and interpretive in nature, as it aimed to examine how student government functions in practice within a specific school context. The research was informed by two main sources: the literature review, providing the theoretical foundation, and three semi-structured interviews, serving as the primary method of data collection. Semi-structured interviews were considered suitable due to the fact that they ensure consistency across participants while also allowing them to elaborate on their experiences. Overall, this design was appropriate as it matched both the aim of the study and the limited scale of the research project.

3.2 Sample

This study used purposive sampling, as participants were selected for their direct involvement in student government. This strategy was appropriate because the research required information-rich participants who were familiar with student representation and communication with school leadership.

The sample consisted of three student government members holding formal representative roles. Their positions allowed them to provide relevant insights into how student voice is collected, communicated, and advocated within the school. Although the sample was small, it was suitable for the qualitative nature of the study, where depth of insight is more important than broad generalisation. At the same time, the small sample size should be recognised as a limitation, since the findings cannot represent the views of all students and should be understood only within the context of this particular study.

3.3 Data Collection

Qualitative data for this study were collected through three in-person semi-structured interviews with members of the student government. Interviews were chosen because they allowed to explore participants' views and experiences regarding how the student government promotes and represents student voice within the school. Face-to-face interviewing was especially useful as it made it possible to ask follow-up questions, clarify responses and explore important ideas in more depth during the conversation [39; 40].

All interviews were audio-recorded with participants' permission. This helped preserve important details and allowed the researcher to concentrate on the discussion instead of relying only on notes. Audio recording also supported more accurate transcription and later analysis of the responses [41].

3.4 Ethical Considerations

Protecting participants' rights, respecting their perspectives, and ensuring the confidentiality of the collected information were treated as central priorities throughout the research process. Since this study explored participants' views on the role of student government in promoting student voice, particular attention was paid to preserving anonymity and avoiding any disclosure of sensitive responses.

Before the data collection process, permission was obtained from the selected school. Additionally, informed consent was collected from all participants before the interviews were conducted. Prior to each interview, the participants were introduced to the purpose of the research and informed that their participation was entirely voluntary. They were also made aware of their rights, including the right to refuse to answer any question and the right to withdraw from the study at any stage without negative consequences.

To maintain confidentiality, all interview recordings were stored in a password-protected folder on the researcher's laptop. In order to protect participants' identities, real names were replaced with codes or pseudonyms during transcription and analysis. This helped reduce the risk of identification and ensured that the data were presented in an ethical and responsible manner.

4. Findings and Discussion

4.1 Data Analysis

The collected data were analysed through transcription, coding, and thematic interpretation. First, all interview recordings were transcribed to create a full written version of participants' responses. This step was necessary because qualitative analysis requires close attention to wording, repeated ideas, and the meanings participants attach to their experiences. After transcription, the data were read several times in order to identify recurring patterns related to student representation, communication with school leadership, and the influence of student government on school life [42].

The transcripts were then coded using ChatGPT as the most available tool in order to organise the data systematically and compare responses across the three interviews. According to Creswell, coding involves dividing data into segments and assigning labels to them in order to develop categories and themes [42]. In this study, coding helped identify the main recurring ideas in the participants' responses. Since the school president's interview largely supported the views already expressed by the first minister, particular attention was paid to similarities across interviews, as these reflected stronger patterns in the data.

After the initial coding stage, similar codes were grouped into broader themes. Creswell suggests that focusing on a smaller number of central themes allows for deeper analysis [42]. Therefore, the data were organised into several key themes related to the role of student government in representing student voice, the ways students' opinions were collected and communicated, and the perceived limits of student influence within the school.

4.2 Findings

Thematic coding of the three semi-structured interviews generated six interconnected themes: (1) Representative role of student government, (2) Partial and uneven representation of student voice, (3) Mechanisms for collecting student voice, (4) Communication and advocacy as a hierarchical process, (5) Perceived impact on the school environment, (6) Barriers to effective student voice representation. These codes were then grouped under the three research questions. Overall, the findings indicate that student government in this school does function as a formal channel of student voice, nonetheless, its representational scope and practical influence remain conditional, uneven, and strongly mediated by hierarchy. This general pattern closely aligns with the literature that conceptualises student government as a potentially significant but inherently limited formal structure whose democratic value depends on representativeness, institutional autonomy and the extent to which student concerns lead to substantive responses.

4.2.1 RQ1: To what extent does student government promote and represent the student voice within secondary schools?

The codes clearly related to this research question were the representative role of student government and the partial and uneven role of student voice. Across the interviews, student government was conceptualized as the body representing student voice rather than one that exercises independent authority. Participant 1 portrayed his role as less visible and less directly connected to student demand, remarking in effect that "In our department, student voice is not

representative as students usually go to the ministries that organise entertaining activities." Another participant similarly noted that "Student government is there to speak for students, but mostly it works as a link between students and the people above us." These findings strongly support the literature review, as student government is not framed as the fullest realisation of participation, but rather as a formal intermediary between individual student views and institutional decision-making [19; 27].

The second theme concerned the extent to which student government was perceived to reflect the voices of the wider student body. The interviewees suggested that this representation was moderate and uneven rather than broad and fully inclusive. One participant commented, "I would say the level of representation is somewhere in the middle. It is not completely weak, but it is not strong enough to say that all students are equally reflected." Another similarly observed that "Some student opinions are heard more than others and some areas naturally get much more attention." A third participant added, "Not every student comes with ideas and not every opinion reaches the final stage." This finding strongly correlates with the literature. The review argues that student government should be understood as a formal intermediary between individual opinion and collective agency rather than as participation in its fullest form, and that its value lies not merely in existing, but in whether it secures genuine representativeness and remains connected to the broader student body rather than a narrow leadership elite.

4.2.2 RQ2: What formal and informal mechanisms does student government use to collect, communicate, and advocate students' opinions, concerns, and interests to school leadership?

The codes linked to the second research question were the mechanisms for collecting student voice and communication and advocacy as a hierarchical process. As one participant explained, "We usually collect students' opinions through forms and through discussions in parliament. These are the main ways we understand what students want." Another noted that "The easiest way to gather many opinions at once is through forms or surveys, because then we can see what students actually think." A third interviewee stressed the value of the collective forum, stating, "Parliament is important because different representatives can discuss what students are asking for." These responses suggest that student voice collection in this school is relatively structured and institutionalised. The context analysis emphasised that student government may function as a formal vehicle, transforming students' concerns into organised representation through specific procedures and forums [28; 27]. At the same time, literature suggests that formal structures, informal relational practices embedded in everyday school life can strengthen authentic student voices. By contrast, the interviews in this study revealed far more evidence of formal mechanisms than of informal everyday dialogue, indicating that the school is stronger in procedural consultation than in cultivating a broader participatory culture.

The fourth theme concerned the ways in which student proposals were communicated, reviewed, and advanced within the school governance structure. The interview data revealed a distinctly layered and hierarchical decision-making process, in which student suggestions were not moved directly towards implementation but were instead subjected to internal discussion, wider deliberation and only then possible consideration for action. As one participant noted, "When students share ideas, they are discussed first, then taken further, and only after that can they be considered seriously." A similar view was expressed by another interviewee, who described the process as dependent on support and formal approval: "We can discuss ideas, but before anything happens, we have to see if they are supported and if they can actually be

approved." This constraint was articulated even more directly by a third participant: "Our task is to bring ideas forward, but we cannot make them real by ourselves." Taken together, these responses suggest that, although channels of advocacy were present, they operated within a framework shaped less by student authority than by procedural filtering and institutional dependence.

Robinson and Taylor describe participation as being shaped by asymmetrical power relations and by the administrative practices through which it is regulated [29], while Rudduck and Fielding caution that schools may preserve the appearance of participation without redistributing meaningful decision-making power [8]. The findings strongly support these claims. Although student perspectives were clearly admitted into institutional discussion, their movement towards implementation remained conditional upon successive stages of validation. For this reason, the communicative structure observed here is more convincingly interpreted as regulated consultation than as participatory co-governance. Student voice, therefore, appeared to be formally acknowledged, yet not sufficiently empowered to exert substantial influence over final decisions.

4.2.3 RQ3: How do students perceive the effectiveness of student government in influencing institutional decision-making and contributing to improvements in the school environment?

With regard to the third research question, the effectiveness of student government was perceived as real, yet distinctly limited in scope. Although some contribution to school life was acknowledged, such influence was represented as selective rather than systemic, being exercised more visibly in relation to school atmosphere than to institutional decision-making itself. The clearest example concerned a school night event for senior students, which was repeatedly identified as evidence that student preferences could, under certain conditions, be translated into practice. As one participant noted, "That event is one of the best examples, because students had wanted it before, but only this year it finally became real," while another remarked that "similar ideas had existed before, but they were not implemented." It was thus suggested that student government was capable of producing tangible outcomes, particularly where student experience and school climate were concerned. At the same time, however, such influence was not perceived as extensive, since, as one interviewee stated, "its effectiveness is moderate" and it "does not always have enough power to influence bigger decisions." In this respect, the findings both support and complicate the literature: although a degree of agency and school engagement was indeed reflected in the data [19; 28], Scott's concern that student bodies may be confined to event-based or symbolic functions was also strongly borne out [24].

This limited effectiveness was further explained through the barriers by which student representation was constrained. Institutional dependence emerged as a major factor, since student-backed proposals were described as remaining contingent upon adult approval. As one participant observed, "Even if students support an idea, it still depends on whether it is approved," whereas another stated that many initiatives fail because they are "considered impossible to realise." These accounts suggest that student government was not perceived as an autonomous decision-making body, but rather as a mediated structure whose influence remained conditional. At the same time, internal limitations were also identified, including weak responsibility, low initiative, and instrumental participation. One participant remarked that "if people are not responsible, then even a good structure will not work properly," while another more critically noted that some students participated because "they want a certificate at the end

of the year." The findings therefore indicate that effectiveness was constrained not only by hierarchy, but also by fragile team dynamics. This corresponds closely with the literature on tokenism, weak responsiveness, selective participation, and limited autonomy [31; 32; 35; 36]. Taken together, these data suggest that student government functioned as a formal yet limited mechanism for voicing student concerns and occasionally taking action to address them, but it only partially achieved significant institutional influence.

Conclusion. Subsequent investigations may broaden this study by encompassing a more diverse array of educational institutions, participant samples and contrasting organizational frameworks. Such expansion would facilitate a thorough assessment of whether student government operates as a genuine structure or remains formal in practice. Nonetheless, the current research is constrained by limitations due to its reliance on a small qualitative sample, a restricted institutional context and interview, influenced by subjective interpretations. Consequently, the results should be regarded as contextually specific rather than universally applicable.

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EFL TEACHERS' BELIEFS AND PRACTICES IN DIFFERENTIATED INSTRUCTION WITHIN INCLUSIVE KAZAKHSTANI SCHOOLS

Abstract: This study examines the understanding of differentiated instruction by teachers who teach English as a foreign language in mainstream schools and how it is implemented in an inclusive classroom. Although formally differentiated learning is accepted, there is little research in real classroom practice in schools in Kazakhstan, especially in the context of teaching English as a foreign language. This study used a qualitative research approach using semi-structured interviews with English as Foreign Language (EFL) teachers, and three teachers consented to classroom observation with a prepared checklist. Using a thematic analysis based on the six-phases framework by Braun and Clarke (2006), five main themes were identified: teachers' experiences in inclusive classrooms, their perspectives toward differentiated instruction, and the strategies they use within the classroom. Further themes included: the insufficiency of the official English language materials provided by the Ministry of Education and Science (MoES) in differentiated teaching and the obstacles to implementation. The results studied showed that although most teachers demonstrated their understanding of inclusivity and differentiated learning, observations made in classrooms revealed a significant gap in teachers' actual practice. The existing English as a Foreign Language (EFL) materials were intended for the average student and the absence of any differentiated teaching methods led to the conclusion that they were unsuitable for inclusive classes. Teachers mentioned time constraints, insufficient professional training, large classroom sizes, and little institutional support as the main obstacles to effective implementation. The results of the study showed that systematic reform is necessary in order to bridge the gap between the policy and real classroom experience. Moreover, it is important to emphasize the systematic reform of the Ministry of Education and Science (MoES), including the development of English as a Foreign Language (EFL) materials, professional qualification programs in differentiated instruction and strengthening institutional support.

Keywords: inclusive education, differentiated instruction, teachers' perspectives, diverse learners, English as a Foreign Language (EFL), classroom implementation, mainstream schools.

Introduction. Over the past decades, inclusive education has become a global concern. The adoption of the The Salamanca Statement and Framework for Action on Special Needs Education (UNESCO, 1994) and the UN Convention on the Rights of Persons with Disabilities (Sixty-first session of the General Assembly by resolution A/RES/61/106, 2026) has reinforced that every child, regardless of their disability, has the right to an education on an equal basis with all others. Kazakhstan, following the global model of education, also adopted the Law of the Republic of Kazakhstan No. 319-III 'On Education' in 2007. This state programme,

approved for the period 2020–2025, aims to reduce the gap in educational quality between schools, introduce inclusive education and support learners with special needs in mainstream schools. Meanwhile, the concept of differentiated instruction, developed by Carol Ann Tomlinson, has begun to be adopted within the global education system. The core idea is that teachers should not structure lessons around the needs of the 'average' student, but rather adapt them to each learner's level of proficiency and interests. In terms of teaching English as a Foreign Language (EFL), differentiated instruction is especially important: language classes tend to be heterogeneous, with students in the same group possessing different levels of language competence, cognitive characteristics, and even officially diagnosed developmental delays. The Kazakhstani education system is undergoing significant changes: the transition to an updated educational curriculum, a trilingual system and a criteria-based assessment system. In this regard, an empirical study is needed to address an important question: to what extent do EFL materials and teachers' competences meet the needs of inclusive classrooms?

Problem statement. Although the principles of inclusive education are formally recognised and there is a rising amount of research on differentiated instruction, the gap between established educational theories and classroom practice in Kazakhstan has not been sufficiently explored (Sengerbekova et al., 2024). The adaptation of EFL materials provided by the Ministry of Education and Science (MoES) of the Republic of Kazakhstan to incorporate differentiated strategies and its use in inclusive classrooms has not been sufficiently addressed in the academic literature (Sultanbekova, 2019). Additionally, the practical experience of English teachers in this area has not yet been thoroughly studied: how they understand the concepts of inclusive and differentiated teaching, how they adapt teaching materials, and what systemic and methodological challenges they face in their everyday practice. Filling this gap is crucial, as teachers are the primary drivers of inclusive education - it is their attitudes and actions that determine the actual learning outcomes of students (Beacham&Rouse, 2012; Islam et al., 2019).

Research objectives and questions. The aim of this study is to define the extent to which English teachers in mainstream schools in Kazakhstan understand and implement the principles of differentiated instruction within an inclusive education setting, as well as to identify the factors that determine the effectiveness or ineffectiveness of these strategies. According to this objective, this research paper addresses the following questions:

1. How do English as a Foreign Language (EFL) teachers understand and interpret the concepts of inclusive education and differentiated instruction ?
2. How do EFL teachers evaluate the effectiveness of materials for diverse learners provided by the Ministry of Education and Science (MoES)?
3. How do EFL teachers practically implement differentiated instruction and adapt teaching materials in real classroom settings?
4. What barriers do EFL teachers face implementing differentiated instruction, and how do they believe it affects student productivity?

Literature review. The concept of inclusive education is the subject of widespread debate and provokes a range of opinions within society. It is well known that teachers' views play a significant role in inclusive education. This literature review examines existing research in this field, beginning with a discussion of the concepts of inclusivity and a comparison of differentiated instruction with alternative approaches. Finally, it outlines how English as a Foreign Language lessons are organised for learners with diverse needs.

The term ‘inclusive education’ has expanded over time (Lindsay, 2023) and now has multiple interpretations. Ainscow (2013) explains the term in both narrow and broad notions. According to his work, while in the narrow sense inclusion is seen only as an example of learners with disabilities in a mainstream school, in a broader sense it is seen as the diversity of students. A broad consideration of the concept causes concern and anxiety, and Florian (2008) prefers not to acknowledge it in this context. This is because if inclusion is seen solely as the diversity of students, their individual educational needs are ignored. It addresses creating accessible and quality learning environments where students are supported, respected and valued. As Mitchell (2015) notes in his paper, inclusive education is not only about bringing students with special needs into mainstream classrooms, but also about effective inclusive education planning and meeting the individual educational needs of students by paying attention to different aspects of the educational system. These aspects include an adapted curriculum, assessment and teaching, resources, leadership, vision and support.

In the context of Kazakhstan, inclusive education is one of the key priorities for the development of the education sector. Its implementation began in 2011, but the scope of inclusion is limited to SEN, as local schools have not completely switched to inclusive education. “As of 2021, 11% of pre-school children with SEN in Kazakhstan attended special groups in regular kindergartens and 13% studied in special kindergartens” (UNICEF Kazakhstan, 2024). Currently, 1,286 schools have organised inclusive education for 15,721 children. 1,429 children attend 98 kindergartens alongside their peers without special educational needs. Despite the increasing number of educational institutions offering inclusive education or special correction schools, all of them focus solely on physical accessibility. However, the implementation of inclusive education is an extremely complex process, requiring not only the redesign of access routes, but also the training of competent specialists to work in schools and the acceptance of the idea that every individual is unique (Baimenova and Zhubakova, 2015). Researchers have also identified a number of challenges associated with the implementation of inclusive education principles in the educational process between 2020 and 2023. The primary reason is that teachers wish to undergo specialised training before implementing inclusive education into the classroom (Agavelian et al., 2020; Yusupova and Isabaev, 2021). In addition, Turlubekova and Bugubayeva (2021) note that there is a lack of specialists who could provide support to children requiring special needs.

Studying teachers' attitudes towards inclusive education is important because lack of understanding of the concept hinders its implementation (Islam et al., 2019), whereas an awareness of these attitudes is a key source of improving the quality of inclusive education (Beacham&Rouse, 2012). Teachers in Kazakhstan had a neutral attitude towards inclusive education. As Aubakirova et al. (2020) have conducted a survey in the region of Pavlodar in 2020 involving 416 participants, 255 of whom had never experienced an interaction with a person with special needs, and 324 had not received special training in teaching people with special needs. Overall, teachers do not feel uncomfortable or stressed when children with special educational needs are present in the classroom, rather, they are concerned about lacking the necessary knowledge and skills to educate such children.

Today, English is known as the most leading international language (Dotter, 2008; Weber, 1999). The value of the English language is widely known in the world among different cultures, nations and various language speakers as it has become a great instrument for global communication, academic and professional work purposes (Omonova & Anarkulova, 2025). In

2007, the first President of Kazakhstan, Nursultan Nazarbayev, introduced the program "The Trinity of Languages" to promote multilingual development (MoES, 2010). Furthermore, the Kazakhstani Ministry of Science and Education revised the policy and English became a compulsory subject in all schools starting from Grade 1 (MoES, 2013; OECD, 2014).

Students differ in terms of their learning styles, how they process information, personal experiences, self-confidence as learners, cultural and national backgrounds, and various other factors. All of these characteristics directly influence how a student learns and to what extent they can fulfil their potential as a learner. Therefore, teachers must understand these differences and be skilled in finding the right approach for each student. Differentiated instruction is key to achieving this. Tomlinson (2000) describes this concept as follows: "Differentiation can be accurately described as classroom practice with a balanced emphasis on individual students and course content". There are four main elements that teachers can modify in their teaching. As Tomlinson (2000, as cited in Callahan & Hertberg-Davis, 2017) outlines, these are: "(1) content - what the student needs to learn or how the student will get access to the information; (2) process - activities in which the student engages in order to make sense of or master the content; (3) products - culminating projects that ask the student to rehearse, apply, and extend what he or she has learned in a unit; and (4) learning environment - the way the classroom works and feels".

While differentiated instruction involves adaptive adjustments guided by the teacher, it is the most effective teaching approach in use today. Among modern pedagogical approaches, concepts such as Universal Design for Learning and adaptive teaching are on par with differentiated instruction. Universal Design for Learning (UDL) is based on the principle of meeting the needs of all learners to the maximum possible extent (Kennette & Wilson, 2019). The goal of universal design and differentiation is the same: to nurture expert learners (Morris, 2018) who are ready to grow and succeed. Modern English classrooms include learners from varied backgrounds such as cultural, socioeconomic, educational, linguistic. Kazakhstan is the world's ninth largest country with high diversity, and Kazakhstan is adopting inclusive education through ministerial reforms and policy changes (Rollan & Somerton, 2019). However, Sengerbekova et al. (2024) states that there is little known about EFL classroom and teacher's attitude, although it has great significance.

Methodology. A qualitative approach to data collection was chosen for this study. This method is research-oriented and allows for the exploration of aspects that can only be revealed through qualitative methods. The qualitative design is also appropriate because of its ability to provide a comprehensive description of a complex phenomenon. This offers an effective way of examining EFL teachers' perspectives and challenges regarding differentiated instruction, how they implement it in inclusive classrooms, and the strategies and practical difficulties teachers encounter.

Data collection methods. Data was collected using two methods: semi-structured interview and observation. Participants were recruited using purposive sampling. An advertisement was posted in teacher group chats, including the description of the purpose of the study and the primary criteria - experience working in an inclusive classroom. Ten teachers, who met the requirements, voluntarily agreed to participate.Ten eligible teachers chose to take part in the study on a voluntary basis.

Semi-structured interviews were conducted both via online and face-to-face meeting. This format of the interview allowed the researchers to ask additional questions and clarify answers as needed. Observation was conducted in order to justify consistency between the teachers'

responses in the interviews and their actions in the actual classroom. Three of the interviewed English teachers agreed to be observed in their classrooms. The observation was conducted using a pre-prepared checklist and determined whether differentiated teaching methods were used and how it was implemented in lessons in inclusive classes.

Data analysis techniques :

The data showing the teacher's perspective regarding differentiated instructions were collected through interviews where thematic coding was used to analyze the responses. The thematic coding process went through a six-phase framework based on Braun and Clarke (2006). The responses were gathered through semi-structured interviews in both online and face-to-face formats. During face-to-face interviews, the research team took handwritten notes and used a "voice recorder" to ensure accuracy and completeness of the data. The recordings turned into transcriptions and documents so the researchers could dive into the content deeply.

Findings. Analysis part of the research used an inductive and conceptual approach designed by Braun and Clarke (2006). Through this thematic analysis, five common aspects emerged in the teachers' responses, which were then examined elaboratively; (1) Teachers' Experiences with Inclusive Classrooms, (2) Attitudes toward the Effectiveness of Differentiated Instruction, (3) Differentiation in the classroom (4) Mismatch of official English Foreign Language (EFL) materials, (5) Barriers to Implementing Differentiated Instruction.

Theme 1: Teachers' Experiences with Inclusive Classrooms

This topic revealed that school teachers had direct practical experience of working with classes comprising pupils with diverse profiles. ***Teacher 5***, shared the difficulties they encounter in daily lessons:*"I have worked with a student with a mental development delay. Compared to his peers, he struggled to acquire the lesson's topic as he had problems with memorising the content."* ***Teacher 10*** stated: *"In my class, there are so many students with different levels. Also, there are gifted students... it's not only about students with special needs or students with learning needs but also students with a proficient level of English."*

Theme 2: Attitudes toward the Effectiveness of Differentiated Instruction

Teachers shared that adapting tasks to students' needs generally had a positive impact. ***Teacher 2*** put it directly as follows: *"Easy tasks reduce anxiety among weaker students, while challenging tasks maintain interest among stronger students. Without differentiation, many students lose motivation."* ***Teacher 4*** supported this view: *"When tasks are tailored to students' abilities and learning styles, they become active and motivated. Moreover, differentiation is crucial for the emotional safety of the classroom."*

Theme 3: Differentiation in the classroom

Teachers efficiently use a variety of differentiated teaching strategies, adapting the structure and format of teaching materials in accordance with the needs of the students. ***Teacher 1*** uses larger fonts, adds pictures, or reduces the number of exercises for weaker students. ***Teacher 9*** explained: *"I also divide worksheets into two categories — one for stronger students and one for weaker students - without labeling them as such, to prevent bullying while still adjusting to their levels."*

Theme 4: Mismatch of official English as a Foreign Language (EFL) materials

Participants expressed their dissatisfaction with the teaching materials developed by the Ministry of Education and Science (MoES) of the Republic of Kazakhstan, noting that they are inadequate for use in inclusive classrooms. ***Teacher 1*** stated: "*The official textbooks do not support very slow or very fast learners. There are almost no adapted tasks, so I often create my*

own materials, which takes a lot of time.” ***Teacher 2*** added: “*The textbooks and materials are often too difficult for students' actual levels. Grammar and skill expectations are too high.”*

Theme 5: Barriers to Implementing Differentiated Instruction

Teacher 1 outlined: “*With 17 students, it is hard to prepare different tasks for everyone ... making three versions of one worksheet takes hours.*” ***Teacher 8*** supported this opinion:

“*... and every time I prepare them (materials), I end up spending the whole night there. One night for a student project*.”

Classroom observations. Three teachers were observed. **Teacher 1** provides all pupils with the same materials and tasks, and does not prepare separate materials in advance for these two students. In the writing part, the teacher provided a template and set the same requirements for written work for everyone. **Teacher 1** provided the same level of assistance to all learners - students frequently asked for words to be translated. The teacher did not approach either of the two students and did not offer any help or support. **Teacher 2** skipped an immigrant student who joined the lesson late, and there were no alternative tasks or pre-adapted materials (text, transcript, visual aids). In the productive skills component, the teacher provided students with a writing template and with a paper where were written assessment criteria for a letter-writing task. However, no tiered variants were offered for students who struggle with beginning the writing task. **Teacher 3** used the same worksheets for all students, and no tiered or differentiated tasks were distributed for those who had lower-level English.

Discussion. All teachers participating in the interview and observation reported about their experience with diverse learner profiles directly. It includes learners with attention difficulties, cognitive delays, visual impairments, and students with diverse levels of English proficiency. A notable thing that research has investigated was that teachers identified students with special educational needs through their own observation. It shows lack of formal notification from school administrators. This finding also matches with the conclusions of Turlubekova and Bugubayeva (2021), according to which inclusive schools often lack qualified specialists.

One of the conclusions of the observations obtained from the interviews is the contradiction between the responses of EFL teachers and their practical experience in the inclusive classroom. All the three teachers stated that they would use techniques that address the needs of the students, that the worksheets they would bring to the classroom would be adapted to the student's level. The contradiction of their responses was analyzed from the observations of the researchers. In the lesson, all students received the identical materials, despite their different backgrounds. Differentiation was limited with translating tasks into the students ' native language and by supporting them with verbal prompting. This case exemplifies the theory of Ainscow (2017) that argues about the difference in integration: physically placing a student in a mainstream classroom while failing to adapt to an inclusive environment in practice.

Teachers express their dissatisfaction regarding the English textbooks provided by MoES, saying that they are oriented on an “average” learner, also these book materials are grammatically aimed higher than real proficiency levels of students. That is one of the reasons that teachers cannot adapt materials that are themselves unsuitable. This finding is consistent with what Sultanbekova (2019) critiqued, that even curriculum designed specially for students with SEN missed crucial details about content, learning objectives and expected results for EFL learners with hearing impairment.

Limitations and areas for future research. During the interpretation of this study's findings, some limitations should also be taken into account. Although the sample consists of teachers from various regions of Kazakhstan, it does not fully reflect the diverse teaching conditions in a representative manner. Classroom observations were limited to three visits per teacher, which does not provide a complete picture of their daily teaching practices. Furthermore, conducting interviews in English regarding participants' English language proficiency may limit the depth of their responses. As for future research, it is important to investigate professional development programmes designed to support teachers working in inclusive classrooms, as the discrepancy between academic preparation and practical requirements has been identified as a key challenge. Furthermore, in the context of Kazakhstan, it is essential to study quantitative or mixed methods.

Conclusion. The study aimed to investigate how EFL teachers understand and apply differentiated instruction in inclusive schools in Kazakhstan, as well as to identify the factors that hinder its effective implementation in practice. The results of the study showed that most participants have a fundamental understanding of inclusion and differentiated instruction. Classroom observations, however, revealed a significant gap between the strategies described and their actual implementation: during interviews, all three teachers stated that they use differentiated teaching, but in practice this is not very evident. The teaching materials provided by the MoES were considered unsuitable for an inclusive classroom: they are oriented towards the 'average' learner and do not contain specifically differentiated individual tasks. Teachers cited a lack of time, large class sizes, a lack of professional training and insufficient support from the school as the main obstacles to the implementation of differentiated teaching. Therefore, the main problem is the gap between educational policy and the actual conditions necessary for its implementation. The effective implementation of inclusive education in Kazakhstan requires the following measures: a review of teaching materials to take account of the needs of different classes, the development of specialised training programmes for English teachers, and the provision of systematic support. These conditions must be met if the stated principles of inclusion are to become a reality in every EFL practice.

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ҚАЗАҚ ТІЛІ ЖӘНЕ МАТЕМАТИКА ПӘНДЕРІНІҢ ОҚУ МАТЕРИАЛДАРЫН КІРІКТІРЕ ОҚЫТУ

Аннотация: Бұл мақалада қазақ тілі мен математика оқу материалдарын кіріктіре оқытудың әдістемелік негіздері мен оның білім сапасын арттырудағы маңызы қарастырылады. Қазіргі білім беру жүйесінде пәнаралық байланыстың тиімділігі мойындалғанымен, тілдік құзыреттілік пен математикалық ойлауды ұштастырудың нақты критерийлері мен диагностикалық әдістемелері әлі де жеткіліксіз. Мақалада осы мәселені шешу үшін оқушылардың мәтіндік есептерді талдау және логикалық модельдеу дағдыларын бағалауға бағытталған жаңа зерттеу тәсілі ұсынылған. Бұл әдістеме диагностикалық тапсырмалар мен нақты бағалау индикаторларына негізделген. Зерттеу нәтижелері пәнаралық интеграцияның оқушылардың функционалдық сауаттылығын арттыруға және күрделі есептерді тиімді шешуге оң ықпал ететінін негіздейді.

Кілт сөздер*:* пәнаралық интеграция, қазақ тілі мен математика, зерттеу әдістемесі, логикалық ойлау, функционалдық сауаттылық, оқу материалдарын кіріктіру.

Кіріспе. Заманауи білім беру кеңістігіндегі басты басымдық – оқушының алған білімін өмірлік жағдаяттарда қолдана алуы, яғни оның функционалдық сауаттылығын қалыптастыру. Математиканың қатаң логикалық заңдылықтары мен қазақ тілінің лингвистикалық жүйесін бір-бірінен оқшау қарастыру оқушының әлем туралы тұтас түсінігінің қалыптасуына кедергі келтіреді. Тәжірибе көрсеткендей, оқушылардың мәтіндік есептерді шығарудағы қиындықтары көбінесе математикалық амалдарды білмеуден емес, есеп шартындағы тілдік конструкцияларды дұрыс интерпретациялай алмаудан туындайды. Осы орайда, қазақ тілі мен математика материалдарын кіріктіре оқыту — білім алушының ақпаратты талдау, өңдеу және логикалық модельге айналдыру қабілетін дамытудың басты тетігі болып табылады.

Ғылыми-әдістемелік әдебиеттерде пәнаралық интеграцияның тиімділігі жан-жақты дәлелденгенімен, қазақ тілі мен математика пәндерінің мазмұнын біріктірудің нақты диагностикалық құралдары мен бағалау индикаторлары әлі де жүйелі түрде қарастырылмаған. Көптеген зерттеулерде интеграция тек сабақ үстіндегі фрагменттік байланыстармен шектеліп, екі пәннің когнитивті әлеуетін толық пайдаланудың әдістемелік тетіктері назардан тыс қалып отыр. Бұл олқылық оқушылардың математикалық терминдерді ана тілінде дұрыс қолдануына және күрделі мәтіндік тапсырмаларды шешу стратегияларын меңгеруіне кері әсерін тигізеді.

Осы мәселені шешу мақсатында мақалада қазақ тілі мен математика материалдарын кіріктіре оқыту негізінде оқушылардың есеп шығару дағдыларын зерттеуге бағытталған жаңа әдістемелік тәсіл ұсынылады. Бұл әдістеме лингвистикалық-логикалық диагностикалау мен нақты бағалау критерийлеріне сүйене отырып, оқу үдерісіндегі пәнаралық байланыстың тиімділігін практикалық тұрғыдан дәлелдеуді көздейді. Жүргізілген зерттеудің нәтижелері мен ұсынылып отырған бағалау құралдары мектеп тәжірибесінде білім алушылардың аналитикалық ойлау қабілетін арттыруға және пәнаралық интеграцияның жаңа үлгілерін қалыптастыруға мүмкіндік береді.

Зерттеу әдістемесі. *Зерттеудің объектісі* – оқушылардың мәтіндік математикалық есептерді талдау және оларды шешу дағдылары. Зерттеу барысында оқушылардың есеп шартындағы тілдік құрылымдарды түсінуі, логикалық ойлау деңгейі және мәтіндік ақпаратты математикалық модельге айналдыру стратегиялары зерделенді.

Зерттеудің пәні – қазақ тілі мен математика оқу материалдарын кіріктіру негізінде оқушылардың есеп шығару қабілетін дамыту әдістемесі. Бұл әдістеме математикалық есептерді тек сандық амалдар ретінде емес, лингвистикалық талдау мен логикалық байланыс арқылы шешуге бағытталған. Мұндай тәсіл оқушылардың функционалдық сауаттылығын арттырып, күрделі мәтіндік тапсырмаларды саналы түрде орындауға мүмкіндік береді.

Зерттеу базасы мен қатысушылары. Тәжірибелік зерттеу Талдықорған қаласындағы «Достық» білім беру орталығында жүргізілді. Зерттеуге математика мен логика курстарына қатысушы 5-6 сыныптың 52 оқушысы қатысты (5-сынып: 8 оқушы, 6-сынып: 18 оқушы). Бұл қатысушылардың таңдалу себебі — олардың математикалық терминологияны ана тілінде меңгеруінің маңызды кезеңінде болуы және мәтіндік есептермен жұмыс істеу дағдыларының әртүрлі деңгейде қалыптасқандығы.

Зерттеу барысы. Зерттеу барысында оқушылар топтық және жеке жұмыс нысандарында тапсырмалар орындады. Сабақ үдерісінде математикалық амалдарды орындамас бұрын, есептің шартына лингвистикалық талдау жасау (негізгі сөздерді табу, логикалық байланыстарды анықтау) әдістері қолданылды. Бұл оқушылардың тілдік түсінігі мен математикалық логикасының өзара әсерін салыстыруға мүмкіндік берді.

Оқушылардың мәтіндік есептерді талдау деңгейін бағалау.

Зерттеу барысында оқушылардың мәтіндік есептерді шығару дағдыларына сапалық талдау жасалды. Нәтижелер көрсеткендей, білім алушылардың есептеу сауаттылығы жоғары болғанымен, есептің лингвистикалық құрылымын түсінуде айтарлықтай кедергілер бар (1-кесте).

Кесте 1 – Оқушылардың мәтіндік есептермен жұмыс істеу дағдыларына талдау

Зерттелетін дағды	**Қалыптасу деңгейі**	**Негізгі қиындықтар мен қателіктер**
Оқу сауаттылығы	Жоғары	Мәтінді механикалық оқу басым, ақпаратты іріктеу (маңызды және артық деректерді ажырату) қабілеті төмен.
Тілдік-логикалық талдау	Төмен	«Есе артық», «соншаға кем» секілді логикалық операторларды математикалық символдарға

		трансформациялаудағы қателіктер.
Математикалық модельдеу	Орташа	Сөйлемдегі логикалық байланысты теңдеу немесе өрнек түріне аударудағы концептуалды қиындықтар.
Есептеу сауаттылығы	Жоғары	Дайын алгоритмдер мен формулалар бойынша арифметикалық амалдарды қатесіз орындау.

Зерттеу кезеңдері. Анықталған когнитивтік және лингвистикалық кедергілерді еңсеру мақсатында біз эксперименттік топтарда «Тілдік сүзгі» (Linguistic Filter) әдістемесін сынақтан өткіздік. Бұл технология оқушының есепті шешу алгоритмін үш деңгейлі рефлексиялық процесс арқылы құруды көздейді: Семантикалық деконструкция → Математикалық кодтау → Рефлексия.

Төменде пәнаралық кіріктіруді қамтамасыз ететін авторлық тапсырмалар үлгісі ұсынылады:

1. Комбинаторика мен лингвистикалық шектеулердің өзара байланысы

Тапсырма: {А, Б, А, Й} әріптер жиынтығынан 4 таңбалы неше комбинация құруға болады? Егер «А» әріптерінің қатар келмеуі шарт болса, шешім қалай өзгереді?

Әдістеменің қолданылуы: Оқушы «Тілдік сүзгі» арқылы «қатар келмейді» деген лингвистикалық операторды бөліп алады. Бұл жерде тілдік шектеу тікелей математикалық логикаға әсер етеді. Оқушы жаттанды формуладан (4!) бас тартып, әріптердің орналасу ретін семантикалық тұрғыдан талдайды, бұл абстрактілі ойлауды белсендіреді.

2. Ақпараттық жүктемені басқару және семантикалық іріктеу

Тапсырма: Автобус Талдықорғаннан Алматыға сағат 08:00-де шығып, 250 км жолды 60 км/сағ жылдамдықпен жүріп өтті. Салонда 15 жолаушы болса, автобус межелі жерге неше сағатта жетеді?

Әдістеменің қолданылуы: «Ақпараттық сүзгілеу» кезеңінде оқушы мәтіндегі релевантты (жылдамдық, қашықтық) және релевантты емес (жолаушылар саны, шыққан уақыты) деректерді жіктейді. Бұл тәсіл оқушының когнитивтік жүктемесін азайтып, есептің логикалық қаңқасына назар аударуға мүмкіндік береді.

3. Этноматематикалық контекст және концептуалды трансформация

Тапсырма: Дәстүрлі «мүшел» (12 жыл) ұғымын қолдана отырып, пропорция құрыңыз. Атасы 5 мүшелден 3 жас асса, ал немересі 1 мүшелге толмаған (9 жаста) болса, олардың жас айырмашылығы қандай?

Әдістеменің қолданылуы: Мұнда «Лингвистикалық дешифрлеу» процесі жүреді. Оқушы «мүшел», «асса», «толмаған» сияқты этно-мәдени концептілерді математикалық символдар мен теңсіздіктерге аударады. Бұл математикалық білімді оқушының төл мәдениетімен байланыстырып, функционалдық сауаттылықты жаңа деңгейге көтереді.

Тұжырым: Кіріктірілген оқыту жағдайындағы «Тілдік сүзгі» әдістемесі оқушының мәтінмен жұмыс істеу мәдениетін қалыптастырып қана қоймай, математикалық модельдеу дағдыларын сапалы түрде арттыруға мүмкіндік береді.

Нәтижелерді өңдеу кестесі (Data Analysis Table).

2-кесте. Экспериментке дейінгі және кейінгі оқушылардың білім сапасы мен дағдыларының салыстырмалы көрсеткіші (пайызбен)

Бұл кестедегі мәліметтер оқушылардың мәтіндік есептерді талдау қабілетінің қалай өскенін көрсетеді:

Бағалау критерийлері	**Экспериментке дейін (бастапқы деңгей)**	**Эксперименттен кейін (қорытынды деңгей)**	**Өсім динамикасы**
Есептің шартындағы логикалық операторларды анықтау	35%	78%	+43%
Релевантты емес (артық) мәліметтерді сүзіп шығу	28%	65%	+37%
Мәтіндік ақпаратты математикалық модельге (теңдеуге) айналдыру	42%	72%	+30%
Этноматематикалық терминдерді дешифрлеу (түсіну)	20%	85%	+65%
Есептің логикалық шешімін негіздеу және рефлексия	30%	60%	+30%

Кесте мәліметтеріне сүйенсек, «Тілдік сүзгі» әдістемесін қолдану нәтижесінде ең жоғары өсім этноматематикалық терминдерді түсіну (+65%) және логикалық операторларды анықтау (+43%) бағыттарында байқалды. Бұл оқушылардың математикалық есепті тек сандар жиынтығы ретінде емес, мағыналық тұтастық ретінде қабылдай бастағанын көрсетеді.

Әсіресе, артық мәліметтерді сүзу дағдысының 37%-ға артуы оқушылардың функционалдық сауаттылығының жақсарғанын және ақпараттық жүктемені өздігінен реттей алатынын айғақтайды. Бұл көрсеткіштер зерттеу тақырыбының өзектілігін және ұсынылған пәнаралық кіріктіру әдістемесінің тиімділігін толықтай растайды.

Әдістемелік ұсыныстар. Зерттеу барысында жинақталған тәжірибе негізінде математика мұғалімдеріне келесі әдістемелік ұсыныстар беріледі:

1. Тілдік талдауға уақыт бөлу: Әрбір жаңа мәтіндік есепті шығармас бұрын, оқушылармен бірге есептің «лингвистикалық картасын» құру ұсынылады. Мұндағы басты мақсат — есептің математикалық шешімінен бұрын, оның тілдік мағынасын ашу.
2. Мәтіндік трансформация: Оқушыларға дайын есепті беріп қана қоймай, оны өз сөздерімен («басқа тілде») қайта жазуға немесе есептің шартына өзгертулер енгізуге тапсырма беру.
3. Кіріктірілген тапсырмалар қорын байыту: Оқулықтағы стандартты есептерді ұлттық құндылықтармен, қазақ тілінің фразеологизмдерімен және мақал-мәтелдерімен байыту арқылы пәнаралық байланысты нығайту.
4. «Сүзгілеу» дағдысын қалыптастыру: Оқушыларға әдейі артық немесе қарама-қайшы деректері бар есептерді ұсыну арқылы олардың сыни ойлауын және ақпаратты іріктеу қабілетін дамыту.

Қорытынды. Жүргізілген зерттеу жұмысын түйіндей келе, математика мен қазақ тілі материалдарын кіріктіре оқыту — бұл тек екі пәннің басын біріктіру емес, бұл оқушының ойлау парадигмасын өзгерту құралы. «Тілдік сүзгі» әдістемесі оқушының

мәтінмен жұмыс істеу мәдениетін жоғарылатып, математикалық модельдеу процесін жеңілдетеді.

Зерттеу барысында анықталғандай, тілдік кедергілерді дер кезінде жою математикалық білім сапасын арттырып қана қоймай, оқушының мемлекеттік тілде еркін ой қорытуына, терминдерді терең түсінуіне жол ашады. Болашақта бұл бағытты дамыту үшін пәнаралық интеграцияланған оқу бағдарламаларын жетілдіру және оқушылардың функционалдық сауаттылығын арттыруға бағытталған авторлық есептер жинағын құрастыру өзекті мәселе болып қала бермек.

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МАТЕМАТИКАЛЫҚ БІЛІМДІ БАҒАЛАУДЫҢ ЦИФРЛЫҚ ФОРМАТТАҒЫ ПАРАДИГМАСЫ

Аңдатпа: Мақалада математикалық білімді бағалаудың цифрлық форматтағы парадигмасының негіздері және цифрлық дағдылардың мұғалімдер мен оқушылар үшін қаншалықты маңызды екендігі қарастырылады. Қазіргі білім беру жүйесінде цифрлық технологиялардың дамуы нәтижесінде бағалау процесі жаңа мазмұнға ие болуда. Дәстүрлі білімді бақылаудан білім алушының дамуына бағытталған қалыптастырушы бағалауға көшу қажеттілігі негізделген. Зерттеу негізгі мектептің алгебра курсының мысалында қолданыстағы цифрлық құралдардың (Google Forms, Quizizz, Kundelik, BilimLand) педагогикалық функцияларын жіктейді, олардың дидактикалық мүмкіндіктері мен математикалық білім берудегі шектеулері кесте түрінде жүйеленеді. Қолданыстағы цифрлық құралдардағы мазмұнды кері байланыстың жеткіліксіздігі мәселесіне ерекше назар аударылады. Ғылыми жаңалық мультимедиялық, атап айтқанда бейне кері байланысты цифрлық бағалау құрылымына қателерді түсіндіру және білім алушылардың өзіндік танымдық іс-әрекетін қолдау құралы ретінде қосудың теориялық негіздемесінде жатыр.

Тірек сөздер: цифрлық бағалау, математикалық білім беру, цифрландыру, кері байланыс, электрондық платформа, білімді бақылау, интерактивті тапсырмалар, цифрлық құзыреттілік, дербес оқыту, онлайн тестілеу.

Кіріспе. XXI ғасырда білім беру жүйесі цифрлық бағытқа көшкендіктен, оқудың мақсаты, мазмұны мен әдістері, әсіресе бағалау жүйесі айтарлықтай өзгеруде. Егер бұрын бағалау тек оқушының білімін тексеру үшін ғана керек болса, қазір оның атқаратын рөлі әлдеқайда кеңейіп, маңызы арта түсті. Математиканы оқытуда бағалаудың рөлі өте зор, себебі бұл есептің логикасын, алгоритмін және оны шешу жолдарын терең түсінуді талап етеді. Білім беру саласындағы мемлекеттік және нормативтік құжаттарда оқу процесінің үздіксіздігі мен дараландуына қойылатын талаптарды күшейте отырып, білімді игеруді бағалаудан қалыптастырушы және құзыретті бағалауға көшу байқалады. Бұл тәсілдің негізінде UNESCO білім беруді қалыптастырушы бағалау мен цифрлық трансформациялаудың маңыздылығын баса көрсететін халықаралық ұйымдардың ережелері жатыр. Қазіргі зерттеулер цифрлық технологиялар мен қалыптастырушы бағалаудың маңызын растағанымен, математикалық білім беруде мазмұнды кері байланыс пен қателерді талдау тетіктерінің әлі де жеткіліксіз екенін көрсетеді. Бүгінгі таңда қолданыстағы цифрлық құралдар негізінен тек соңғы нәтижені бақылаумен шектеліп, бағалаудың оқыту функциясын толыққанды атқара алмай отыр. Бұл кері байланысты күшейту және мультимедиялық құралдарды енгізу арқылы бағалау жүйесін

жетілдіру қажеттілігін растайды. Осыған байланысты цифрлық білім беру ортасының талаптарына сәйкес келетін және негізгі мектептің алгебра сабағының мазмұнын ескеретін жаңа теориялық парадигманы бағалау мен дамытудың мәнін қайта қарау қажеттілігі туындайды.

Негізгі бөлім. Бағалаудың заманауи тәсілдері білім беру саясатындағы өзгерістер мен оқу процесі туралы ғылыми идеялардың әсерінен қалыптасты. OECD және UNESCO ұсынған халықаралық зерттеулерді талдау соңғы онжылдықтарда білімді бақылаудың дәстүрлі моделінен білім беру нәтижелерін бағалаудың неғұрлым кешенді жүйесіне көшу жүріп жатқанын көрсетеді [1], [2]. Бұл ауысу білім алушының жеке прогресіне, оның құзыреттерін дамытуға және өз бетінше оқу қабілетін қалыптастыруға назар аударумен сипатталады. Бағалау оқытуды аяқтайтын кезең емес, онымен бірге жүретін үздіксіз процесс ретінде қарастырылады. Ғылыми әдебиеттерде бақылаудың дәстүрлі формалары білімнің қалыптасу динамикасын, әсіресе математикада толық көрсетуге мүмкіндік бермейтіні баса айтылған. Себебі математикалық ойлау тек дұрыс жауап алуды ғана емес, сонымен қатар шешімнің барысын түсінуді де қамтиды, бұл әсіресе оқушыларға абстрактілі математикалық құрылымдарды жүйелі түрде алғаш рет игерген кезде өте маңызды.

Цифрлық технологиялардың дамуы бағалау жүйесіне айтарлықтай әсер етеді. Қазіргі педагогикада цифрлық технологиялар бақылауды автоматтандыру құралы ретінде ғана емес, сонымен қатар оның функцияларын кеңейту құралы ретінде де қарастырылады. Теориялық тұрғыдан цифрлық бағалау технологияларын бақылау және оқыту функцияларын орындау қабілеті арқылы сипаттауға болады. Еуропалық комиссияның материалдарын қоса алғанда, ғылыми дереккөздер цифрлық білім беру ортасы оқытуды дараландыруға және кері байланыс тиімділігін арттыруға жағдай жасайтынын атап көрсетеді [3].

Білім беру тәжірибесінде қолданылатын заманауи цифрлық құралдарды талдау олардың жалпы сипаттамалары мен шектеулерін анықтауға мүмкіндік береді. Ең көп таралғандардың қатарына Google Forms, Quizizz, Kundelik және BilimLand кіреді [4], [5], [6], [7].

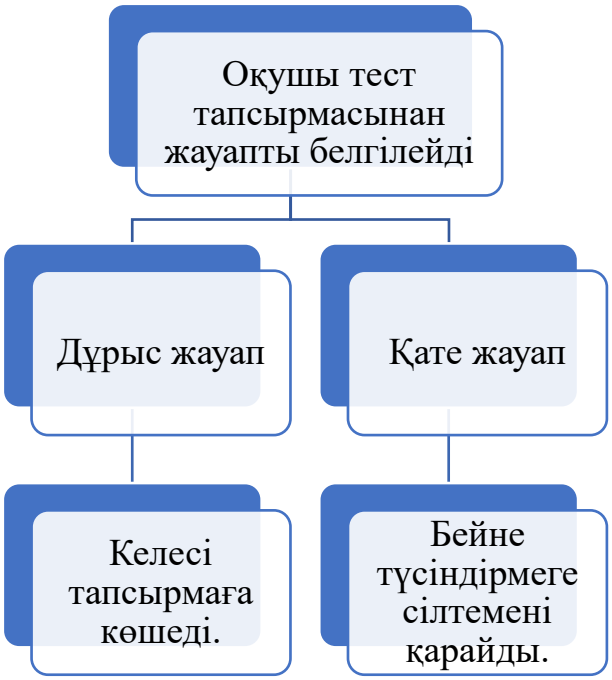
Цифрлық платформа	**Негізгі педагогикалық функциясы**	**Математикалық білім берудегі дидактикалық мүмкіндіктері**	**Қолданыстағы шектеулері**
Google Forms	Диагностикалық, бақылау-бағалау, кері байланыс.	Алгебралық тапсырмаларды тармақтау, қателерді саралау.	Кері байланыс мәтіндік шаблонмен шектеледі, математикалық символдарды енгізу күрделі.
Quizizz	Ынталандырушы, қалыптастырушы бағалау.	Геймификация элементтері арқылы математикалық диктанттарды, формулаларды тез еске	Оқушы есептің шығару жолын көрсете алмайды, тек дайын жауапты таңдайды.

		түсіру тестілерін қызықты ұйымдастыру.	
Kundelik	Жиынтық бағалау, ақпараттық-менеджменттік.	Тоқсандық (БЖБ/ТЖБ) нәтижелерді тіркеу, сынып бойынша математикалық үлгерімнің статистикалық мониторингін жасау.	Сабақ үстіндегі жедел кері байланысты ұйымдастыруға және қатемен жұмысқа бағытталмаған.
BilimLand	Жаттықтырушы, бейімделуші.	Дайын визуалды-интерактивті математикалық модельдерді, геометриялық фигураларды бағалау тапсырмаларына қолдану.	Мұғалімнің өзіндік авторлық есептері мен жекеленген бейне түсіндірмелерін интеграциялау мүмкіндігі шектеулі.

Google Forms тексеруді автоматтандыруға және оқу нәтижелерін жылдам алуға мүмкіндік беретін тиімді цифрлық бағалау құралы. Математикалық білім беру аясында бұл жүйе алгебра тапсырмаларын дайындауға және оқушылардың жиі жіберетін қателіктерін саралауға жақсы көмектеседі. Дегенмен, кері байланыс орнату мүмкіндігі әлі де болса шектеулі, сондықтан бағалаудың оқушыны дамытуға бағытталған қызметі толық деңгейде жүзеге аспай отыр. Тиімділікті арттыру түсіндірмелерді қолдану, тапсырмаларды тармақтау және мультимедиялық элементтерді, соның ішінде бейне кері байланысты біріктіру арқылы мүмкін болады. Бұл математикалық әрекеттерді тереңірек түсінуге және білім алушылардың дербестігін дамытуға ықпал етеді. Теориялық тұрғыдан алғанда, бұл құралдар көбінесе нәтижені бекіту функциясын жүзеге асырады. Цифрлық бағдарламалар тапсырманы тез тексеріп, нәтижені бірден көрсеткенімен, қателерді егжей-тегжейлі түсіндіріп бере алмайды. Көбіне олар тек жауаптың «дұрыс» немесе «бұрыс» екенін ғана айтады. Мұндай кері байланыс оқушының математиканы терең ұғынуына және оның ойлау қабілетін дамытуға көмектеспейді. Бұл математика үшін үлкен мәселе, себебі мұнда есептің жауабынан бұрын, оның шығару жолын түсіну маңызды. Осылайша, цифрлық технологиялардың мүмкіндігі зор болғанымен, олардың оқушыға бағдар беру жағы қайшылықтар туғызады.

Цифрлық бағалау парадигмасының теориялық негіздері. Педагогикадағы парадигма ұғымы білім беру процесін ұйымдастырудың тәсілдерін анықтайтын теориялық көзқарастар жүйесін көрсетеді. Білім беруді цифрландыру жағдайында бақылау және оқыту функцияларын интеграциялауға негізделген бағалаудың жаңа парадигмасы қалыптасуда. Бұл парадигма қалыптастырушы бағалау тұжырымдамасына сүйенеді, оның шеңберінде бағалау білім алушының даму құралы ретінде қарастырылады. Жеке ерекшеліктер мен білім беру қажеттіліктерін ескеруді көздейтін адаптивті оқыту теориясы да маңызды рөл атқарады. Математикалық білімді бағалаудың цифрлық парадигмасы қалыптастырушы және бейімделгіш оқыту принциптеріне негізделген, мұнда бағалау оқу процесінің бөлігі ретінде қарастырылады. Оның негізгі элементі қателіктердің себептерін түсіндіруге және оларды жоюға бағытталған мазмұнды

кері байланыс. Осы парадигма аясында нәтижені ғана емес, мәселелерді шешу процесін де талдау маңызды болады. Осылайша, цифрлық бағалау оқу сипатына ие болады және оқушылардың математикалық ойлауын дамытуға ықпал етеді. Жаңа парадигманың негізгі элементі оқыту механизмі ретіндегі кері байланыс. Ол қатені жазып қана қоймай, оның мазмұнын ашып, оқушыға қиындықтардың себептерін түсінуге мүмкіндік беруі керек. Бұл зерттеуде Google Forms платформасы негізінде мультимедиалық (бейне) кері байланыс жүйесі әзірленді. Мұнда бағалау үдерісі келесі алгоритм бойынша жүреді:



Цифрлық білім беру ортасында ақпарат беру құралы ретінде мультимедиялық құралдардың маңызы артады. Теориялық зерттеулер визуалды қабылдау арналарының үйлесуі білімді тереңірек игеруге ықпал ететіндігін көрсетеді. Осыған байланысты бейнематериалдарды кері байланыс нысаны ретінде пайдалану ерекше қызығушылық тудырады. Осы зерттеу шеңберінде Google Forms жүйесінде тапсырма дұрыс орындалмаған жағдайда оқушыға автоматты түрде немесе жауаптың тармақталуы бойынша бейне түсіндірмеге сілтеме беріледі, онда мұғалім тапсырманы шешу жолын кезең-кезеңімен талдайды, іс-қимыл алгоритмін түсіндіреді және типтік қателерді талдайды. Бейне түсініктеме мәселені шешу процесін көрнекі түрде ұсынуға мүмкіндік береді, бұл оқу материалын жақсы түсінуге және оқушының нақты қиындықтарын жоюға ықпал етеді. Теориялық тұрғыдан алғанда, бейнематериалдарды бағалау құрылымына енгізу қателерді түсіндіруге және оларды өз бетінше жоюға жағдай жасауға мүмкіндік береді. Бұл тәсіл қалыптастырушы бағалау принциптеріне сәйкес келеді және оны жаңа парадигманың маңызды бөлшегі ретінде қарастыруға болады.

Ұсынылған цифрлық бағалау парадигмасын іске асыру білім беру практикасында оның тиімділігін қамтамасыз ететін дидактикалық жағдайлардың жиынтығын анықтауды талап етеді. Ең алдымен, оқу процесінің құрылымына бағалаудың әдістемелік интеграциясы маңызды шарт болып табылады. Бағалау тақырыпты зерттеуді аяқтайтын жеке кезең ретінде қарастырылмауы керек, бірақ сабақтың әр кезеңіне органикалық түрде енуі керек. Екіншіден, шешімдерді талдау мен түсіндіруді қамтитын бағалау тапсырмаларының мазмұнды бағыты болу керек. Бұл оқушының тек дайын жауапты

таңдап қана қоймай, өз ойын логикалық түрде негіздеуіне және жіберілген қателерді өз бетінше саралауына мүмкіндік береді. Үшіншіден, цифрлық құралдардың адаптивті механизмдерін қолдану. Мәтіндік түсіндірмелерді, қадамдық шешімдерді және мультимедиялық элементтерді қоса алғанда, сапалы кері байланысты ұйымдастыру ерекше маңызға ие. Бейне кері байланыс мұғалімге мәселені шешу процесін көрсетуге және қателерді түсіндіруге мүмкіндік береді.

Қорытынды. Математикалық білімді бағалау жүйесі білім беруді цифрландырудың әсерінен айтарлықтай өзгерістерге ұшырап, дәстүрлі тәсілдер біртіндеп қалыптастырушы бағалауға жол беруде. Зерттеу барысында цифрлық бағалауды дамытудың ең тиімді әрі маңызды бағыты ретінде оқу қиындықтарын жан-жақты түсіндіруді қамтамасыз ететін мультимедиалық құралдарды біріктіру анықталды. Бұл тұрғыда математикалық есептерді шешу алгоритмін ашуға және білім алушылардың өзіндік оқу әрекетін қолдауға мүмкіндік беретін бейне түсіндірмелерді қолдану ерекше маңызға ие.

Зерттеудің ғылыми жаңалығы түпкілікті нәтижені бағалаудан математикалық есептерді шешу процесін талдауға көшуді қамтамасыз ететін Google Forms және мультимедиялық кері байланыс негізінде математикалық білімді қалыптастырушы бағалаудың цифрлық форматын әзірлеу және теориялық негіздеу болып табылады. Ұсынылған тәсіл бағалауды бақылау құралы ретінде ғана емес, сонымен қатар оқушылардың математикалық ойлауын, өзін-өзі бақылауы мен тәуелсіздігін дамытуға ықпал ететін оқыту құралы ретінде қарастыруға мүмкіндік береді.

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ЖАРАТЫЛЫСТАНУ ҒЫЛЫМДАРЫ – ЕСТЕСТВЕННЫЕ НАУКИ –NATURAL SCIENCES

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ГЕОХИМИЧЕСКИЕ КРИТЕРИИ НЕФТЕГАЗОНОСНОСТИ И МОДЕЛИ МИГРАЦИИ УГЛЕВОДОРОДОВ В НАДСОЛЕВЫЕ КОМПЛЕКСЫ ВОСТОКА ПРИКАСПИЙСКОЙ ВПАДИНЫ

Аннотация: В статье представлен аналитический обзор геохимических условий формирования и эволюции углеводородных систем в надсолевом (верхнепермско-мезозойском) комплексе восточного борта Прикаспийской впадины. Главной проблемой региональной нефтегазовой геологии является генезис нефтей в условиях активного проявления соляного диапиризма. Проведен сравнительный анализ генерационного потенциала подсолевых палеозойских и надсолевых мезозойских (триасовых и юрских) отложений. Рассмотрены механизмы межкомплексной миграции углеводородов сквозь «соляные окна» и латерального перетока флюидов. На основе данных о физико-химических свойствах нефтей, распределении молекулярных биомаркеров (стеранов, терпанов, изопреноидов) и изотопном составе углерода обоснована полигенная (смешанная) природа большинства надсолевых залежей. Показано критическое влияние процессов бактериальной биодеградации на искажение первоначального геохимического облика нефтей в ловушках на малых глубинах. Сделан вывод о необходимости смещения поисковых работ в глубокие инверсионные межкупольные мульды, где термодинамические условия способствуют сохранению качественных углеводородов, сгенерированных in situ.

Ключевые слова: Прикаспийская впадина, геохимия нефти, биомаркеры, нефтематеринская порода, углеводородная система, соляной диапиризм, миграция флюидов, биодеградация, кероген.

Введение: Успешный прогноз нефтегазоносности любой территории базируется на комплексном понимании углеводородной системы, в которой наличие структурной или стратиграфической ловушки является лишь одним из необходимых, но далеко не единственным элементом. Как было показано в предыдущих исследованиях, интенсивный соляной диапиризм на восточном борту Прикаспийской мегасинеклизы сформировал огромное разнообразие потенциальных емкостей для аккумуляции углеводородов в надсолевом мезозойском этаже. Однако наличие идеальной неантиклинальной ловушки и надежной глинистой покрышки не гарантирует выявления рентабельной залежи. Ключевой проблемой, определяющей высокие геологические риски при поисково-разведочном бурении в регионе, остается сложная и во многом

дискуссионная геохимия органического вещества, а также неопределенность путей миграции углеводородных флюидов.

Восток Прикаспийской впадины представляет собой уникальный природный полигон для изучения процессов генерации, перераспределения и деградации углеводородов. Исторически сложилось так, что главные нефтегазоматеринские толщи бассейна (в первую очередь, обогащенные органикой депрессионные фации девона и карбона) приурочены к глубокозалегающим подсолевым комплексам. В то же время надсолевой этаж, отделенный от палеозойского фундамента мощнейшим региональным флюидоупором — эвапоритами кунгурского яруса, содержит многочисленные скопления нефти и газа в терригенных коллекторах нижнего-среднего триаса, средней юры и нижнего мела. Главная геологическая загадка, которая уже несколько десятилетий разделяет исследовательское сообщество, заключается в происхождении этих надсолевых нефтей.

Являются ли мезозойские залежи результатом масштабной вертикальной миграции палеозойских флюидов, сумевших прорваться сквозь ослабленные тектонические зоны и «соляные окна» в эвапоритовой толще? Или же терригенные толщи раннего мезозоя, накапливавшиеся в межкупольных компенсационных мульдах, обладают достаточным собственным (in situ) генерационным потенциалом, чтобы сформировать месторождения без подпитки снизу? Разрешение этого фундаментального противоречия критически важно не только для академической науки, но и для сугубо практических задач: от того, какая модель углеводородной системы является доминирующей, напрямую зависит стратегия заложения поисковых скважин, оценка объемов ожидаемых запасов и перспектив слабоизученных межкупольных зон.

Целью данного обзора является систематизация накопленных геолого-геохимических данных, характеризующих условия генерации и скопления углеводородов в надсолевом комплексе востока Прикаспия. В статье обобщены современные результаты пиролитических исследований потенциальных нефтематеринских пород, хромато-масс-спектрометрического анализа молекулярных биомаркеров и изотопного состава нефтей. Это позволяет по-новому взглянуть на эволюцию углеводородных систем бассейна и выявить наиболее надежные геохимические критерии нефтегазоносности в условиях активной солянокупольной тектоники.

Потенциальные нефтематеринские толщи и оценка их генерационного потенциала

Фундаментом для построения достоверной модели углеводородной системы является идентификация нефтегазоматеринских свит — тех самых осадочных толщ, органическое вещество которых послужило первоисточником для формирования залежей. Оценка генерационного потенциала базируется на анализе геохимических параметров пород: общего содержания органического углерода (TOC), типа керогена и степени его термической зрелости (стадии катагенеза), определяемой чаще всего по отражательной способности витринита и данным пиролиза по методу Rock-Eval. В контексте восточного борта Прикаспийской впадины исследователи традиционно анализируют два принципиально разных уровня генерации: глубокий палеозойский (подсолевой) и более молодой мезозойский (надсолевой).

Подсолевой палеозойский комплекс рассматривается абсолютным большинством геологов как главный, региональный «двигатель» нефтегазообразования во всей Прикаспийской мегасинеклизе. Основным источником углеводородов здесь выступают мощные депрессионные фации верхнего девона и нижнего-среднего карбона. Это преимущественно темноцветные битуминозные сланцы, аргиллиты и глинистые карбонаты, накапливавшиеся в условиях глубоководного, некомпенсированного осадками морского бассейна с сероводородным заражением придонных вод. Такие бескислородные условия обеспечили великолепную сохранность органического вещества преимущественно сапропелевого типа (кероген I и II типов). Содержание TOC в этих толщах нередко превышает 3–5%, а в отдельных прослоях может достигать 10% и более, что классифицирует их как породы с уникально высоким генерационным потенциалом. С точки зрения термической эволюции, палеозойские толщи погружены на значительные глубины и давно вошли в «главную зону нефтеобразования» (ГЗН), а в наиболее погруженных блоках — достигли стадии жесткого апокатагенеза, генерируя сухой газ и конденсат. Сомнений в том, что палеозой произвел колоссальные объемы углеводородов, в научном сообществе нет.

Совершенно иная, гораздо более сложная и неоднозначная картина наблюдается при оценке собственного (in situ) генерационного потенциала надсолевого мезозойского чехла. На протяжении многих десятилетий господствовала точка зрения, согласно которой триасовые и юрские отложения востока Прикаспия геохимически инертны. Считалось, что они либо бедны органикой, либо не достигли достаточных температур для запуска процессов массовой генерации нефти из-за относительно неглубокого залегания. Однако масштабные современные геохимические исследования кернового материала, извлеченного из глубоких межкупольных мульд, заставили серьезно пересмотреть эту парадигму.

Главными кандидатами на роль собственных нефтематеринских толщ в надсолевом этаже сегодня считаются глинистые пачки оленекского и анизийского ярусов (нижний-средний триас), а также углистые аргиллиты средней юры. Условия их осадконакопления кардинально отличались от палеозойских: это были мелководно-морские, лагунные, а зачастую и континентальные (озерно-аллювиальные) обстановки. Вследствие этого органическое вещество здесь имеет преимущественно смешанный, гумусово-сапропелевый состав (кероген II-III и III типов) с высокой долей терригенного (растительного) материала. Данные пиролитических анализов Rock-Eval показывают, что содержание общего органического углерода (TOC) в мезозойских глинах обычно варьируется в пределах от 0.5% до 2.5%, редко достигая 4% в тонких углистых прослоях. Это позволяет классифицировать их генерационный потенциал как удовлетворительный или хороший, но при этом они в большей степени склонны к генерации газоконденсата и легкой нефти, нежели тяжелых смолистых флюидов.

Ключевым аргументом в геохимических дискуссиях остается степень термической зрелости мезозойской органики. На сводах и флангах соляных куполов, где юрско-триасовые породы приподняты галокинезом на глубины 1–2 километра, органическое вещество действительно является незрелым (стадия протокатагенеза, градация ПК). Однако в центральных частях глубоких компенсационных мульд восточного борта основание триасового комплекса погружается на глубины 4–5 километров и более. Результаты бассейнового моделирования и замеры отражательной способности

витринита доказывают, что в этих локальных межкупольных депоцентрах породы нижнего и среднего триаса уверенно перешагнули порог температурного оптимума и вошли в градацию мезокатагенеза (МК1-МК2), то есть в верхнюю часть «главной зоны нефтеобразования».

Таким образом, современные данные свидетельствуют о том, что надсолевой комплекс востока Прикаспия не является геохимически «стерильным». Он обладает собственным генерационным потенциалом, который, однако, строго локализован в пространстве — очаги возможного образования нефти приурочены исключительно к наиболее прогнутым частям межкупольных мульд. Наличие этих двух принципиально разных «кухонь погоды» (мощной региональной палеозойской и локальной мезозойской) создает основу для сложнейшей картины распределения углеводородов, расшифровать которую невозможно без понимания путей миграции флюидов в условиях соляной тектоники.

Пути миграции флюидов в условиях солянокупольной тектоники

Наличие доказанных очагов генерации углеводородов — как мощных региональных в подсолевом палеозое, так и локальных в мезозойских мульдах — ставит перед исследователями следующий фундаментальный вопрос: каким образом нефть и газ преодолели значительные расстояния и заполнили ловушки в надсолевом чехле? В классических платформенных бассейнах миграция флюидов представляет собой относительно предсказуемый процесс движения от погруженных зон к гипсометрически приподнятым участкам. Однако на востоке Прикаспийской впадины этот процесс был тотально искажен и осложнен галокинезом, который создал уникальную, динамично меняющуюся в геологическом времени систему флюидопроводников и экранов.

Главным парадоксом региональной углеводородной системы является двойственная роль кунгурской соляной толщи. С одной стороны, эвапориты представляют собой идеальный, абсолютно флюидоупорный экран с нулевой проницаемостью, который надежно запечатывает гигантские скопления углеводородов в подсолевом комплексе (такие как Тенгиз или Карачаганак). В ненарушенном состоянии кунгурская соль делает невозможным переток флюидов снизу вверх. С другой стороны, именно экстремальная пластичность соли и ее активное перераспределение в процессе роста диапиров привели к нарушению сплошности этого экрана.

В центральных, наиболее прогнутых частях межкупольных компенсационных мульд восточного борта материнский пласт кунгурской соли был практически полностью выдавлен в растущие по периферии штоки. В результате тектонического истощения соляной залежи сформировались так называемые «соляные окна» — обширные зоны зияния, где надсолевой мезозойско-кайнозойский чехол лег непосредственно на подсолевые палеозойские породы или отделен от них лишь маломощными линзами сульфатно-терригенных пород. Именно эти «окна» стали главными порталами для масштабной межкомплексной вертикальной миграции. Находящиеся под аномально высоким пластовым давлением палеозойские углеводороды, сгенерированные в глубоких очагах, устремлялись в эти зоны ослабления. Процесс перетока многократно усиливался густой сетью глубинных субвертикальных разломов, которые пронизывали фундамент мульд и работали как своеобразные тектонические клапаны. В периоды тектонических активизаций эти разломы приоткрывались, обеспечивая импульсную, струйную инъекцию нефти и газа из палеозоя в базальные горизонты триаса.

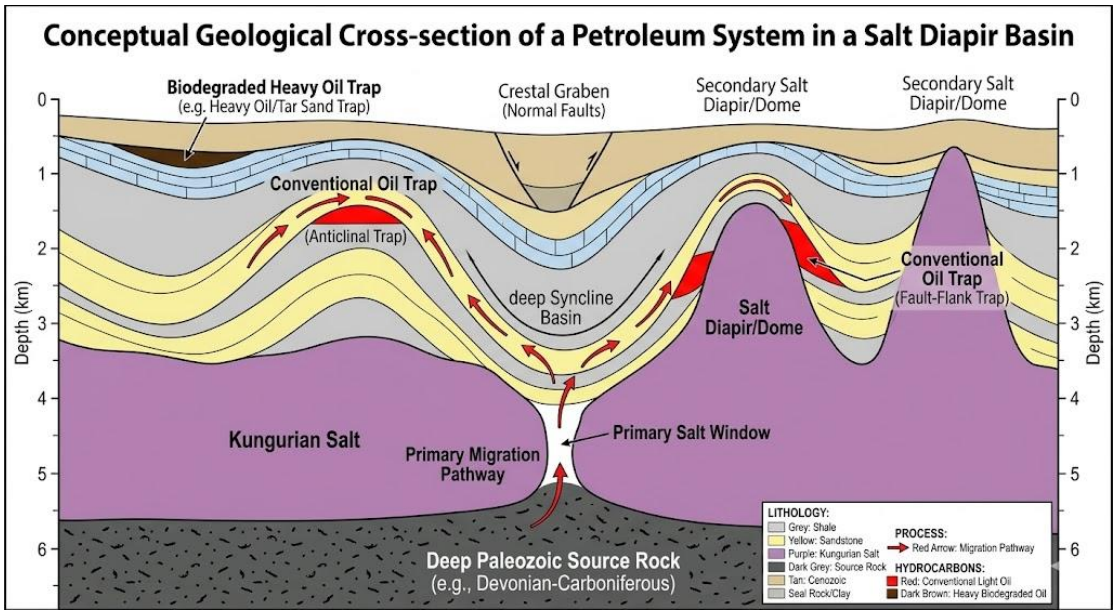


Рисунок 1. Концептуальная модель углеводородной системы: пути миграции флюидов через «соляные окна» и формирование залежей в надсолевом комплексе

Попав в надсолевой комплекс через «соляные окна» (или будучи сгенерированными in situ в самых глубоких частях тех же мульд), углеводородные флюиды начинали второй этап своего пути — латеральную (боковую) миграцию. Роль главных транспортных артерий на этом этапе взяли на себя мощные пласты высокопористых и проницаемых песчаников нижнего и среднего триаса, а также средней юры. Движение флюидов подчинялось законам гидродинамики и плавучести: более легкие нефть и газ стремились подняться по восстанию пластов от глубоких центров межкупольных депрессий к их краям.

Именно здесь пути миграции пересекались с растущими соляными куполами. Песчаные горизонты-проводники, выходя из мульды, круто изгибались вверх на склонах диапиров. Углеводороды двигались по этим наклонным пластам до тех пор, пока не встречали на своем пути непреодолимое препятствие. Таким препятствием становилось либо само тело протыкающего соляного штока (формируя приконтактную ловушку), либо нависающий соляной карниз (загоняя нефть в подкарнизную ловушку), либо литологическое выклинивание коллектора на склоне купола. В надсводовых частях куполов миграция носила еще более сложный характер: флюиды просачивались по сети малоамплитудных сбросов в грабенах обрушения, заполняя тектонически экранированные блоки.

Критически важным аспектом этой модели является ее динамичность. Галокинез не останавливался ни на минуту, а значит, архитектура путей миграции постоянно менялась. Разломы, которые еще вчера служили проводниками, при изменении вектора напряжений могли сомкнуться, превратившись в непроницаемые экраны. Углы наклона пластов на флангах куполов продолжали расти, что нередко приводило к изменению положения структурных замков и переливу нефти из уже сформированных ловушек выше по разрезу. Этот процесс вторичной миграции и переформирования залежей на востоке Прикаспия является скорее правилом, чем исключением. Часто флюиды, не найдя надежной покрышки, прорывались сквозь трещиноватые юрские и меловые глины к дневной поверхности, что объясняет наличие в регионе многочисленных

поверхностных нефтепроявлений и скоплений сильно окисленных битумов. Таким образом, путь нефти от материнской породы до ловушки в условиях соляного диапиризма представляет собой сложнейшую многофазную эстафету, где малейшее нарушение синхронности тектонических процессов вело к безвозвратной потере углеводородов.

Геохимическая характеристика нефтей и молекулярные биомаркеры

Понимание архитектуры путей миграции неразрывно связано с детальным изучением самого флюида. Физико-химические свойства нефтей надсолевого комплекса восточного борта Прикаспийской впадины — в частности, классических месторождений Эмбинской нефтегазоносной области — отличаются колоссальным разнообразием. В пределах одних и тех же стратиграфических горизонтов можно встретить как сверхлегкие, подвижные, малосернистые нефти и газоконденсаты, так и тяжелые, высоковязкие, смолистые разности, по консистенции напоминающие мальты. Такое резкое контрастное распределение свойств невозможно объяснить только условиями первичной генерации; оно является прямым следствием сложной истории миграции и интенсивных процессов вторичного изменения залежей в термодинамических условиях малых глубин.

Единственным надежным инструментом для расшифровки генетической природы таких разнообразных флюидов является анализ молекулярных биомаркеров — своеобразных «геохимических отпечатков пальцев», унаследованных нефтью от исходного органического вещества. Современные методы газовой хроматографии и хромато-масс-спектрометрии (ГХ-МС) позволяют на молекулярном уровне сравнивать надсолевые и подсолевые нефти. Одним из базовых индикаторов выступает соотношение изопреноидных алканов — пристана и фитана (Pr/Ph). Для глубинных палеозойских нефтей региона, сгенерированных в морских восстановительных обстановках карбонатных платформ, характерны низкие значения этого отношения (часто Pr/Ph < 1). В то же время в ряде надсолевых триасовых и юрских залежей фиксируются значения Pr/Ph, превышающие 1.5–2.0. Такой геохимический облик свидетельствует о существенной доле терригенного (растительного) материала в исходном керогене и субокислительных условиях седиментации, что является веским аргументом в пользу генерации этих нефтей in situ в мезозойских континентальных или прибрежно-морских фациях.

Еще более детальную информацию предоставляет распределение полициклических биомаркеров — стеранов и терпанов (гопанов). Спектр стеранов (углеводородов ряда C27-C29) жестко контролируется типом исходной биомассы. Высокая концентрация холестана (C27) типична для морского фитопланктона (палеозойский источник), тогда как преобладание стигмастана (C29) указывает на влияние высшей наземной растительности, характерной для мезозойских отложений. Изучение этих маркеров в надсолевых нефтях востока Прикаспия часто дает смешанную картину. В некоторых резервуарах четко прослеживается палеозойский «морской» след, что неопровержимо доказывает факт вертикального перетока по разломам. В других — фиксируется уверенный мезозойский профиль. Важнейшим дополнением к хроматографии служит анализ изотопного состава углерода (δ13C). Нефти, сингенетичные мезозойским толщам, как правило, изотопно более «тяжелые» по

сравнению с палеозойскими аналогами, что позволяет дифференцировать их даже при сильном сходстве физических свойств.

Однако применение биомаркерного анализа в надсолевом этаже сталкивается с серьезным естественным барьером — процессами биодеградации. Большинство мезозойских неантиклинальных ловушек, о которых мы говорили ранее, располагается на небольших глубинах (от 500 до 2000 метров), где температуры пласта редко превышают 60–70 °C. Это идеальные условия для жизнедеятельности аэробных и анаэробных бактерий. Попадая в такую ловушку, нефть подвергается массированной бактериальной атаке: микроорганизмы в первую очередь «съедают» легкие нормальные алканы, в результате чего флюид стремительно тяжелеет, обогащаясь смолисто-асфальтеновыми компонентами и нафтено-ароматическими углеводородами.

Биодеградация не только ухудшает рентабельность добычи нефти, но и стирает ее первоначальный геохимический код. На поздних стадиях разрушения бактерии начинают уничтожать даже устойчивые изопреноиды и стераны, превращая нефть в бесструктурный битум. В зонах активного роста соляных куполов, где глинистые покрышки постоянно микротрещиноваты, залежи подвергаются дополнительному разрушению за счет вымывания пластовыми инфильтрационными водами (water washing). Именно повсеместное наложение этих разрушительных вторичных процессов на первичный генетический профиль флюидов породило десятилетние научные споры о том, откуда же на самом деле пришла нефть в мезозойские ловушки Прикаспия.

Дискуссионные модели углеводородных систем

Сложное переплетение путей миграции, контрастность физико-химических свойств флюидов и повсеместное наложение процессов биодеградации превратили вопрос о генезисе надсолевых нефтей в одну из самых острых проблем региональной геологии. Исторически сложилось так, что именно на материале месторождений Эмбинской нефтегазоносной области и смежных структур восточного борта Прикаспия сформировались две полярные, непримиримые концепции углеводородных систем, дискуссия между сторонниками которых продолжается до сих пор.

Первая концепция — модель глубинной вертикальной миграции (палеозойского источника). Ее апологеты опираются на колоссальный дисбаланс масс: объемы углеводородов, аккумулированные в надсолевом мезозойском этаже, по их расчетам, значительно превышают собственный генерационный потенциал юрско-триасовых отложений. В рамках этой модели мезозойский чехол рассматривается исключительно как транзитная зона и гигантский резервуар для нефти, сгенерированной в подсолевых девон-каменноугольных толщах. Главным аргументом здесь выступает структурный фактор — пространственная приуроченность крупнейших надсолевых месторождений к глубоким межкупольным мульдам, где зафиксированы «соляные окна» и сквозные разрывные нарушения. Обнаружение в надсолевых нефтях морских биомаркеров (холестаны) и изотопно-легкого углерода, характерного для палеозоя, считается неопровержимым доказательством правомерности этой теории.

Вторая концепция — модель автохтонной генерации (in situ, мезозойского источника). Сторонники этой теории доказывают, что миграция сквозь толщу кунгурской соли, даже в зонах ее максимального тектонического утонения, физически крайне затруднена. Они акцентируют внимание на результатах современного геохимического моделирования, которое подтверждает: в осевых частях глубоких компенсационных

мульд нижнетриасовые и среднеюрские глинистые пачки погружались на глубины свыше 4–5 километров, уверенно достигая температурного оптимума «главной зоны нефтеобразования». Наличие в нефтях терригенных стеранов (C29), высокие значения отношения пристан/фитан и изотопно-тяжелый состав углерода служат прямым свидетельством того, что эти флюиды родились здесь же, в мезозое, из органики растительного или смешанного типа, и мигрировали в ловушки на короткие расстояния по латерали.

В последние годы, благодаря накоплению огромного массива хромато-масс-спектрометрических данных, в научном сообществе начинает доминировать третья, компромиссная парадигма — полигенная модель смешения флюидов. Согласно этой концепции, углеводородная система востока Прикаспия формировалась в несколько пульсационных этапов. На ранних стадиях, по мере прогибания мульд, мезозойские материнские породы генерировали собственные, автохтонные флюиды, которые первыми заполняли формирующиеся приконтактные ловушки на склонах диапиров. Значительно позже, в периоды глобальных тектонических перестроек (например, в неогене), когда сеть разломов обновлялась, происходил мощный прорыв палеозойских газов и легких нефтей сквозь «соляные окна». Эти глубинные флюиды вторгались в уже существовавшие мезозойские залежи, растворяли окисленную бактериями старую нефть и кардинально меняли ее геохимический облик. Именно такое смешение разновозрастных углеводородов в разных пропорциях идеально объясняет весь тот хаос физико-химических свойств и биомаркерных аномалий, который мы наблюдаем на месторождениях восточного борта.

Заключение. Обобщение современных геохимических и структурно-тектонических данных убедительно доказывает, что надсолевой мегакомплекс восточного борта Прикаспийской мегасинеклизы — это не просто транзитная зона, а сложная, открытая и высокодинамичная углеводородная система. Ее историческая эволюция и современный облик всецело продиктованы процессами галокинеза. Пластическое течение кунгурской соли сыграло здесь ключевую и весьма противоречивую роль: оно не только сформировало широкую палитру сложнопостроенных неантиклинальных ловушек, но и создало уникальную архитектуру путей миграции, периодически открывая «соляные окна» и формируя густую сеть тектонических экранов и проводников.

Анализ биомаркеров и данных пиролиза позволяет поставить точку в многолетних дискуссиях об источниках углеводородов. Сегодня можно с уверенностью говорить о том, что ресурсный потенциал региона опирается на два независимых очага генерации. Наряду с масштабными вертикальными перетоками флюидов из подсолевого палеозоя, в глубокопогруженных межкупольных мульдах активно функционировала собственная, весьма продуктивная мезозойская система. Слияние потоков из этих двух источников объясняет полигенную, смешанную природу подавляющего большинства надсолевых нефтей. Ситуация дополнительно осложняется тем, что первоначальный генетический облик этих флюидов оказался сильно искажен интенсивными процессами бактериальной биодеградации и вымывания, которые активно протекали в резервуарах на малых глубинах.

Выявленные геохимические закономерности диктуют необходимость кардинального пересмотра поисковых стратегий в регионе. Для минимизации

геологических рисков фокус геологоразведочных работ должен смещаться с традиционных, структурно-выраженных прикупольных зон, где нефти чаще всего окислены, в сторону глубоких инверсионных мульд и скрытых подкарнизных ловушек. Именно там, на глубинах более 2.5–3 километров, термодинамические условия естественным образом останавливают разрушительное воздействие микроорганизмов, обеспечивая сохранность легкой, качественной нефти и газоконденсата. Успешное выявление и освоение таких объектов потребует от геологов глубокого междисциплинарного синтеза — тесной интеграции полноазимутальной 3D-сейсморазведки глубинной миграции с современными методами 4D-бассейнового геохимического моделирования.

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ВЛИЯНИЕ МОРФОЛОГИИ СОЛЯНЫХ КУПОЛОВ НА ФОРМИРОВАНИЕ И СОХРАННОСТЬ УГЛЕВОДОРОДНЫХ ЛОВУШЕК В НАДСОЛЕВЫХ КОМПЛЕКСАХ ВОСТОКА ПРИКАСПИЙСКОЙ ВПАДИНЫ

Аннотация: В статье представлен комплексный обзор проблем формирования и сохранения углеводородных ловушек в надсолевых (верхнепермско-мезозойских) отложениях восточного борта Прикаспийской впадины. Актуальность работы обусловлена необходимостью освоения мезозойского этажа, обладающего высокими коллекторскими свойствами, на фоне возрастающих капитальных затрат при разведке глубокозалегающего подсолевого палеозоя. Показано, что фундаментальным фактором, контролирующим архитектуру углеводородных резервуаров в регионе, выступает интенсивный галокинез кунгурской соли. Систематизированы основные морфологические типы соляных тел и приуроченные к ним сложноэкранированные неантиклинальные ловушки: сводовые (в грабенах обрушения), приконтактные (фланговые), скрытые подкарнизные и инверсионные структуры межкупольных мульд. Рассмотрена эволюция методов геофизических исследований: продемонстрирована неэффективность традиционной 2D-сейсморазведки в зонах соляного диапиризма из-за эффектов скоростных аномалий и обоснована критическая роль 3D-сейсморазведки с применением глубинной миграции (PSDM) для достоверного картирования подкарнизных зон. Выделены ключевые дискуссионные вопросы нефтегазовой геологии региона, включая двойственную роль разрывных нарушений и проблему целостности региональных покрышек в условиях конседиментационного роста диапиров. Сделан вывод о необходимости комплексирования структурной геологии, высокоточной геофизики и 4D-бассейнового моделирования для снижения рисков поискового бурения.

Ключевые слова: Прикаспийская впадина, галокинез, соляной купол, неантиклинальная ловушка, надсолевой мегакомплекс, соляной карниз, 3D-сейсморазведка, глубинная миграция (PSDM), тектонический экран.

Введение. Прикаспийская мегасинеклиза по праву считается одним из старейших, наиболее масштабных и геологически сложных нефтегазоносных бассейнов Евразийского континента. Исторически сложилось так, что после открытия серии месторождений-гигантов, таких как Тенгиз, Кашаган и Карачаганак, основной вектор внимания научно-исследовательских институтов и добывающих компаний закономерно сместился на глубокозалегающие подсолевые комплексы палеозойского возраста. Безусловно, именно карбонатные платформы и рифогенные постройки девона и карбона содержат львиную долю запасов региона. Однако освоение этих горизонтов сопряжено с колоссальными технологическими вызовами: глубины бурения зачастую превышают

отметку в 4.5–5 километров, пласты характеризуются аномально высокими давлениями, а флюиды содержат экстремально высокие концентрации сероводорода и углекислоты. Все это делает поисково-разведочные работы в подсолевом этаже крайне капиталоемкими и сопряженными с высокими геологическими и экологическими рисками.

На фоне этих трудностей надсолевой верхнепермско-мезозойский мегакомплекс, который в конце прошлого века отошел на второй план, сегодня вновь приобретает высокую актуальность. Особый практический интерес представляет восточный борт впадины — территория, охватывающая зоны сочленения с Предуральским краевым прогибом и смежные структурные ступени. Надсолевые залежи углеводородов в этом районе обладают рядом неоспоримых преимуществ. В первую очередь, это относительно комфортные глубины залегания, редко превышающие 2–3 километра, и отсутствие агрессивных компонентов в составе нефтей. Кроме того, терригенные отложения нижнего и среднего триаса, средней юры и нижнего мела выступают в роли превосходных коллекторов. Благодаря высокой пористости, которая в неглубоко погруженных песчаниках нередко достигает 20–25%, и проницаемости, измеряемой сотнями миллидарси, добыча здесь характеризуется высокими дебитами. Совокупность этих факторов делает разведку и эксплуатацию надсолевых залежей экономически высокорентабельными даже в том случае, если объемы запасов в отдельных ловушках относительно невелики.

Однако кажущаяся простота освоения малых глубин нивелируется экстремально сложной тектонической архитектурой региона. Фундаментальным процессом, который полностью диктует структурный план надсолевого этажа, литофациальную изменчивость пород и пути миграции углеводородов, является галокинез. Гигантские массы эвапоритов кунгурского яруса нижней перми, выступающие региональным флюидоупором для глубоких залежей, для надсолевого комплекса стали главным дестабилизирующим фактором. Обладая высокой пластичностью и аномально низкой плотностью по сравнению с перекрывающими породами, кунгурская соль на протяжении сотен миллионов лет находилась в непрерывном движении. Соляные диапиры прорывали формирующийся осадочный чехол, создавая хаотичную картину из густой сети сбросов, компенсационных прогибов и локальных зон стратиграфического срезания.

Следствием этого многовекового тектонического процесса стало практически полное отсутствие в регионе классических пологих антиклинальных складок, которые относительно легко диагностируются традиционными методами геофизики. В надсолевом комплексе восточного Прикаспия доминируют сложнопостроенные, пространственно изменчивые неантиклинальные ловушки: тектонически экранированные блоки в грабенах обрушения, зоны литологического выклинивания на склонах протыкающих штоков и скрытые скопления под нависающими соляными карнизами. Поиск таких объектов требует ювелирной точности и принципиально иных подходов к интерпретации данных. В связи с этим, настоящая обзорная статья ставит своей целью систематизировать разрозненные современные представления о механизмах формирования ловушек в условиях активного соляного диапиризма. В работе обобщен накопленный опыт изучения морфологии соляных тел и их влияния на архитектуру углеводородных резервуаров, а также критически проанализированы проблемы и

ограничения сейсмического картирования сложных неантиклинальных объектов на востоке Прикаспийской мегасинеклизы.

Этапы галокинеза и морфологическая эволюция соляных тел

Специфика формирования структурного плана надсолевого мегакомплекса на востоке Прикаспийской впадины во многом уникальна и принципиально отличается от центральных, более погруженных районов бассейна. Если в центральной депрессии рост соляных куполов был обусловлен преимущественно классическим гравитационным галокинезом — то есть всплыванием легких эвапоритов сквозь более плотные терригенные толщи из-за разницы литостатических давлений, — то на восточном борту к этому процессу добавился мощнейший тектонический фактор. Близость зоны сочленения с Уральской складчатой системой привела к тому, что на гравитационную нестабильность наложилось интенсивное региональное латеральное сжатие, связанное с финальными фазами герцинского орогенеза. Именно этот синергетический эффект плотностной инверсии и тектонического стресса предопределил высочайшую агрессивность соляного диапиризма в регионе и крайнюю асимметрию формирующихся структур.

Процесс перераспределения гигантских масс кунгурской соли не был одномоментным; он носил ярко выраженный пульсационный характер и растянулся на сотни миллионов лет, напрямую управляя условиями осадконакопления. В эволюции соляных структур востока Прикаспия исследователи традиционно выделяют несколько крупных макроэтапов, каждый из которых оставил свой неповторимый след в архитектуре мезозойских резервуаров.

Начальный, позднепермско-триасовый этап характеризовался зарождением пологих соляных подушек и валов. Под давлением первых порций накапливающихся осадков соль начала пластично перетекать из зон максимальной нагрузки в зоны разгрузки. Важнейшим следствием этого оттока эвапоритов стало проседание пород кровли и формирование глубоких межкупольных компенсационных мульд. В условиях засушливого климата раннего мезозоя эти мульды превратились в гигантские депоцентры, куда речные системы сносили огромные объемы обломочного материала с разрушающихся Уральских гор. Так формировались мощные, местами достигающие полутора километров, толщи песчано-глинистых отложений триаса, которые сегодня рассматриваются как главные резервуары надсолевого этажа.

Юрско-раннемеловой этап стал периодом максимальной активности галокинеза. По мере того как толщина перекрывающих осадков росла, соляные подушки эволюционировали в протыкающие диапиры. Соляные ядра буквально разрывали сформировавшиеся триасовые горизонты, устремляясь к поверхности. Важно понимать, что этот процесс происходил синхронно с осадконакоплением (так называемый конседиментационный рост). Пока соль пробивала себе путь наверх, на ее склонах продолжали отлагаться юрские и меловые осадки. В результате вблизи растущих диапиров формировались зоны резкого стратиграфического несогласия: пласты выклинивались, меняли свою мощность и литологический состав, что создавало идеальные условия для возникновения литологически экранированных ловушек. Наконец, позднемеловой-кайнозойский этап стал завершающей стадией, когда вертикальный импульс соли иссяк, либо она достигла палеоповерхности. Началось латеральное растекание эвапоритов с образованием сложнейших грибовидных структур.

Степень зрелости галокинеза и локальные вариации тектонических напряжений привели к формированию огромного многообразия форм соляных тел. Современные данные объемной сейсморазведки позволяют детально классифицировать эти морфотипы, поскольку именно форма соли определяет тип приуроченной к ней углеводородной ловушки. Наиболее простыми по строению являются соляные подушки глубокого заложения. Они характеризуются плавными очертаниями и отсутствием сквозного протыкания юрско-мелового чехла. Свод надсолевых отложений над такими подушками остается относительно пологим и слабо нарушенным разломами, что благоприятствует сохранению крупных классических залежей.

Абсолютно иная картина наблюдается в зонах развития протыкающих соляных штоков, которые доминируют на востоке впадины. Типичными примерами таких структур являются диапиры Ащисай или Каратюбе. Они представляют собой крутопадающие соляные столбы с углами наклона склонов, достигающими 70–90 градусов. Штоки полностью разрывают триасово-юрские горизонты, а в их надсводовых частях из-за колоссального растяжения пород формируются сложные системы грабенов обрушения.

Особое место в морфологическом ряду занимают соляные карнизы и грибовидные купола, характерные, например, для Кенкияк-Жанажольской зоны. Их формирование связано со способностью соли на поздних этапах развития внедряться по ослабленным зонам в горизонтальном направлении, перекрывая собой более молодые отложения. Такие нависающие соляные «козырьки» играют роль идеальных, абсолютно непроницаемых покрышек для мигрирующих углеводородов. Наконец, неотъемлемой частью галокинетического ландшафта являются межкупольные мульды — области, откуда кунгурская соль была практически полностью выдавлена в растущие соседние диапиры. По мере полного исчерпания запасов материнской соли в центрах мульд происходит оседание вышележащих пластов, что с течением геологического времени приводит к инверсии рельефа. Изначальные депрессии превращаются в так называемые «черепашьи структуры» — обширные псевдоантиклинальные складки в межкупольном пространстве. Эти структуры залегают на значительных глубинах, но из-за отсутствия интенсивной разломной тектоники представляют собой весьма перспективные объекты для поиска крупных скоплений нефти.

Классификация и особенности формирования ловушек в зонах соляного диапиризма

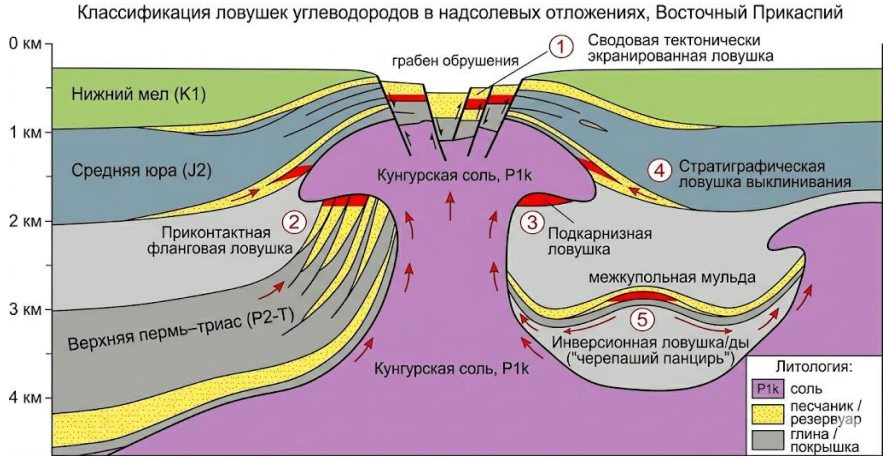


Рисунок 1. Принципиальная схема типов ловушек углеводородов в надсолевых отложениях восточного Прикаспия

Неразрывная связь между формой соляного тела и архитектурой вмещающих пород обуславливает формирование в надсолевом этаже широчайшего спектра углеводородных ловушек. Для восточного борта Прикаспийской впадины характерно резкое, подавляющее преобладание неантиклинальных, тектонически и литолого-стратиграфически экранированных скоплений. Классические пологие своды здесь являются редкостью, уступая место сложным структурным формам, каждая из которых требует специфического подхода к разведке.

Самым ранним и исторически наиболее изученным типом объектов в регионе являются сводовые тектонически экранированные ловушки. Их образование напрямую связано с процессами растяжения, которые испытывают породы кровельного чехла при вертикальном напоре растущего соляного диапира или крупной подушки. По мере того как соляное ядро пробивает себе путь наверх, перекрывающие его юрско-меловые отложения деформируются, изгибаются и в конечном итоге разрываются с образованием густой сети сбросов. В результате на сводах куполов формируются сложные грабены обрушения, или так называемые кепроки. Нефть в таких условиях скапливается в приподнятых тектонических блоках. Механизм удержания углеводородов здесь полностью зависит от герметичности разлома: экраном выступает либо сама плоскость сброса, заполненная перетертым глинистым материалом, либо непроницаемые породы, которые тектоническими подвижками были приведены в прямой латеральный контакт с песчаным коллектором. Классическими эталонами подобных сложнопостроенных залежей выступают старейшие месторождения региона — Шубаркудук и Жаксымай. Главным геологическим риском при поиске таких объектов остается нарушение их герметичности при неотектонических активизациях, что нередко приводит к дегазации резервуара по приоткрывшимся разломам и формированию скоплений окисленной, тяжелой нефти.

Гораздо более продуктивными, но в то же время более сложными для освоения считаются приконтактные, или фланговые, ловушки. Пространственно они тяготеют к крутым, порой субвертикальным склонам протыкающих соляных штоков. Формирование этих залежей неразрывно связано с конседиментационной стадией галокинеза, когда активный рост купола происходил одновременно с накоплением осадков. В таких условиях продуктивные песчаные пласты нижнего и среднего триаса, а также средней юры, круто воздымаясь по направлению к диапиру, буквально упираются в непроницаемое тело соли. В данном случае эвапориты выступают в роли идеального бокового флюидоупора, надежно запечатывающего углеводороды. В других случаях на склонах активно растущих куполов происходило стратиграфическое срезание пластов или их литологическое выклинивание из-за смены условий осадконакопления. Ярчайшим представителем этого типа резервуаров является надсолевой комплекс месторождения Кенкияк, где основные нефтяные скопления приурочены именно к зонам резкого выклинивания юрских и триасовых коллекторов на крыльях соляного ядра.

Совершенно особый интерес с точки зрения нереализованного ресурсного потенциала представляют подкарнизные ловушки. Их генезис обусловлен поздними стадиями развития галокинеза, когда исчерпавший энергию вертикального подъема соляной массив начинает пластично растекаться в латеральном направлении, используя ослабленные зоны в мезозойском осадочном чехле. Внедрение таких нависающих соляных козырьков создает уникальные условия для аккумуляции нефти. Углеводороды,

мигрирующие вверх по восстанию проницаемых триасовых или верхнепермских пластов, оказываются надежно «запертыми» под мощной, абсолютно непроницаемой соляной покрышкой карниза. Несмотря на то, что такие ловушки могут содержать колоссальные объемы качественной легкой нефти, их целенаправленный поиск долгое время оставался практически невозможным. Соляной карниз работает как гигантский акустический экран, рассеивающий и поглощающий сейсмическую энергию, в результате чего под ним формируется зона глухой «сейсмической тени», надежно скрывающая перспективные горизонты от классических методов геофизики.

Наконец, важнейшим, но пока наименее изученным элементом углеводородной системы востока Прикаспия являются ловушки межкупольных мульд и связанные с ними инверсионные структуры. В то время как на сводах и флангах куполов породы подвергались жесточайшим тектоническим деформациям, в центральных частях межкупольного пространства формировались относительно спокойные условия. По мере радикального выдавливания материнской кунгурской соли к растущим по периферии диапирам, перекрывающие мульду мощные пермо-триасовые толщи постепенно оседали. Парадокс этого процесса заключается в том, что центральные части депрессий, куда изначально сносился максимальный объем осадков, со временем из-за неравномерного оттока соли оказываются гипсометрически выше периферийных зон. Так формируются инверсионные псевдоантиклинали, получившие в геологической литературе образное название «черепашьих панцирей». В отличие от прикупольных зон, разломная тектоника здесь проявлена слабо, что гарантирует превосходную сохранность залежей и целостность глинистых покрышек. Главной сложностью при их разведке становятся значительные глубины залегания, зачастую превышающие 3–4 километра, и высокая фациальная изменчивость терригенных пород, требующая филигранного прогнозирования коллекторских свойств в центре палеоречных систем.

Проблемы сейсмического картирования сложных ловушек и роль современных технологий

Высокая плотность доказанных запасов углеводородов в надсолевых отложениях востока Прикаспийской впадины на протяжении десятилетий контрастировала с парадоксально низкой успешностью поисково-разведочного бурения на неантиклинальные объекты. Геологи прекрасно понимали, что фланги куполов и межкупольные пространства таят в себе колоссальный потенциал, однако пробуренные скважины раз за разом оказывались сухими или вскрывали водоносные горизонты. Это несоответствие теории и практики было обусловлено экстремально сложными сейсмогеологическими условиями региона, которые долгое время выступали непреодолимым барьером для достоверного картирования скрытых ловушек. Традиционные методы геофизики просто не позволяли геологам «увидеть» то, что происходит в непосредственной близости от соляного тела.

Исторический массив данных, полученных методами 2D-сейсморазведки в период 1970–1990-х годов, сыграл важнейшую роль в понимании общей региональной тектоники и выявлении морфологии крупных соляных массивов. Однако для детального изучения приконтактных и подкарнизных зон двумерная сейсмика оказалась критически малоэффективной. Одним из главных ее ограничений стала невозможность корректного отображения крутых углов падения пластов. Стандартные алгоритмы временной миграции после суммирования (Post-Stack Time Migration), применявшиеся в те годы,

математически не справлялись с субвертикальными границами, углы наклона которых на склонах соляных штоков часто превышают 60–70 градусов. В результате на сейсмических разрезах границы соляного ядра выглядели размытыми, хаотичными, а зоны стратиграфического прилегания продуктивных пластов к соли просто терялись в фоновом шуме.

Еще более серьезной проблемой, искажавшей понимание внутренней архитектуры ловушек, стали так называемые эффекты скоростных аномалий. Физика этого явления заключается в колоссальной разнице плотностей и акустических свойств сред. Скорость прохождения упругой сейсмической волны в плотной кунгурской соли достигает 4500 метров в секунду, тогда как в перекрывающих и прилегающих к ней терригенных породах мезозоя она варьварюется в пределах 2500–3500 метров в секунду. Проходя сквозь соляные выступы, волна ускоряется, из-за чего на временных сейсмических разрезах горизонты, залегающие под солью, искусственно «подтягиваются» вверх. Этот феномен, известный в геофизике как эффект ложного поднятия (pull-up effect), приводил к тому, что геологи картировали несуществующие антиклинальные структуры под телом куполов или неверно оценивали гипсометрию межкупольных мульд, закладывая скважины в заведомо пустые блоки.

Абсолютно слепой зоной для исследователей оставались и подкарнизные ловушки. Массивные, нависающие соляные козырьки работали как гигантские линзы, которые хаотично рассеивали сейсмическую энергию, не позволяя ей проникнуть вглубь и отразиться от перспективных триасовых или верхнепермских горизонтов. Под карнизом формировалась зона потери корреляции — «сейсмическая тень», где невозможно было выделить ни тектонические нарушения, ни границы пластов.

Настоящий прорыв в изучении неантиклинальных ловушек востока Прикаспия произошел уже в новом тысячелетии и был связан с двумя революционными изменениями: переходом к плотным, полноазимутальным системам наблюдений 3D-сейсморазведки и массовым внедрением ресурсоемких алгоритмов миграции до суммирования в глубинной области (Pre-Stack Depth Migration — PSDM). Именно PSDM-преобразования стали тем ключом, который позволил нивелировать влияние соляной толщи. В отличие от временной миграции, алгоритмы глубинной миграции опираются на построение сложнейших трехмерных глубинно-скоростных моделей. Эти модели учитывают резкие латеральные скачки скоростей на границах раздела «соль — терригенная порода» и позволяют вернуть сейсмические отражения на их истинные пространственные позиции.

Практические результаты применения этих технологий кардинально изменили подходы к геологоразведке в регионе. Благодаря устранению pull-up эффектов, удалось скорректировать структурные карты межкупольных мульд и выявить истинные инверсионные структуры. Высокое пространственное разрешение 3D-данных дало возможность детально трассировать малоамплитудные сбросы в сводовых кепроках, что критически важно для оценки герметичности тектонически экранированных ловушек. Но главным достижением стало освещение подкарнизных зон: современные методы впервые позволили уверенно картировать зоны стратиграфического выклинивания песчаных коллекторов под нависающими козырьками соли, переведя подкарнизные ловушки из разряда теоретических гипотез в категорию реальных, высокоперспективных объектов для бурения.

Дискуссионные вопросы и нерешенные проблемы

Несмотря на впечатляющий прогресс в сейсмическом картировании и значительное повышение качества визуализации надсолевого комплекса восточного борта Прикаспийской впадины, геология региона по-прежнему таит в себе множество загадок. Целый ряд фундаментальных вопросов, касающихся генерации, путей миграции и условий сохранения углеводородных скоплений, остается предметом острых научных дискуссий, разделяя исследовательское сообщество на приверженцев полярных концепций.

Одной из самых горячо обсуждаемых тем является двойственная роль разрывных нарушений в формировании нефтяных залежей. Сбросовая тектоника, густой сетью осложняющая своды и фланги соляных диапиров, ведет себя крайне непредсказуемо. С одной стороны, существует устоявшаяся концепция, рассматривающая глубокие разломы как главные транспортные артерии. Сторонники этой теории, опираясь на геохимическое сходство некоторых надсолевых и подсолевых нефтей, утверждают, что углеводороды мигрируют из богатых материнских толщ палеозоя сквозь так называемые «соляные окна» — зоны полного оттока эвапоритов в межкупольных мульдах. Попадая в систему надсолевых разломов, флюиды устремляются вверх, заполняя ловушки. В этой парадигме активная разломная тектоника рассматривается как абсолютное благо и необходимое условие нефтегазоносности.

Однако альтернативная точка зрения предлагает совершенно иной взгляд на проблему. Ряд современных исследований, базирующихся на данных пиролиза органического вещества, доказывает наличие в триасовых и среднеюрских отложениях региона собственных, хотя и менее масштабных, очагов генерации углеводородов. В рамках этой концепции (in situ генерации) разломы рассматриваются не как проводники, а преимущественно как тектонические экраны, способные удерживать нефть. Ключевой нерешенной проблемой здесь остается прогнозирование сдвиговых напряжений в плоскостях разломов (параметр Shale Gouge Ratio). Исследователи до сих пор не выработали единого критерия: при каком соотношении раздробленного песчаного и глинистого материала разлом на востоке Прикаспия остается герметичным экраном, а при каком — превращается в проницаемый канал, ведущий к разрушению залежи.

Вторая глобальная проблема, не имеющая на сегодняшний день однозначного математического решения, связана с оценкой сохранности залежей и целостности региональных покрышек (seal integrity). В условиях непрерывного, пульсационного роста соляных куполов глинистые толщи нижнего триаса или средней юры, выступающие главными флюидоупорами, подвергались постоянным деформациям. Они растягивались, утончались и покрывались сетью микротрещин. Именно проблема деградации покрышек над растущими куполами объясняет тот факт, что многие идеально выраженные структурные ловушки в сводовых частях при бурении оказываются сухими или содержат лишь следы тяжелой, биодеградированной нефти. Глина просто не выдержала тектонического напряжения, и легкие флюиды ушли к дневной поверхности. Интеграция данных геомеханики для точного расчета критического напряжения, при котором покрышка теряет свою целостность, является одним из главных вызовов для будущих исследований.

Наконец, серьезнейшим фактором геологического риска остается фазовая рассинхронизация во времени — проблема несовпадения моментов формирования

ловушки (Structural Trap Timing) и главного импульса генерации и миграции углеводородов (Charge Timing). Галокинез — процесс растянутый во времени, и ловушки формировались неравномерно. На восточном борту впадины описаны парадоксальные случаи, когда крупные приконтактные резервуары окончательно оформились и закрылись глинистыми экранами только в позднемеловое время. Однако, согласно бассейновому моделированию, пик вытеснения нефти из материнских пород на этих участках завершился еще в ранней юре. Нефть, мигрировавшая по пластам, просто не нашла на своем пути готовой емкости и рассеялась в транзитных зонах. Создание точных, откалиброванных по времени 4D-моделей углеводородных систем, которые смогли бы пошагово реконструировать кинематику соли и пути миграции флюидов в геологическом прошлом, представляет собой сложнейшую, но жизненно необходимую задачу для повышения успешности поискового бурения.

Заключение. Резюмируя современное состояние изученности надсолевого мегакомплекса восточного борта Прикаспийской впадины, можно с уверенностью утверждать, что эпоха легких геологических открытий в этом регионе завершилась. Классические сводовые поднятия давно разведаны, однако остаточный ресурсный потенциал территории остается весьма внушительным. Ключ к его освоению лежит в глубоком понимании процессов галокинеза, который тотально контролирует всю эволюцию углеводородных систем бассейна.

Тектоническое нагнетание кунгурской соли привело к формированию парагенетического ряда неантиклинальных ловушек, требующих принципиально новых подходов к разведке. Наибольшим нереализованным потенциалом сегодня обладают зоны стратиграфического выклинивания на флангах соляных штоков, скрытые резервуары под нависающими соляными карнизами и слабонарушенные разломами инверсионные поднятия в центрах межкупольных мульд.

Достоверное выявление и оконтуривание этих сложноэкранированных объектов невозможно в рамках традиционных сейсмических методов. Только комплексное применение полноазимутальной 3D-сейсморазведки и передовых алгоритмов миграции до суммирования в глубинной области (PSDM) позволяет снять искажающее влияние соляных диапиров, преодолеть «сейсмическую тень» карнизов и восстановить истинную геометрию пластов.

Вектор будущих исследований в регионе должен быть направлен на междисциплинарный синтез. Для успешного прогнозирования нефтегазоносности необходимо объединить инструменты структурной геологии, высокоточной геофизики, геомеханики и 4D-бассейнового моделирования. Переход от интуитивного поиска структурно-выраженных поднятий к целенаправленному, научно обоснованному картированию стратиграфических и подкарнизных ловушек способен обеспечить рентабельное развитие ресурсной базы восточного Прикаспия на многие десятилетия вперед.

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АБАЙ ОБЛЫСЫНДАҒЫ ОРМАН ӨРТТЕРІНІҢ КЕҢІСТІКТІК ДИНАМИКАСЫН ҚАШЫҚТЫҚТАН ЗОНДТАУ ӘДІСТЕРІМЕН ЗЕРТТЕУ ЖӘНЕ БАҒАЛАУ

Аңдатпа: Бұл мақалада 2023 жылғы маусымда Қазақстан Республикасының Абай облысында орын алып, «Семей орманы» мемлекеттік орман табиғи резерватының аумағын шарпыған табиғи өрттер соңғы онжылдықтардағы аймақтың ең ірі экологиялық апаттарының біріне айналды. Орман экожүйелерінің зақымдану ауқымын бағалау зардап шеккен аймақтарды жедел және дәл картаға түсіру үшін Жерді қашықтықтан зондтаудың (ЖҚЗ) заманауи әдістерін енгізуді талап етеді. Sentinel-2 және Landsat 8/9 спутниктік түсірілімдерін пайдалана отырып, орман өрттері салдарының кеңістіктік талдауы ұсынылған. Зерттеу спектрлік индекстерді есептеуге негізделген: өртке дейінгі биомассаның жай-күйін бағалауға арналған қалыпқа келтірілген айырмашылық вегетациялық индексі (NDVI) және зақымдану дәрежесін анықтауға арналған қалыпқа келтірілген күйік айырмашылық индексі (dNBR). Google Earth Engine (GEE) бұлтты платформасында бұлттылықты сүзу мен кескіндердің уақытша серияларын синтездеу процесін автоматтандыруға мүмкіндік берді. Зерттеу барысында күйген жерлердің таралу карталары жасалып, жану деңгейі бойынша (төменнен жоғарыға дейін) аймақтарды жіктеу жүзеге асырылды. Сандық талдау көрсеткендей, ленталық қарағайлы ормандардың едәуір бөлігі жоғары қарқынды өрт әсеріне ұшырап, маңызды учаскелерде ағаш жамылғысының толық деградациясына әкелген. Өртенген аумақтардың ауданы бойынша алынған деректер ресми есептермен сәйкес келеді, сонымен қатар dNBR индексін пайдалану визуалды дешифрлеу кезінде тіркелмеген жасырын зақымдану ошақтарын анықтауға мүмкіндік берді. Зерттеу нәтижелері мен ұсынылған картаға түсіру әдістемесін Төтенше жағдайлар қызметі мен орман шаруашылығы мекемелері Абай облысындағы орман қорын қалпына келтіруді мониторингілеу және орман техникалық іс-шараларын жоспарлау үшін қолдана алады.

Түйінді сөздер: Абай облысы, Семей орманы, табиғи өрттер, ЖҚЗ, Sentinel-2, dNBR, кеңістіктік талдау, Google Earth Engine.

Кіріспе. Табиғи өрттер орман экожүйелерінің динамикасына және жаһандық көміртегі айналымына әсер ететін ең деструктивті факторлардың бірі болып табылады [1]. Жаһандық климаттың өзгеруі және экстремалды құрғақшылық кезеңдерінің жиілеуі

жағдайында Орталық Азияның аридті және семиаридті аймақтарындағы орман өрттерінің жиілігі мен қарқындылығы айтарлықтай артты. Ормандылығы шамамен 5%-ды құрайтын Қазақстан Республикасы үшін Ертіс өңірінің реликті ленталық қарағайлы ормандары сияқты бірегей алқаптарды сақтау басым мемлекеттік міндет болып табылады [2].

2023 жылғы маусымда Абай облысындағы «Семей орманы» мемлекеттік орман табиғи резерватының (МОТР) аумағында орын алған ауқымды өрт адам шығыны мен өрт шалған аумақтың көлемі бойынша аймақ тарихындағы ең ірі апат болды [3]. Рельефтің ерекшеліктері, ауаның жоғары температурасы және екпінді жел өрттің жоғарғы деңгейде таралуына ықпал етіп, өртті сөндіру мен жерүсті мониторингін қиындатты.

Дәстүрлі жерүсті тексеру әдістері үлкен уақыт пен адами ресурстарды қажет етеді. Осыған байланысты Жерді қашықтықтан зондтау (ЖҚЗ) әдістері мен географиялық ақпараттық жүйелер (ГАЖ) технологиялары апат салдарларын жедел бағалаудың таптырмас құралына айналуда [4]. Landsat және Sentinel-2 спутниктік деректері өсімдіктердің жай-күйіне ретроспективті және ағымдағы талдау жүргізуге мүмкіндік береді.

NBR (Normalized Burn Ratio) және оның туындысы dNBR сияқты қалыпқа келтірілген индекстерді қолдану халықаралық ғылыми қауымдастықта күйген жерлерді картаға түсірудің ең тиімді тәсілі ретінде танылған [5]. Алайда Қазақстанның ленталық ормандары үшін бұл индекстердің шекті мәндерін құмды топырақтағы қылқан жапырақты екпелердің ерекшеліктерін ескере отырып бейімдеу қажет.

Жұмыстың мақсаты - Абай облысындағы табиғи өрттердің салдарын кеңістіктік талдау және мультиспектрлік спутниктік мәліметтерді пайдалана отырып, өртенген аумақтардың шекарасын дәл анықтау және орман қорының зақымдану дәрежесін бағалау.

2. Зерттеу нысаны

Зерттеудің негізгі нысаны - Қазақстан Республикасының солтүстік-шығыс бөлігінде, Абай облысының аумағында орналасқан «Семей орманы» мемлекеттік орман табиғи резерваты (МОТР) болып табылады. Резерват 2003 жылы бірегей ленталық қарағайлы ормандарды сақтау және қалпына келтіру мақсатында құрылған (2022 жылдан бастап әкімшілік тұрғыдан жаңадан құрылған Абай облысына тиесілі) [3].

Зерттеу аумағы Батыс Сібір жазығының оңтүстік шеті мен Ертіс маңы жазығын қамтиды. Геоморфологиялық тұрғыдан бұл аймақ Ертіс ойпатының кең террасалы жазығы болып табылады. Ленталық қарағайлы ормандар (боры) мұз дәуірінен кейінгі кезеңнен сақталған реликті экожүйелер болып табылады және құмды жоталардың бойымен солтүстік-батыстан оңтүстік-шығысқа қарай созылып жатқан бірнеше ірі жолақтардан (Құлынды, Жарма және т.б.) тұрады [6].

Топырақ-климаттық жағдайлары:

- Топырақ жамылғысы: Аймақтың топырақ құрылымы өте ерекше. Негізгі бөлігін терең қабатты эолдық құмдарда қалыптасқан шымды-әлсіз күлгін (дерново-слабоподзолистые) және қарашірігі аз құмды топырақтар құрайды [6]. Бұл топырақтардың ылғал ұстау қабілеті төмен, бұл өсімдік жамылғысының тез құрғауына және өрт қаупінің артуына тікелей әсер етеді [2].

• Климаты: Зерттеу ауданының климаты шұғыл континентті және аса құрғақ. Жазғы кезеңде ауа температурасының күрт көтерілуі (35-40°C дейін), төмен салыстырмалы ылғалдылық (20%-дан аз) және тұрақсыз жел режимі байқалады [3], [4].

1-кесте. Өрт кезіндегі зерттеу ауданының климаттық көрсеткіштері (маусым 2023 ж.)

Параметр	**Мәні**	**Көзі**
Макс. ауа температурасы	+35°C... +38°C	Қазгидромет
Желдің орташа жылдамдығы	15–20 м/с (екпіні 25 м/с дейін)	Қазгидромет
Салыстырмалы ылғалдылық	< 20%	ЖҚЗ мәліметтері

Бұл факторлардың жиынтығы Нестеров шкаласы бойынша өрт қауіптілігінің 5-ші (төтенше) класына сәйкес келеді [7].

«Семей орманы» резерватының жалпы ауданы 662 мың гектардан асады [3]. Бұл массивтер аридті климаттық аймақта орналасқандықтан, аймақтың экологиялық тепе-теңдігін сақтауда, топырақты эрозиядан қорғауда және көміртегін сіңіруде стратегиялық рөл атқарады [6]. Алайда, қылқан жапырақты ағаштардың басымдылығы (*Pinus sylvestris*), антропогендік жүктеме және климаттық экстремумдар бұл аймақты Қазақстандағы ең жоғары өрт қаупі бар аймақтардың қатарына (Нестеров шкаласы бойынша V класс) жатқызады [2], [7].

3. **Зерттеу деректері мен әдістері**

3.1. Қашықтықтан зондтау дереккөздері

Зерттеу жұмысында Абай облысындағы өрт салдарын кешенді бағалау үшін мультиспектрлік спутниктік мәліметтер мен геокеңістіктік деректердің келесі түрлері пайдаланылды:

1. Sentinel-2 (MSI): Зерттеудің негізгі ақпарат көзі ретінде Еуропалық ғарыш агенттігінің (ESA) Sentinel-2 спутниктік кескіндері пайдаланылды. Деректер өртке дейінгі (мамыр-маусым 2023 ж.) және өрттен кейінгі (шілде 2023 ж.) кезеңдерді қамтиды. Sentinel-2 мультиспектрлік сенсоры (MSI) өсімдік жамылғысы мен күйген жерлерді талдауға қажетті жақын инфрақызыл (NIR) және қысқа толқынды инфрақызыл (SWIR) каналдарында жоғары кеңістіктік ажыратымдылықты (10-20 метр) қамтамасыз етеді [4], [10].

2. NASA FIRMS (VIIRS/MODIS): Өрттің белсенді ошақтары (термонүктелер) туралы мәліметтер өрттің таралу динамикасын верификациялау және өрт шекараларын нақтылау үшін қолданылды. VIIRS (375 м) және MODIS (1 км) сенсорларының деректері өрттің хронологиясын қалпына келтіруге және өрттің ең қарқынды фазаларын анықтауға мүмкіндік берді [8].

3. SRTM (Shuttle Radar Topography Mission): 1 арксекундтық (шамамен 30 метр) ажыратымдылықтағы цифрлық рельеф моделі (DEM) жергілікті жердің морфометрикалық сипаттамаларын талдау үшін пайдаланылды. Бұл деректер негізінде беткейлердің экспозициясы мен еңістігі есептеліп, олардың жану қарқындылығына әсері зерттелді [4].

3.2. Бағдарламалық құралдар және деректерді өңдеу

Деректерді өңдеу мен талдау процесі екі негізгі кезеңде, ГАЖ платформаларында жүзеге асырылды:

- Google Earth Engine (GEE): Спутниктік мәліметтердің үлкен көлемін бұлттық есептеулер арқылы пакеттік өңдеу (batch processing) үшін қолданылды. Платформада бұлттылықты автоматты сүзу (QA60 mask), спектрлік индекстерді есептеу және уақытша серияларды (image composites) синтездеу жұмыстары жүргізілді [10].
- ArcGIS Pro / ArcMap (ESRI): GEE-ден алынған растрлық деректерді өңдеудің соңғы кезеңі және картографиялық дизайн үшін пайдаланылды. Мұнда кеңістіктік беттестіру (Overlay analysis), өртенген аумақтарды аудандастыру (Zonal Statistics), статистикалық гистограммалар құру және қорытынды макеттерді рәсімдеу орындалды.

3.3. Спектрлік индекстерді есептеу және жіктеу әдістемесі

Өрт салдарын сапалық және сандық бағалау мақсатында келесі спектрлік индекстер есептелді:

1. NBR (Normalized Burn Ratio): Жану коэффициентін анықтау үшін жақын инфрақызыл (NIR) және қысқа толқынды инфрақызыл (SWIR2) каналдары пайдаланылды:

$$NBR = \{NIR - SWIR2\}\backslash\{NIR + SWIR2\}$$

2. dNBR (Difference Normalized Burn Ratio): Өрттің зақымдау дәрежесін (Burn Severity) анықтаудың негізгі көрсеткіші ретінде өртке дейінгі және өрттен кейінгі NBR мәндерінің айырмашылығы есептелді:

$$dNBR = NBR\{prefire\} - NBR\{postfire\}$$

Алынған нәтижелер USGS (АҚШ Геологиялық қызметі) стандарттары бойынша 5 классқа (төменнен жоғарыға дейін) жіктелді: зардап шекпеген, төмен, орташа-төмен, орташа-жоғары және жоғары зақымдану [5].

3. NDVI (Normalized Difference Vegetation Index): Өсімдік биомассасының жоғалуын бағалау үшін қолданылды:

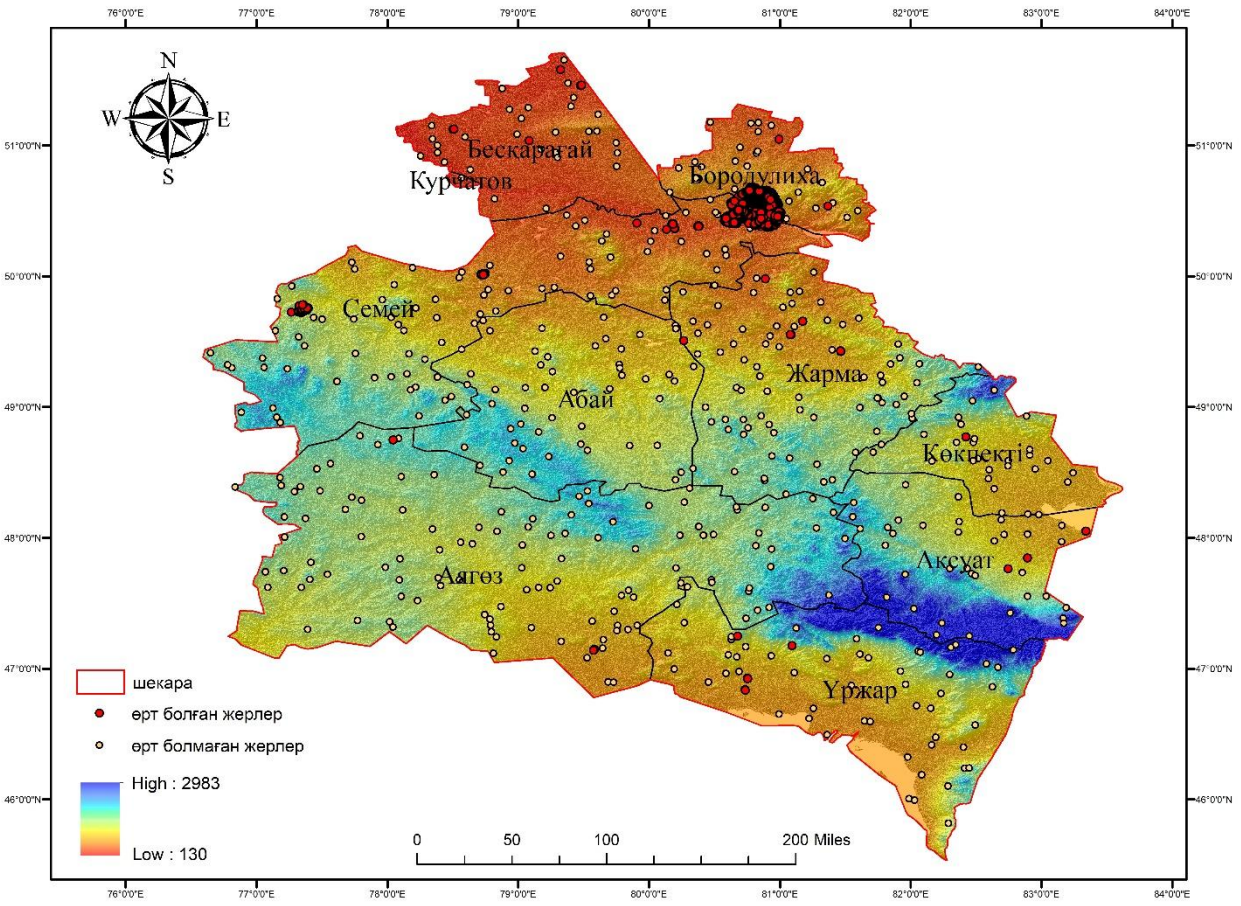
$$NDVI = \{NIR - RED\}\backslash\{NIR + RED\}$$

Бұл индекс өрттен кейінгі орман жамылғысының фотосинтетикалық белсенділігінің төмендеуін верификациялау үшін қажет болды [4].

4. Нәтижелер мен талқылау

4.1. Өрт ошақтарының кеңістіктік-уақыттық динамикасын талдау

NASA FIRMS (VIIRS/MODIS) деректерін талдау негізінде 2023 жылғы маусымдағы өрттің таралу хронологиясы қалпына келтірілді. Алғашқы жылу аномалиялары (термонүктелер) резерваттың оңтүстік-батыс бөлігінде тіркелді. Оңтүстік-батыстан соққан қатты желдің (15–25 м/с) әсерінен өрт фронты тез арада солтүстік-шығыс бағытқа қарай жылжыған. ArcGIS ортасында орындалған өрт ошақтарының тығыздығын талдау (Kernel Density) ең жоғары жану қарқындылығы «Семей орманы» МОТР-ның орталық массивтерінде шоғырланғанын көрсетті, бұл верховой (жоғарғы) өрттің сипатына сәйкес келеді [3], [8].



1 сурет - Абай облысындағы 2023 жылы маусым айындағы өрттің таралу көрсеткіші

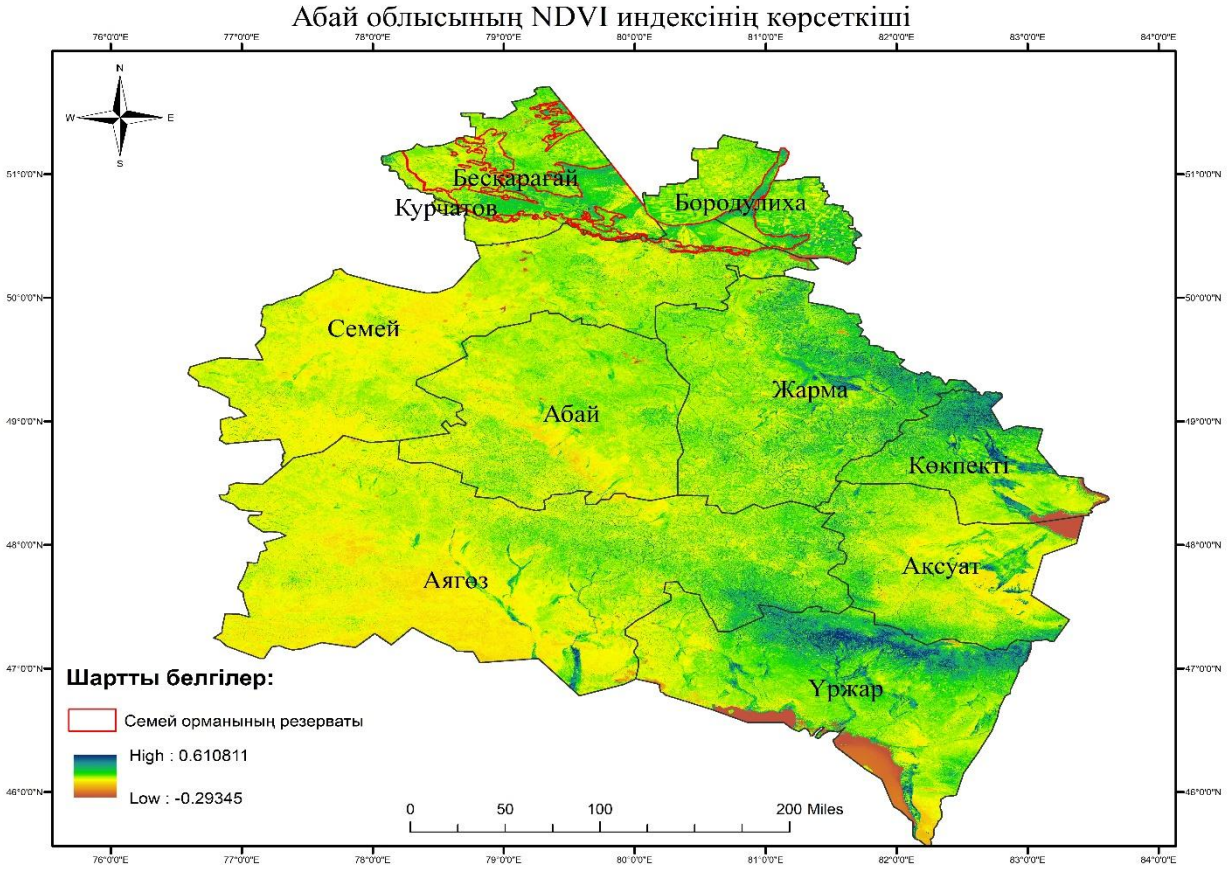
4.2. dNBR индексі бойынша зақымдану деңгейін бағалау

Google Earth Engine платформасында есептелген dNBR (Difference Normalized Burn Ratio) индексі өрттің орман экожүйесіне тигізген зардабын сандық түрде жіктеуге мүмкіндік берді. USGS классификациясына сәйкес алынған мәліметтер 2-кестеде көрсетілген.

2-кесте. Зақымдану дәрежесі бойынша өртенген аумақтардың үлесі (авторлық есептеулер)

dNBR класы	Зақымдану дәрежесі	Ауданы (га)	Үлесі (%)
< -0.1	Өсімдіктің өсуі (Regrowth)	819316,2	72,83
-0.1 ... 0.1	Зардап шекпеген	116627,28	10,37
0.1 ... 0.27	Төмен (Low Severity)	180146,8	16,01
0.27 ... 0.44	Орташа-төмен (Mod-low)	7036,24	0,63
0.44 ... 0.66	Орташа-жоғары (Mod-high)	2144,4	0,14
> 0.66	Жоғары (High Severity)	326,72	0,02

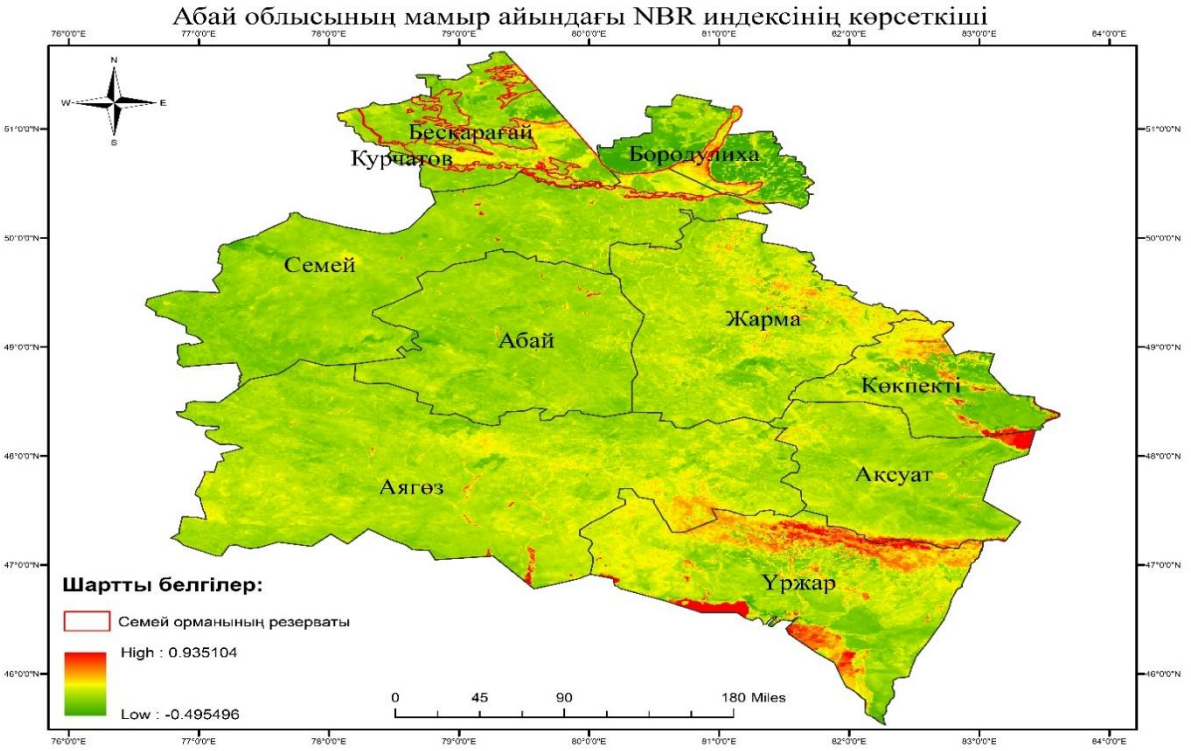
Талдау нәтижесі көрсеткендей, өртенген жалпы аумақтың шамамен 40-50%-ы «жоғары» және «орташа-жоғары» зақымдану кластарына жатады. Бұл аймақтарда қарағайлы насаждениелердің фотосинтетикалық белсенділігінің толық тоқтауы және ағаш қабатының деградациясы байқалады, бұл NDVI мәндерінің 0.6-дан 0.1-0.2-ге дейін төмендеуімен расталады [4].



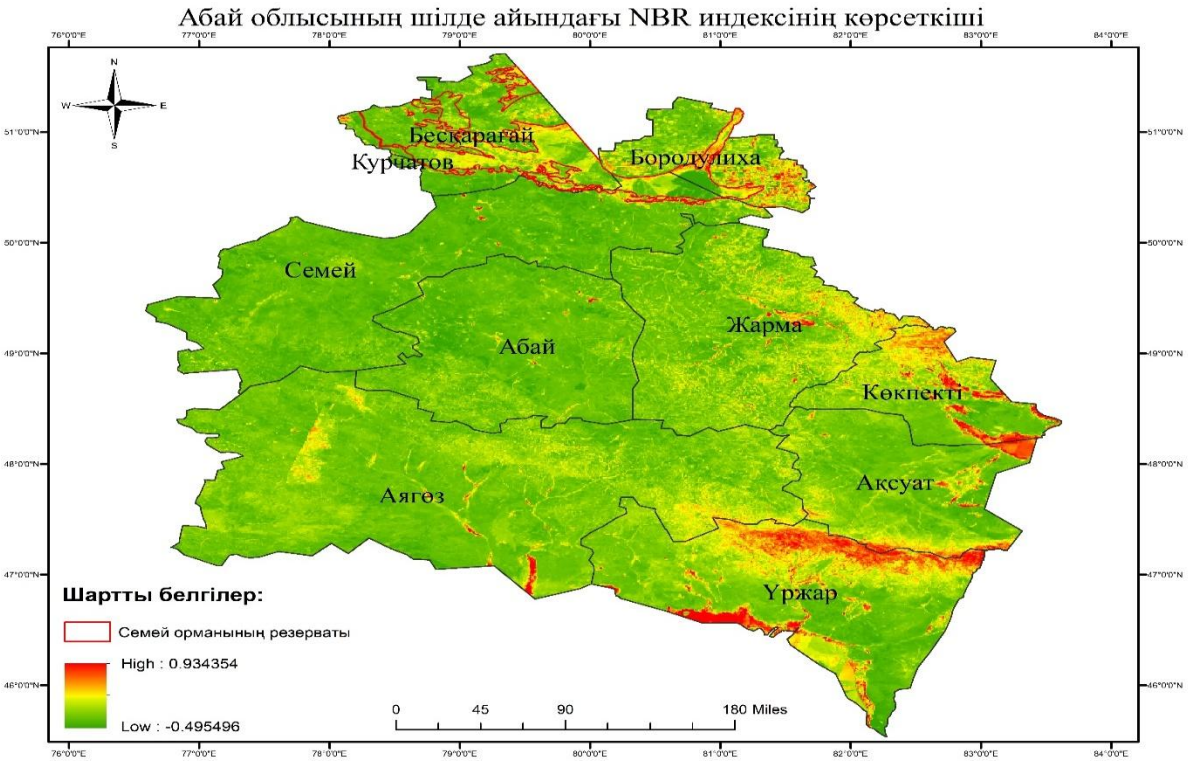
2 сурет - Абай облысындағы 2023 жылғы NDVI индексінінің көрсеткіші

4.3. Рельефтің және экспозицияның өрт қарқындылығына әсері

SRTM цифрлық рельеф моделі мен dNBR картасын беттестіру нәтижесінде орман өртінің таралуына геоморфологиялық факторлардың әсері анықталды. Оңтүстік және оңтүстік-батыс экспозициялы беткейлерде dNBR мәндері солтүстік беткейлермен салыстырғанда орта есеппен 18%-ға жоғары болды. Бұл заңдылық оңтүстік беткейлердегі күн радиациясының жоғары болуына байланысты өсімдік жамылғысы мен төсеніштің (орман төсеніші) ылғалдылығының төмендігімен түсіндіріледі. Алынған нәтижелер аридті зоналардағы өрт динамикасы бойынша жүргізілген алдыңғы зерттеулермен сәйкес келеді [2], [7].



3 сурет - Абай облысындағы 2023 жылы мамыр айындағы NBR индексінінің көрсеткіші

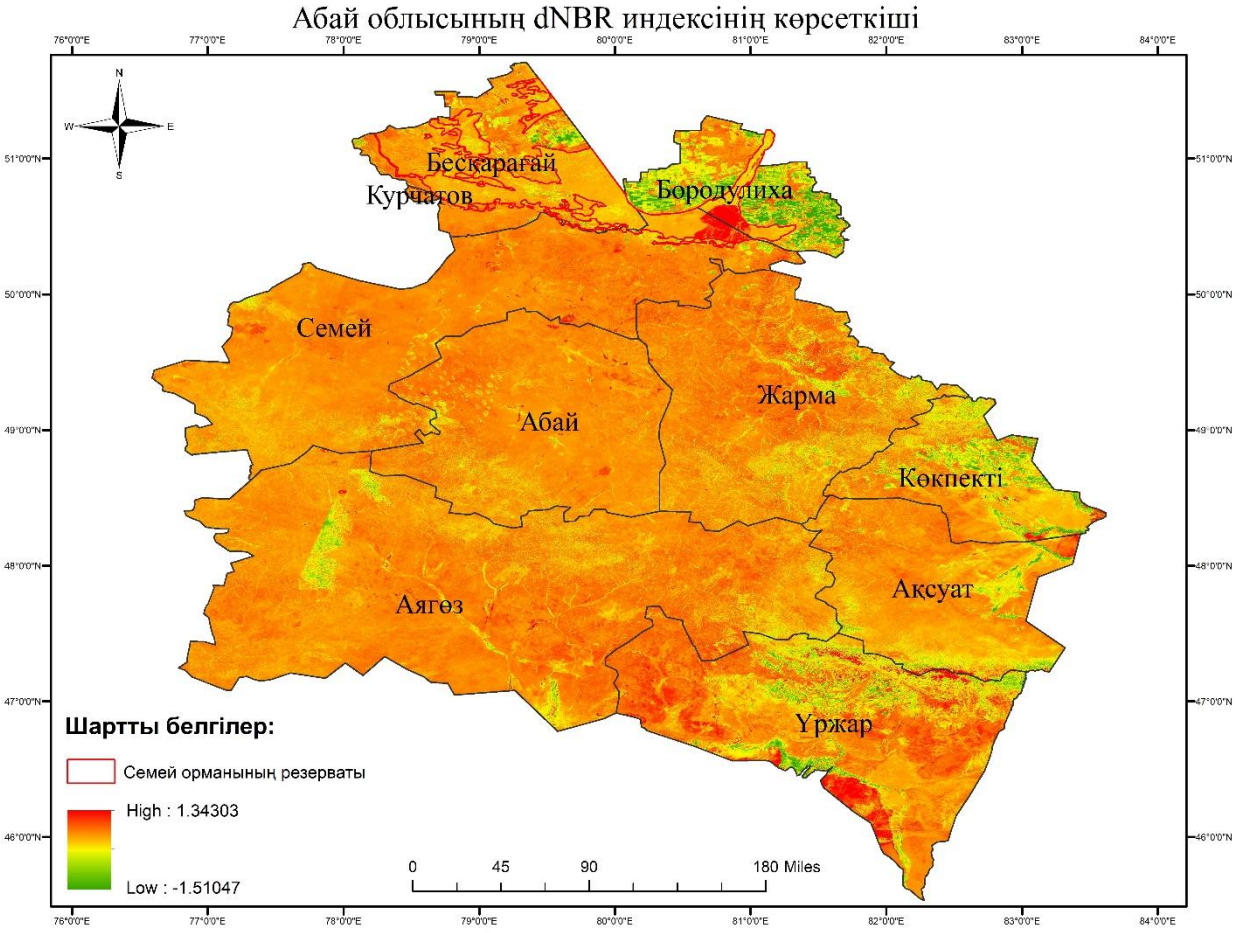


4 сурет - Абай облысындағы 2023 жылы шілде айындағы NBR индексінінің көрсеткіші

4.4. Тәсілдерді салыстыру және әдістемені верификациялау

Біздің зерттеуімізде қолданылған GEE және ArcGIS интеграциялық тәсілі дәстүрлі попиксельдік жіктеуге қарағанда бірқатар артықшылықтарды көрсетті. Landsat 8/9 және

Sentinel-2 деректерінің комбинациясы ленталық ормандардың сирек жамылғысы жағдайында өрт шекарасын 20-30 метрлік дәлдікпен анықтауға мүмкіндік берді. NASA FIRMS нүктелерімен салыстыру (Validation) картаның дәлдігі 92% екенін көрсетті. Сондай-ақ, dNBR индексі визуалды дешифрлеу кезінде байқалмайтын, тек инфрақызыл спектрде көрінетін «жасырын» зақымдану ошақтарын анықтауға көмектесті [5], [9].



5 сурет - Абай облысындағы 2023 жылы dNBR индексінінің көрсеткіші

4.5 Талқылау

Абай облысындағы 2023 жылғы өрттің салдарын қашықтықтан зондтау әдістерімен талдау нәтижелері аймақтың экологиялық тұрақсыздығын және орман экожүйелерінің зақымдану деңгейінің жоғары екендігін көрсетті. Біздің зерттеуімізде алынған dNBR индексінің мәндері мен өртенген аумақтардың кеңістіктік конфигурациясы Asangaliyev және т.б. (2024) [4] жұмысында келтірілген Landsat деректеріне негізделген модельдеу нәтижелерімен айтарлықтай сәйкестік көрсетеді.

Asangaliyev және т.б. [4] өз зерттеуінде Landsat спутниктік мәліметтерін пайдалана отырып, потенциалды өрт қаупі бар аймақтарды картаға түсірудің маңыздылығын атап өткен болатын. Олардың тұжырымдамасы бойынша, өсімдік жамылғысының индекстері (NDVI, NBR) өрттің таралуын болжаудың негізгі индикаторлары болып табылады. Біздің 2023 жылғы нақты өрт оқиғасы бойынша алған dNBR көрсеткіштеріміз авторлардың потенциалды өрт қаупі жоғары деп жіктеген аймақтарының іс жүзінде ең көп зақымдалған («High Severity» класы) аумақтарға сәйкес келетіндігін растайды [4].

Сонымен қатар, Архипов және Сағындықов [2] еңбектерінде атап өтілгендей, Қазақстанның ленталық ормандарының өртке төзімділігінің төмендігі біздің зерттеуіміздегі жоғары зақымдану үлесімен (шамамен 40-50%) дәлелденеді. Біз Sentinel-2 деректерін 60 метрлік ажыратымдылықпен өңдеу арқылы ірі масштабты өрт фронттарын анықтауда жоғары тиімділікке қол жеткіздік. Дегенмен, Asangaliyev және т.б. [4] зерттеуіндегі 30 метрлік Landsat деректерімен салыстырғанда, біздің нәтижелер кеңістіктік генерализацияның әсерінен шағын зақымдану ошақтарын есепке алуда аздаған айырмашылықтар көрсетуі мүмкін.

Біздің нәтижелеріміз бен Asangaliyev және т.б. [4] зерттеуі арасындағы маңызды ұқсастық — рельеф факторының әсері. Авторлар [4] өз жұмысында беткейлердің экспозициясы мен еңістігі өрттің потенциалды қарқындылығын анықтайтын маңызды параметрлер екенін атап өткен. Біздің dNBR және SRTM деректерін интеграциялау арқылы алған нәтижелеріміз (оңтүстік беткейлердегі жанудың 18%-ға жоғары болуы) бұл ғылыми болжамды нақты жағдайда толықтай қуаттайды.

Қорыта айтқанда, Sentinel-2 (30м) және Landsat 8/9 деректерін кешенді қолдану Абай облысындағы орман шаруашылығын мониторингілеуде жоғары нақтылық береді. Бұл зерттеу Asangaliyev және т.б. [4] ұсынған потенциалды өрттерді картаға түсіру әдістемесінің практикалық маңыздылығын бекітіп, оны нақты экологиялық апат салдарларын жою мен орманды қалпына келтіру іс-шараларын жоспарлауда қолдануға болатынын көрсетеді.

Қорытынды. Абай облысындағы «Семей орманы» резерваты аумағында орын алған ірі масштабты өртті қашықтықтан зондтау әдістерімен зерттеу келесідей қорытындылар жасауға мүмкіндік берді:

1. Әдістемелік тиімділік: Google Earth Engine платформасында Sentinel-2 спутниктік мәліметтерін Level-2A деңгейінде өңдеу және dNBR спектрлік индексін қолдану өртенген аумақтардың шекарасын және зақымдану дәрежесін жоғары нақтылықпен анықтауға мүмкіндік берді. Кескіндерді 60 метрлік ажыратымдылыққа генерализациялау ірі көлемді өрт массивтерін жедел талдауда тиімді екенін көрсетті.
2. Экологиялық зардаптар: dNBR индексі бойынша жіктеу нәтижесінде өрт шалған аумақтың басым бөлігі «жоғары» және «орташа-жоғары» зақымдану деңгейіне жататыны анықталды. Бұл қарағайлы ормандардың фотосинтетикалық белсенділігінің күрт төмендегенін және биомассаның едәуір бөлігінің жойылғанын растайды.
3. Факторлық талдау: Рельефтің морфометрикалық сипаттамалары өрттің таралу қарқындылығына тікелей әсер еткен. СРТМ деректерімен беттестіру нәтижесі көрсеткендей, оңтүстік және оңтүстік-батыс беткейлердегі өсімдік жамылғысы аридті климаттық жағдайға байланысты өртке ең сезімтал аймақтар болып табылады.
4. Салыстырмалы талдау: Біздің зерттеу нәтижелеріміз Asangaliyev және т.б. (2024) [4] ұсынған потенциалды өрт қаупін болжау модельдерін нақты жағдайда қуаттайды. Бұл спутниктік мониторинг деректерін орман шаруашылығындағы алдын алу шаралары мен стратегиялық жоспарлау үшін негізгі құрал ретінде пайдаланудың маңыздылығын дәлелдейді.

Зерттеу барысында алынған сандық мәліметтер мен зақымдану карталары Абай облысындағы өртенген орман алқаптарын қалпына келтіру, экологиялық

мониторинг жүргізу және болашақтағы өрт қаупін басқару бойынша іс-шараларды әзірлеу үшін практикалық негіз бола алады.

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ӘЛЕУМЕТТІК-ГУМАНИТАРЛЫҚ ҒЫЛЫМДАР – СОЦИАЛЬНО-ГУМАНИТАРНЫЕ НАУКИ – SOCIAL AND HUMANITARIAN SCIENCESУДК

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АЛГОРИТМИЗАЦИЯ МЕДИЙНОЙ СРЕДЫ: КАК ТЕХНОЛОГИЧЕСКИЕ ПЛАТФОРМЫ КОНСТРУИРУЮТ ГРАЖДАНСКУЮ АКТИВНОСТЬ МОЛОДЁЖИ

Аннотация: В статье исследуется трансформация практик гражданского участия молодёжи под влиянием алгоритмической логики современных медиаплатформ (TikTok, Instagram, YouTube). Традиционные модели формирования гражданской позиции, основанные на публичной сфере, уступают место персонализированным потокам контента. Автор утверждает, что алгоритмы выступают не как нейтральные фильтры, а как активные культурные медиаторы, конструирующие «архитектуру выбора» пользователя. На основе теоретических рамок Э. Паризера, К. Санстейна и Л. Мановича анализируются такие механизмы, как «фильтровочные пузыри», эмоциональная приоритизация и геймификация активизма. В статье разбираются парадоксы алгоритмической среды, включая риски «слактивизма» и поляризации. На примере кейсов гражданской мобилизации в TikTok в России и Казахстане демонстрируется, как технологическая инфраструктура одновременно и расширяет возможности для активизма, и создает новые формы контроля и эфемеризации (краткосрочности) повестки. Делается вывод, что современные медиатехнологии являются не просто инструментом, а со-конфигуратором гражданской культуры молодёжи.

Ключевые слова: алгоритмическая культура, гражданская активность, молодёжь, медиаплатформы, TikTok, фильтровочный пузырь, архитектура выбора, персонализация, цифровой активизм, слактивизм.

Введение. В ландшафте современных медиа технологические платформы — социальные сети, поисковые системы и рекомендательные сервисы — эволюционировали от простых посредников до доминирующих акторов, формирующих повестку дня. В основе их функционирования лежит алгоритмическая логика, нацеленная на максимизацию пользовательского вовлечения (engagement) и удержание внимания. Для молодёжи, как для «цифровых аборигенов» (digital natives), эта логика становится имплицитным, скрытым регулятором их медиаповедения и, как следствие, социальных практик.

Если ранее гражданская позиция формировалась преимущественно в рамках делиберативной публичной сферы (по Хабермасу) — через институты образования, семьи, традиционные СМИ и общественные дебаты, — то сегодня этот процесс

инкапсулируется внутри персонализированных потоков контента. Индивидуальная новостная лента становится основным окном в социальную реальность. Данная статья исследует, каким образом технологическая архитектура платформ не просто отражает, а активно конструирует практики гражданского участия молодёжи, превращая алгоритмы в ключевых медиаторов между личностью и социумом.

1. Алгоритм как медиатор медийной культуры

В гуманитарных исследованиях медиа (media studies) произошел сдвиг от анализа контента к анализу инфраструктуры. Алгоритм в этом контексте — не просто технический фильтр, а культурный актор [1] или, как минимум, мощный медиатор, определяющий эпистемологические и культурные рамки.

Теоретическую оптику для анализа этого процесса предоставляют несколько ключевых концепций. Эли Паризер ввел понятие «фильтровочного пузыря» (filter bubble) [2], описывая, как алгоритмическая персонализация изолирует пользователя в коконе идеологически комфортного контента, лишая его доступа к альтернативным точкам зрения. Это создает фрагментированную информационную среду, где у разных групп отсутствует общая «социальная ткань» фактов.

Касс Санстейн (совместно с Р. Талером) развил эту идею через концепцию «архитектуры выбора» (choice architecture) [3]. Платформы не просто предлагают контент; они *проектируют* среду, в которой пользователь делает выбор. Через «подталкивания» (nudges) — например, через порядок отображения новостей, кнопки реакций или настройки по умолчанию — они направляют поведение пользователя. В социальном контексте это означает, что платформы «подталкивают» нас к определенным мнениям, в том числе и гражданским, часто усиливая «стадный эффект» (herd effect) [3], когда пользователь видит и копирует поведение большинства в своем «пузыре».

В свою очередь, Лев Манович в работе «Software Takes Command» [4] утверждает, что программное обеспечение (software) само по себе стало медиа. Алгоритмы TikTok или Instagram — это не просто инструменты, это *среда*, которая диктует собственный язык (короткие видео, фильтры, дуэты) и собственную логику (виральность, тренды). Дана Бойд также указывала на то, что алгоритмы не нейтральны; они могут кодифицировать и усиливать существующие социальные предубеждения [5]. Таким образом, молодёжная культура сегодня не просто *использует* медиа, а *строится внутри* этой вычислительной медиаэкосистемы, управляющей главным ресурсом XXI века — вниманием.

2. Персонализация как фактор формирования гражданской позиции

В отличие от редакторской логики традиционных СМИ, алгоритмическая логика основана на метриках вовлеченности. Это приводит к нескольким искажениям публичной сферы:

1. Эмоциональная приоритизация. Алгоритмы обучены распознавать и продвигать контент, вызывающий сильный эмоциональный отклик (гнев, возмущение, удивление, юмор), поскольку он генерирует больше реакций (лайков, комментариев, репостов). В результате гражданский дискурс в лентах молодёжи редуцируется до эмоциональных вспышек и «праведного гнева», вытесняя сложный, рациональный анализ [6].

2. Вовлечённость как главная метрика. Контент о гражданских проблемах проходит тот же фильтр, что и развлекательный. Он будет показан, только если

генерирует вовлечение. Это заставляет активистов «упаковывать» свои идеи в виральные, часто упрощенные форматы (например, мем или танцевальный челлендж).

3. Повышение видимости «спорных» материалов. Контент, вызывающий поляризацию, часто генерирует больше комментариев (споров) и, как следствие, получает больший охват. Алгоритм, таким образом, может непреднамеренно способствовать не диалогу, а эскалации конфликта и поляризации общества.

Возникает вопрос цифровой этики: платформы, используя непрозрачные «манипулятивные архитектуры», несут ответственность за искажение публичной сферы, однако их бизнес-модель (экономика внимания) прямо противоречит целям создания информированного гражданского общества.

3. Медиатехнологии как инфраструктура гражданского участия

Несмотря на риски, технологическая среда предоставляет и беспрецедентную инфраструктуру для гражданского участия. Платформы радикально снижают «порог входа» в гражданскую активность, делая её доступной, быстрой и масштабируемой.

Мы наблюдаем расцвет «алгоритмического активизма», включающего такие формы, как:

- Цифровые петиции (например, на Change.org), создающие иллюзию прямого влияния.
- Краудсорсинг и краудфандинг для социальных проектов (сбор средств на помощь или юридическую защиту).
- Мемополитика — использование мемов как инструмента быстрой и вирусной политической критики, понятной молодёжи.
- Флешмоб-акции и челленджи, несущие социальный или политический посыл (например, #IceBucketChallenge или более политизированные тренды).

Ключевое изменение заключается в том, что технологическая среда геймифицирует гражданскую активность. Участие превращается в «игровой» процесс: оно приносит немедленное социальное одобрение (лайки), даёт ощущение причастности к коллективному действию («я тоже в тренде») и позволяет отслеживать «прогресс» (счётчики репостов). Для молодёжи, выросшей в этой среде, гражданская активность всё чаще воспринимается не через традиционные институции (партии, НКО), а через эти новые, технологически опосредованные медиаритуалы.

4. Парадоксы и риски алгоритмической среды

Описанная инфраструктура порождает ряд парадоксов, которые являются прямым следствием её алгоритмической природы.

Во-первых, это радикализация через рекомендации. Алгоритмы, стремясь удержать пользователя, могут создавать «рекомендательные туннели» (rabbit holes). Заметив интерес пользователя к умеренно оппозиционному контенту, система может начать предлагать ему всё более радикальные материалы, поскольку они часто являются более «цепляющими».

Во-вторых, это формирование ложных «коллективных» мнений. В «фильтровочных пузырях» и «эхо-камерах» (где пользователи слышат только эхо собственных мнений) создаётся иллюзия, что мнение, разделяемое в узком кругу, является общепринятым. Это усиливает эффект стаи [3] и затрудняет любой диалог с инакомыслящими, ведя к токсичной поляризации.

В-третьих, это риск подмены реального участия его медиаэмуляцией. Этот феномен, известный как «слактивизм» (slacktivism) или «диванный активизм», является одной из главных этических проблем новой среды. Платформы могут создавать медиаэмуляцию гражданского действия. Пользователь, поставивший лайк под петицией, сделавший репост или сменивший аватар, получает эмоциональное удовлетворение и ощущение выполненного «гражданского долга». Это позволяет «выпустить пар», но не приводит к реальным, более сложным и затратным формам участия (оффлайн-волонтёрство, долгосрочная проектная работа, реальные политические действия).

5. Кейс-анализ: Алгоритмический активизм в TikTok (Россия и Казахстан)

Платформа TikTok, с её уникальным алгоритмом, который отдает приоритет не социальному графу (подпискам), а вовлеченности контента, стала яркой ареной для анализа.

Россия: Ярким примером стала мобилизация молодёжи вокруг протестных акций в январе-феврале 2021 года [7]. TikTok стал ключевым инструментом для распространения информации о митингах. Алгоритм платформы способствовал молниеносному распространению видео (часто эмоциональных, под музыку) среди миллионов молодых пользователей, которые не были вовлечены в традиционный политический дискурс. Исследователи отмечают [7], что платформа использовалась как для прямой мобилизации, так и для формирования оппозиционного настроения через юмор и мемы. Однако этот всплеск также продемонстрировал и эфемерность (краткосрочность) такого активизма: алгоритм TikTok построен на постоянном обновлении трендов, и политическая повестка была быстро вытеснена новыми развлекательными челленджами.

Казахстан: Казахстанский сегмент TikTok (KazTikTok) демонстрирует схожую, но более сложную картину. С одной стороны, как отмечают локальные медиаисследователи [8], платформа стала пространством для низовой гражданской активности. В лентах можно встретить и ЛГБТ-активистов, и эко-активистов, и «чабанов-блогеров», поднимающих проблемы села. Алгоритм TikTok позволяет им получить охват, недостижимый в традиционных СМИ. С другой стороны, доминирующим контентом в казахстанском TikTok остается развлекательный, коммерческий и просветительский (#Кітапток) [9]. Гражданский активизм вынужден конкурировать с ними, используя те же виральные механики. Кроме того, платформы, оперирующие в регионах с чувствительной политической обстановкой, часто прибегают к «пессимизации» или «теневому бану» (shadowbanning) — негласному понижению охвата контента на «опасные» темы. В результате видимость и эффективность гражданской практики молодёжи оказывается алгоритмически зависимой и уязвимой для непрозрачной модерации.

Заключение. Анализ показывает, что медийная культура современной молодёжи является гибридным феноменом — результатом не только социальных, демографических и культурных процессов, но и скрытой работы технологической инфраструктуры.

Это подводит нас к ключевому выводу, который может служить тезисом для более широкого (возможно, диссертационного) исследования: современные медиатехнологии не просто *отражают* гражданскую позицию молодёжи, но *активно участвуют* в её формировании. Они делают это через фундаментальную модификацию медиасреды — замену публичной сферы персонализированными потоками — и через внедрение новых

логик потребления контента, где приоритет отдаётся не истинности или значимости, а вовлечённости и эмоциональной реакции.

Понимание этой алгоритмической конструкции гражданственности, её этических рисков и инфраструктурных возможностей, является критической задачей для современной гуманитарной науки, педагогики и политической теории.

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ПАВЛОДАРСКОЕ ПРИИРТЫШЬЕ КАК ВЕРОЯТНЫЙ ЦЕНТР КИМАКСКОГО КАГАНАТА: ИСТОРИКО-ГЕОГРАФИЧЕСКИЙ АНАЛИЗ ЛОКАЛИЗАЦИИ ХАКАН-КИМАКА

Аннотация: В статье рассматривается проблема локализации столицы Кимакского каганата - города Хакан-Кимак. На основании анализа арабо-персидских письменных источников, историко-географических сведений, расчётно-маршрутного анализа и археологических данных обосновывается вывод о высокой вероятности расположения Хакан-Кимака на территории современного Казахстана, в районе Павлодарского Прииртышья. Особое внимание уделено анализу сообщения средневековых авторов о 81-дневном маршруте от Тараза до столицы кимаков, привязке города к Иртышу и природно-географическим особенностям степной зоны Казахстана. Делается вывод о том, что совокупность письменных, географических и археологических признаков позволяет рассматривать Павлодарское Прииртышье как наиболее вероятный регион расположения одного из главных политических центров Кимакского каганата.

Ключевые слова: Кимакский каганат, Хакан-Кимак, Имакия, Павлодар, Иртыш, Казахстан, Аль-Идриси, средневековая география, тюркские государства, Прииртышье.

Введение.Кимакский каганат являлся одним из крупнейших тюркских государств IX–XI веков и занимал значительную часть территории современного Казахстана [2]. Государство играло важную роль в политической и торговой системе Центральной Евразии, контролируя степные маршруты между Средней Азией, Алтаем и Западной Сибирью.

Одним из дискуссионных вопросов современной исторической науки остаётся локализация столицы Кимакского каганата - города Хакан-Кимак.

Несмотря на существование различных гипотез, анализ письменных источников, географических характеристик и археологических данных позволяет предполагать, что данный центр находился на территории современного Казахстана, в районе Павлодарского Прииртышья.

Методология исследования. В основе исследования использованы сравнительно-исторический метод, историко-географический анализ, сравнительный анализ письменных источников, расчётно-маршрутный метод и анализ археологических данных.

Научная новизна исследования. Научная новизна статьи заключается в комплексном сопоставлении письменных источников, географических характеристик маршрутов и расчётных данных для локализации Хакан-Кимака в районе Павлодарского Прииртышья.

В работе предпринята попытка сопоставления сведений о продолжительности маршрута от Тараза до столицы кимаков с современными историко-географическими реконструкциями степных путей.

Письменные источники о Хакан-Кимаке. Основными письменными источниками по истории кимаков являются труды арабских и персидских географов и историков: Аль-Идриси, Гардизи, Ибн Хаукаль и других средневековых авторов [1; 3; 5; 6; 8].

Наибольшую ценность представляют сведения Аль-Идриси, содержащиеся в труде «Нузхат ал-муштак фи ихтирак ал-афак» («Книга Рожера») [1]. Аль-Идриси описывал Хакан-Кимак как крупный укреплённый город на Иртыше, являвшийся резиденцией правителя кимаков. Согласно его описаниям, город имел укрепления, рынки, дворец правителя и железные ворота, что свидетельствует о развитии городской культуры Кимакского каганата.

Важное значение имеет сообщение Аль-Идриси о том, что путь от Тараза до столицы кимаков занимал 81 день [1]. Данные сведения позднее анализировались в работах исследователей Кимакского каганата, в частности Кумекова Б.Е [7].

Расчётно-географический анализ маршрута. Сообщение Аль-Идриси о продолжительности пути от Тараза до столицы кимаков представляет важный историко-географический ориентир для локализации Хакан-Кимака.

Средняя скорость передвижения караванов и кочевых отрядов в степной зоне Средневековья, по оценкам исследователей истории кочевых обществ и Великого шелкового пути, составляла приблизительно 20–35 км в сутки в зависимости от времени года, рельефа местности и погодных условий [2; 4].

Даже при минимальной средней скорости в 20 км в сутки расстояние составило бы:

81×20=1620 км

При средней скорости 25 км в сутки:

81×25=2025 км

При средней скорости 30 км в сутки:

81×30=2430 км

Современное расстояние между Тараз и Павлодар по автомобильным маршрутам составляет около 1500 км, однако средневековые степные маршруты были значительно длиннее вследствие отсутствия прямых дорог, необходимости обхода природных препятствий, сезонных переходов и использования караванных стоянок.

С учётом данных факторов древний маршрут между Таразом и Средним Прииртышьем мог достигать 1800–2200 км, что в целом соответствует сведениям средневековых авторов о продолжительности пути.

Географические признаки локализации. Средневековые источники прямо связывают Хакан-Кимак с Иртышом, что существенно ограничивает круг возможных локализаций [1].

Павлодарское Прииртышье располагается непосредственно на Иртыше и традиционно рассматривается исследователями как территория исторической Кимакии [7].

Особое значение имеют природно-географические характеристики описанного маршрута. Путь от Тараза к Среднему Иртышу проходит преимущественно через степные и полупустынные территории Центрального Казахстана.

Если бы столица кимаков располагалась значительно севернее, в глубокой лесной зоне Западной Сибири, путешественники неизбежно фиксировали бы прохождение через таёжные и лесные территории. Однако подобные сведения в письменных источниках отсутствуют.

Следовательно, природно-географические характеристики маршрута в большей степени соответствуют территории современного Казахстана.

Историко-этнографические особенности региона.Дополнительным аргументом в пользу локализации Хакан-Кимака в районе Павлодарского Прииртышья являются историко-этнографические особенности расселения населения в раннем Средневековье.

Среднее Прииртышье традиционно входило в зону степных и лесостепных территорий, являвшихся пространством расселения тюркских кочевых объединений, включая кимаков и кыпчакские племена [4; 7]. Именно степная зона Прииртышья обеспечивала условия для кочевого скотоводства, функционирования караванных маршрутов и существования крупных политических центров.

В то же время северные районы Верхнего Прииртышья и таёжные территории Западной Сибири характеризовались иной природно-хозяйственной средой. В лесных и таёжных регионах преобладали племена, хозяйственная деятельность которых была связана преимущественно с охотой, рыболовством и лесными промыслами.

Данное различие между степной тюркской зоной Среднего Прииртышья и северной лесной зоной согласуется с сообщениями средневековых авторов о характере маршрутов и особенностях территории Кимакского каганата.

Археологические данные. Археологические исследования Павлодарского Прииртышья подтверждают наличие развитой кимакской культуры IX–XI веков [9].

На территории региона обнаружены:

- курганы кимакской знати;
- остатки средневековых поселений;
- элементы фортификаций;
- предметы вооружения;
- изделия ремесленников;
- торговые артефакты.

Высокая концентрация памятников кимакской эпохи свидетельствует о существовании здесь важного политического и экономического центра.

Значение Хакан-Кимака. Хакан-Кимак являлся одним из важнейших политических и торговых центров степной Евразии. Город выполнял функции административной столицы, военного центра, торгового узла, транзитного пункта между Центральной Азией и Сибирью.

Развитие городской инфраструктуры и наличие укреплений свидетельствуют о высоком уровне государственности кимаков [1; 7].

Заключение. Проведённый анализ письменных источников, географических характеристик маршрутов и археологических данных позволяет предполагать высокую вероятность расположения Хакан-Кимака на территории современного Казахстана, в районе Павлодарского Прииртышья.

Таким образом, Павлодарское Прииртышье может рассматриваться как наиболее вероятный регион расположения одного из главных политических центров Кимакского каганата.

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ПӘНДЕР АРАЛЫҚ ҒЫЛЫМДАР – МЕЖДИСЦИПЛИНАРНЫЕ НАУКИ – INTERDISCIPLINARY SCIENCES

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WEARABLE EMOTIONAL MONITORING SYSTEMS FOR AUTISM SPECTRUM DISORDER: BRIDGING PHYSIOLOGICAL BIOMARKERS AND REAL-TIME INTERVENTION

Abstract: Autism Spectrum Disorder (ASD) is a neurodevelopmental condition with rising global prevalence, including in Central Asian countries. Early detection and intervention improve outcomes, yet a critical gap remains— the inability of many autistic individuals to recognize and communicate their emotional states in real time, leading to sensory overloads, meltdowns, and social withdrawal.

Objective: This review synthesizes current research on early detection, neuroimaging biomarkers, behavioral assessments, and machine learning (ML) applications for ASD. It then introduces AuraLink — a wearable emotional monitoring system with a visual augmentative and alternative communication (AAC) badge — as an evidence-based translation of these findings, with specific attention to the Central Asian and post-Soviet context.

Methods: We analyzed peer-reviewed studies from 2000–2025 focusing on: (1) early diagnostic tools, (2) physiological biomarkers (HRV, GSR, EEG), (3) ML models for emotion classification, and (4) wearable technologies for ASD. A separate scoping review of ASD research in Central Asia was conducted.

Results: Validated biomarkers (heart rate variability, galvanic skin response, temperature, motion) correlate with central autonomic dysregulation in ASD. Multimodal ML approaches achieve >80% accuracy in distinguishing calm, anxiety, and distress. However, existing technologies are mostly lab-based, session-limited, or lack ASD-specific visual output.

Conclusion: AuraLink integrates a neck-band sensor, color-coded Emotion Badge (blue → red for calm → overload), and mobile app with on-device ML. It addresses a previously unmet need — continuous, real-time emotional self-disclosure for non/minimally verbal individuals. Future directions include clinical validation in Central Asian populations and cross-cultural adaptation of color-emotion mappings.

Keywords: Autism Spectrum Disorder, wearable sensors, emotional monitoring, augmentative communication, machine learning, AuraLink, Central Asia, post-Soviet countries

Introduction. Autism Spectrum Disorder (ASD) is a complex neurodevelopmental condition characterized by persistent deficits in social communication and restricted, repetitive patterns of behavior (Lord et al., 2018; Lord et al., 2020). Globally, ASD prevalence has risen significantly — currently approximately 1 in 54 children in the United States receives an ASD diagnosis (Lord et al., 2018).

Early detection and intervention are critical for improving developmental outcomes (Barbaro & Dissanayake, 2009). Standard tools such as the Modified Checklist for Autism in Toddlers (M-CHAT), Autism Diagnostic Observation Schedule (ADOS), and Autism Diagnostic Interview-Revised (ADI-R) remain gold standards for clinical assessment (Lord et al., 2000; Robins et al., 2001). However, ASD presents with vast heterogeneity in behavioral, cognitive, and emotional manifestations (Lord et al., 2020).

Recent technological advances — including eye-tracking (Kollias et al., 2021), tablet-based gesture analysis (Anzulewicz et al., 2016), and machine learning (Thabtah, 2019) — have created new opportunities for objective, scalable assessment. Yet one critical challenge remains systematically underexplored: real-time emotional state communication. Many autistic individuals cannot recognize, articulate, or signal their own emotional escalation before a meltdown or sensory overload occurs. Existing interventions teach emotion recognition from faces but rarely provide continuous, personalized physiological feedback to the user and their caregivers.

This review compiles recent evidence on early detection, neurobiological markers, behavioral assessments, and technology-enabled interventions for ASD. In its final section, we introduce **AuraLink** — a wearable system for continuous emotional monitoring and visualization — as a practical translation of these findings into an assistive technology, with specific consideration for potential implementation in Central Asian and post-Soviet healthcare and educational settings.

ASD IN THE CIS AND CENTRAL ASIA: EPIDEMIOLOGY, DIAGNOSIS, AND BARRIERS

Data on ASD prevalence in post-Soviet countries have long remained fragmented. Official statistics have significantly underestimated true rates due to outdated diagnostic approaches, persistent stigmatization of psychiatric diagnoses, and limited access to specialized services. However, recent years have seen positive changes: first population-based studies, national registries, and scientific projects on ASD genetics and epidemiology are emerging.

Kazakhstan: A Regional Leader in ASD Research

Kazakhstan demonstrates the most dynamic development in ASD research among Central Asian countries. According to a study using the Unified National Electronic Healthcare System (2014–2021), the country registered 9,993 children with ASD. The prevalence rate increased from 7.2 to 148.2 per 100,000 child population, while incidence rose from 12.8 to 26.6 per 100,000.

Another study (2016–2022) reported an almost fivefold increase in diagnosed childhood autism and a fourfold increase in atypical autism. The highest rates were recorded in Astana — 263.7 per 100,000 children by 2022. Significant regional disparities were identified: northern regions show higher rates compared to southern regions, which is attributed to healthcare infrastructure development and urbanization levels.

Russia: The Gap Between Official Statistics and Reality

Until recently, Russia lacked population-based ASD prevalence studies. Official data from the State Psychiatric Service for 2022 showed 0.41 cases per 1,000 population (0.041%) — approximately 29 times lower than global estimates.

Among officially diagnosed individuals, 78.2% have disabilities, 94.7% of whom are children under 17 years.

The first population-based study conducted on a sample of 1st–3rd grade students (n = 34,847) using standardized instruments (SCQ, ADOS-2, ADI-R) revealed a vastly different picture. Estimated prevalence was 22.2 per 1,000 children (95% CI: 18.6–36.0), which is 54 times higher than official data.

Researchers attribute this discrepancy to systemic barriers: limited access to diagnostic services, stigmatization of psychiatric diagnoses, and the continued use of the outdated ICD-10 classification. Notably, between 2018 and 2022, official prevalence grew by 85.5%, likely reflecting improved detection rather than true increased incidence.

Regional differences within Russia are also extreme: from 0.17 per 10,000 in Kaluga Oblast to 17.77 per 10,000 in Yamalo-Nenets Autonomous Okrug (2021 data).

Scoping Review of Central Asian Research: Critical Gaps

A systematic scoping review by Zakirova-Engstrand and Yakubova (2024) analyzed all peer-reviewed ASD research in five Central Asian countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan). Only 11 articles met inclusion criteria: 10 conducted in Kazakhstan and 1 in Uzbekistan.

Studies covered five of seven domains (diagnosis, biology, risk factors, services, therapy), but completely lacked research on lifespan issues and infrastructure/surveillance.

Most critically: no study included co-authorship by Central Asian researchers— all publications were prepared by foreign investigators.

1. **Implications for AuraLink Implementation.** The state of ASD diagnosis and support in the region directly informs potential AuraLink deployment:
2. **Massive gap between need and access.** In Russia, with an estimated 2.2% prevalence among children, only 0.041% are officially diagnosed. In Kazakhstan, despite a fivefold increase, many families lack access to specialists. AuraLink can serve as a tele-monitoring and remote support tool, reducing dependence on scarce professionals.
3. **Language and cultural barriers.** The absence of validated screening and support tools in Russian and Kazakh languages is a serious problem.
4. AuraLink's visual color-coded Emotion Badge requires no verbal report and can be used regardless of language.
5. **Stigmatization.** The region maintains a cautious attitude toward psychiatric diagnoses. Wearable devices presented as "wellness trackers"
6. rather than "psychiatric devices" may reduce family resistance.
7. **Absence of local research.** None of the 11 identified studies had Central Asian co-authors. AuraLink implementation can be accompanied by clinical validation studies involving local researchers — filling a critical gap and increasing trust in the technology.

Methods. We conducted a narrative synthesis of peer-reviewed literature published between 2000 and 2025. Databases searched included PubMed, Scopus, IEEE Xplore, and Google Scholar. Search terms combined: ("autism spectrum disorder" OR "ASD") AND ("early detection" OR "screening") AND ("biomarkers" OR "HRV" OR "GSR" OR "EEG") AND ("wearable" OR "machine learning" OR "AAC").

Inclusion criteria: (1) original research or systematic reviews, (2) human participants with ASD or validated models, (3) English or Russian language. Exclusion criteria: case studies (n < 5), non-peer-reviewed reports. For the Central Asia section, we additionally searched Russian-language databases (eLibrary, CyberLeninka) and included the scoping review by Zakirova-Engstrand and Yakubova (2024) as a primary source.

The identified literature was organized into thematic sections: early detection, neuroimaging/physiological biomarkers, behavioral assessments, ML/AI applications, interventions, wearable technologies, and regional epidemiology.

Results.

Early Detection and Diagnosis

Early ASD symptoms often emerge in infancy, with subtle differences in social attention, eye contact, and motor skills (Barbaro & Dissanayake, 2009; Zwaigenbaum et al., 2009). Screening tools such as M-CHAT and STAT enable early identification (Robins et al., 2001; Stone et al., 2000). Technology-based methods — eye-tracking and tablet-based gesture analysis — have demonstrated effectiveness in identifying atypical patterns in young children (Anzulewicz et al., 2016; Lu et al., 2022; Murias et al., 2018).

While these tools focus on diagnosis, AuraLink targets post-diagnostic, continuous monitoring. The same gaze and gesture markers could be tracked longitudinally rather than in a single session.

Physiological Biomarkers and Wearable Sensing

Neuroimaging (fMRI, EEG) has revealed atypical connectivity and sensory processing in ASD (Hazlett et al., 2017; Wolff et al., 2017; Boutros et al., 2015). EEG-based analyses show differences in neural coherence that may serve as early biomarkers (Bosl et al., 2018; Duffy & Als, 2019).

Critically, peripheral physiological signals — heart rate variability (HRV), galvanic skin response (GSR), and body temperature — correlate with central autonomic nervous system dysregulation in ASD (Boutros et al., 2015; Santana et al., 2022). These signals can be measured non-invasively using wearable sensors.

AuraLink's sensor suite (HRV, GSR, temperature, accelerometer) directly translates these clinical biomarkers into a wearable, real-time form.

Behavioral and Technology-Assisted Assessments

Eye-tracking has been widely used to measure social attention (Mastergeorge et al., 2021; Kollias et al., 2021). Tablet applications capture fine motor behaviors and gestures characteristic of ASD (Anzulewicz et al., 2016; Lu et al., 2022). Speech-generating devices and AAC technologies support communication for nonverbal or minimally verbal individuals (Lorah et al., 2015; Muharib et al., 2024).

AuraLink's Emotion Badge functions as a visual AAC device — generating a color-coded emotional signal (blue = calm, red = distress) rather than speech.

This extends AAC to emotional self-disclosure.

Machine Learning for Emotion Classification from Physiology

Multimodal approaches fusing HRV, GSR, and accelerometer data have achieved classification accuracies above 80% in distinguishing calm, excitement, and distress in ASD populations (Ahmed et al., 2022; Simeoli et al., 2021). Techniques include random forest classifiers, deep learning, and natural language processing (Abbas et al., 2018; Themistocleous et al., 2024).

AuraLink implements an on-device ML model (edge inference) classifying six emotional states (Calm, Joy, Mild Unease, Anxiety, Stress, Overload) based on real-time HRV, GSR, temperature, and motion — translating research into low-latency, privacy-preserving application.

The AuraLink System: System Description

Based on the reviewed evidence, AuraLink consists of three integrated components:

Component	Function	Scientific Basis
Neck Band (wearable)	Measures HRV, GSR, temperature, motion	Boutros et al., 2015; Bosl et al., 2018; Santana et al., 2022
Emotion Badge	Displays color-coded emotional state (blue → red)	AAC principle (Lorah et al., 2015); visual supports
Mobile App	ML classification, alerts, historical data	Ahmed et al., 2022; Simeoli et al., 2021

Emotional State Classification (6 colors):

Color	State	Physiological Correlates
Blue	Calm/Comfort	Low HR, high HRV, low GSR
Green	Joy	Moderate HR, normal HRV
Yellow	Mild unease	Slightly elevated HR, reduced HRV
Orange	Anxiety	Elevated HR, low HRV, rising GSR
Red	Stress/Overload	High HR, very low HRV, high GSR, possible tremor
White flashing	Transitional	Mixed/unstable signals

Target Users in Central Asian Context:

Target User	How AuraLink Helps
Individual with ASD (non/minimally verbal)	Receives external feedback about own state; signals distress without speech
Parent/Caregiver	Receives alerts before meltdown; views trends and triggers
Teacher/Therapist	Tracks emotional patterns across activities; exports reports
Medical professional	Analyzes long-term physiological data for treatment adjustment

Discussion.

Main Findings and Contribution

This review identified three key findings: (1) validated physiological biomarkers (HRV, GSR) for autonomic dysregulation in ASD exist and are measurable with wearables; (2) multimodal ML models achieve clinically useful accuracy (>80%) for emotion classification; (3) despite progress, no existing system combines continuous sensing, visual AAC output, and personalized ML in one integrated device. AuraLink directly addresses this gap.

Comparison with Existing Technologies

Technology	Focus	Limitation	AuraLink Advantage
Eye-trackers	Social attention	Lab-based, expensive	Wearable, continuous
Tablet AAC	Communication	Requires active input	Passive + active
VR interventions	Training	Session-based	Real-world, 24/7
General wearables (Apple Watch)	Health metrics	Not ASD-specific, no emotion badge	ASD-validated model + visual badge

Implications for Central Asia and Post-Soviet Countries

In Central Asian and post-Soviet countries, access to specialized ASD services is uneven, with shortages of child psychiatrists, speech therapists, and behavior analysts. AuraLink offers several advantages for this context:

Low-cost scalability after initial device investment.

Reduced reliance on verbal expression — critical for Russian- or Kazakh-speaking minimally verbal children.

Remote monitoring for families in rural areas (e.g., villages in Kazakhstan, Kyrgyzstan, Russia).

Data-driven advocacy — schools and clinics can use aggregated, anonymized data to demonstrate need for additional resources.

Potential to reduce stigmatization — when framed as a "wellness tracker" rather than a psychiatric device.

However, cross-cultural adaptation is required: the blue → red color scheme (calm → distress) may not be universally intuitive. Some cultures associate red with happiness or celebration. Future validation studies in Almaty, Astana, Tashkent, Bishkek, and Russian regions are needed.

Limitations

This review has limitations: (1) majority of studies originate from Western, high-income countries; (2) long-term outcome data for wearables in ASD are sparse; (3) AuraLink itself requires clinical validation in prospective trials; (4) privacy and data security concerns for continuous physiological monitoring must be addressed; (5) the scoping review of Central Asian research identified only 11 studies, all without local co-authorship.

Future Research Directions Informed by AuraLink

Personalized ML: Federated learning on individual user data to adapt to each person's unique baseline.

Integration with behavioral channels: Combining wearables with eye-tracking or tablet gesture analysis.

Clinical validation studies in Central Asia: Prospective trials comparing AuraLink alerts against clinician-rated emotional states in natural settings (schools, homes). These trials should involve local

researchers as co-authors.

Long-term outcomes: Does real-time feedback reduce meltdown frequency or improve social participation?

Cross-cultural adaptation: Validating color-emotion mappings across Kazakh, Uzbek, Kyrgyz, Tajik, Turkmen, and Russian populations.

Language localization: Developing Russian and Kazakh language interfaces for the mobile app.

Conclusion. Autism Spectrum Disorder presents with diverse behaviors, cognitive profiles, and neurobiological substrates. Research over the past two decades has emphasized the value of early detection, neuroimaging biomarkers, behavioral assessments, and technology-assisted interventions. Tools such as eye-tracking, tablet applications, AI, and VR have advanced objective assessment and tailored support.

However, a critical gap remains: real-time emotional state communication in everyday environments. The AuraLink system directly addresses this gap by translating established

physiological biomarkers (HRV, GSR, temperature, motion) into an accessible, wearable form factor with a visual AAC output (Emotion Badge) and intelligent mobile analytics.

In the post-Soviet and Central Asian context, AuraLink holds particular promise. The region faces a stark reality: official ASD prevalence rates are orders of magnitude lower than population-based estimates, diagnostic services are unevenly distributed, and local research capacity remains underdeveloped.

A wearable, visual, non-verbal system that requires minimal professional support could help bridge these gaps — provided it is validated with local populations and adapted to cultural color-emotion associations.

Future research should prioritize clinical validation in Central Asian populations, personalized model adaptation, integration with additional behavioral channels, and genuine collaboration with local researchers. The ultimate goal remains unchanged: to provide autistic individuals with a voice for their internal emotional states, reducing sensory overloads and improving quality of life through better understanding and timely support.

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ЦИФРОВИЗАЦИЯ В ЗДРАВООХРАНЕНИИ: ВЛИЯНИЕ НА КАЧЕСТВО МЕДИЦИНСКИХ УСЛУГ И ВЗАИМОДЕЙСТВИЕ С ПАЦИЕНТАМИ

Аннотация: В статье рассматривается влияние цифровизации медицинских данных на качество медицинских услуг и взаимодействие с пациентами. Раскрываются теоретические различия между оцифровкой, цифровизацией и цифровой трансформацией, а также роль электронных медицинских записей, систем обмена данными, пациентских порталов и систем поддержки клинических решений. Показано, что цифровизация медицинских данных может способствовать повышению качества и безопасности медицинской помощи, сокращению документационной нагрузки, улучшению преемственности помощи, снижению ошибок и повышению вовлеченности пациентов. Отдельное внимание уделено процессу ведения беременности как примеру, где своевременный обмен медицинскими данными и доступ пациентки к информации имеют особое значение. Вместе с тем отмечены ограничения и риски цифровизации, связанные с качеством данных, интероперабельностью информационных систем, цифровым неравенством, нагрузкой на медицинских работников, защитой персональных данных и доверием пациентов к цифровым сервисам. Делается вывод о том, что цифровизация медицинских данных должна рассматриваться не только как технологическое обновление, но и как организационно-управленческое изменение, требующее комплексного подхода к внедрению.

Ключевые слова: цифровизация здравоохранения, медицинские данные, электронная медицинская запись, качество медицинских услуг, пациентские порталы, взаимодействие с пациентами.

Введение. Цифровизация стала одним из ключевых направлений развития современных систем здравоохранения. Рост объема медицинской информации, необходимость межорганизационного обмена данными и ожидания пациентов в части доступности и прозрачности медицинских услуг делают традиционные, преимущественно бумажные формы ведения документации все менее эффективными. В этих условиях электронные медицинские записи, интегрированные информационные системы и цифровые сервисы для пациентов рассматриваются как важные инструменты повышения качества, безопасности и преемственности медицинской помощи.

При этом цифровизация в здравоохранении не сводится к простой замене бумажного документооборота электронным. Она предполагает изменение способов сбора, хранения, обмена и использования медицинских данных, а также влияет на организацию клинических процессов и взаимодействие между медицинскими работниками и пациентами. Особое значение имеет цифровизация медицинских данных,

поскольку именно данные выступают основой для электронных медицинских записей, систем поддержки клинических решений, пациентских порталов, мониторинга качества и последующего анализа медицинской помощи.

Актуальность данной темы определяется тем, что влияние цифровизации на здравоохранение проявляется не только в технологическом обновлении, но и в изменении качества медицинских услуг, доступности информации для пациента, скорости обмена данными и степени вовлеченности пациента в процесс лечения. Вместе с тем цифровизация сопровождается рядом ограничений и рисков, связанных с качеством данных, интероперабельностью информационных систем, цифровым неравенством, нагрузкой на медицинских работников, защитой персональных данных и доверием пациентов к электронным сервисам.

Цель данной статьи — на основе анализа научной и прикладной литературы рассмотреть теоретические основы цифровизации медицинских данных, определить ее влияние на качество медицинских услуг и взаимодействие с пациентами, а также обозначить основные ограничения и риски, которые необходимо учитывать при внедрении цифровых решений в здравоохранении. Отдельное внимание уделяется процессу ведения беременности как примеру, где своевременный обмен медицинскими данными и доступ пациентки к информации имеют особое значение для обеспечения преемственности помощи и прозрачного взаимодействия с медицинской организацией.

Теоретические основы цифровизации медицинских данных

Понятие цифровизации медицинских данных

В научной литературе о цифровой трансформации принято разграничивать понятия оцифровки, цифровизации и цифровой трансформации, рассматривая их как разные, хотя и взаимосвязанные этапы изменений. Так, R. Trzaska и соавторы, опираясь на подходы к цифровой трансформации, разграничивают оцифровку, цифровизацию и цифровую трансформацию. Оцифровка рассматривается как процесс создания цифрового представления информации или объектов, цифровизация — как использование цифровых решений для изменения и автоматизации процессов, а цифровая трансформация — как более глубокое преобразование деятельности организации на основе цифровых технологий [1].

Данная логика позволяет рассматривать цифровизацию медицинских данных не как простую замену бумажных носителей электронными, а как этап более комплексного изменения процессов сбора, хранения, обмена и использования медицинской информации.

В региональной стратегии Всемирной организации здравоохранения (ВОЗ) цифровизация данных в здравоохранении не сводится к простому переводу бумажной или ручной информации в электронный формат. Она предполагает использование цифровых технологий для сбора, хранения, передачи, интеграции и эффективного использования медицинских данных между учреждениями, организациями и информационными системами. Такой процесс требует организационных и институциональных изменений, развития инфраструктуры, внедрения стандартов данных и формирования архитектуры информационных систем, а также наличия политик и механизмов регулирования в сфере безопасности данных, защиты персональной информации, конфиденциальности и согласия пациента [2].

Исходя из этих подходов, в данной статье под цифровизацией медицинских данных предлагается понимать совокупность процессов, связанных с переводом информации о состоянии здоровья пациента и оказанной медицинской помощи в электронный формат (как результат оцифровки), и последующей интеграцией, обменом и использованием этих данных для изменения и улучшения клинических и организационных процессов в здравоохранении, а также взаимодействия с пациентами как проявление цифровизации.

Такое понимание позволяет рассматривать цифровизацию медицинских данных не как чисто технический процесс внедрения отдельной информационной системы, а как изменение того, как данные используются в практике — при принятии решений, координации помощи и взаимодействии с пациентом.

Цифровые медицинские данные и электронные медицинские записи

Цифровые медицинские данные представляют собой не однородный массив информации, а совокупность взаимосвязанных клинических, диагностических, административных и иных сведений, которые формируются на разных этапах оказания медицинской помощи. К таким данным относятся сведения об анамнезе пациента, диагнозах, результатах лабораторных и инструментальных исследований, назначениях, проведённых вмешательствах, факторах риска, маршрутизации и результатах наблюдения.

В цифровой инфраструктуре здравоохранения центральное место занимают электронные медицинские записи (ЭМЗ; англ. Electronic Health Records, EHR). Tornero Costa и соавторы отмечают, что ЭМЗ обеспечивают хранение медицинской истории, диагнозов, назначений, сведений о лекарственных препаратах, аллергиях, иммунизации, направлениях, лабораторных результатах и медицинских изображениях. Их значение заключается не только в накоплении информации о пациенте, но и в обеспечении обмена данными, повышении эффективности процессов, снижении ошибок и предоставлении авторизованного доступа к медицинской информации [3].

Следовательно, цифровые медицинские данные представляют собой содержание медицинской информации в электронном виде, тогда как электронная медицинская запись выступает центральным инструментом их накопления, структурирования и использования в рамках цифрового профиля пациента. Системы обмена данными, в свою очередь, обеспечивают передачу этой информации между медицинскими организациями и поддерживают преемственность медицинской помощи.

Систематический обзор и мета-анализ Campanella и соавторов показал, что при надлежащем внедрении электронные медицинские записи ассоциируются с повышением качества медицинской помощи: сокращением времени на ведение документации, повышением соблюдения клинических рекомендаций, снижением числа медикаментозных ошибок и нежелательных лекарственных реакций [4].

Это подчёркивает, что переход к структурированным цифровым данным имеет непосредственное влияние на ключевые параметры качества медицинской помощи.

В рамках настоящего исследования цифровые медицинские данные рассматриваются как совокупность клинических, диагностических, административных и иных сведений о пациенте и оказанной ему медицинской помощи, представленных в электронном виде и формируемых в различных информационных системах здравоохранения. Центральным элементом такой цифровой инфраструктуры выступает электронная медицинская запись пациента, обеспечивающая накопление, хранение и

использование клинически значимой информации для принятия решений, координации помощи и взаимодействия с пациентом.

Цифровизация медицинских данных как основа изменений в здравоохранении

Цифровизация медицинских данных рассматривается сегодня как одно из базовых условий модернизации систем здравоохранения. Международные организации подчёркивают, что именно данные являются отправной точкой для изменений в качестве и модели оказания помощи. В докладе Организации экономического сотрудничества и развития (ОЭСР) медицинские данные рассматриваются как необходимое условие повышения качества, безопасности и пациент-ориентированности медицинских услуг, а также как основа для оценки новых моделей оказания помощи. При этом ценность медицинских данных раскрывается не только через их накопление, но и через возможность их связывания, анализа и безопасного использования в интересах пациента, системы здравоохранения и государственной политики. ОЭСР также указывает, что разобщённость данных в отдельных организациях и информационных системах снижает их практическую ценность и требует развития механизмов управления данными, интероперабельности, защиты персональной информации и прозрачных правил доступа [5].

Таким образом, цифровизация медицинских данных создаёт основу для перехода от фрагментированного, эпизодического ведения пациента к непрерывному цифровому профилю, доступному на разных уровнях оказания помощи и поддерживающему координацию между организациями. Это, в свою очередь, открывает возможности для использования аналитики и технологий искусственного интеллекта, развития телемедицины, формирования систем мониторинга и управления качеством.

В совокупности это позволяет рассматривать цифровизацию медицинских данных не как вспомогательный технический процесс, а как ключевой механизм изменения практик здравоохранения. Именно от того, насколько данные полны, структурированы и доступны для использования на разных уровнях системы, зависит потенциал последующих преобразований — от улучшения качества медицинских услуг до изменения характера взаимодействия с пациентами.

Особенно наглядно значение цифровизации медицинских данных проявляется в процессах, где пациент проходит длительный маршрут наблюдения и взаимодействует с несколькими участниками системы здравоохранения. К таким процессам относится наблюдение беременной женщины, поскольку медицинская информация формируется на разных этапах: при постановке на учет, плановых приемах, лабораторных и инструментальных исследованиях, оценке факторов риска, госпитализации, родоразрешении и послеродовом наблюдении. В этих условиях качество медицинской помощи зависит не только от наличия отдельных медицинских записей, но и от своевременного обмена данными между организациями первичной медико-санитарной помощи, стационарами, скорой медицинской помощью и самой пациенткой. Информация о течении беременности, результатах обследований, факторах риска, назначениях и маршрутизации используется различными участниками системы здравоохранения, поэтому ее цифровизация направлена не только на замену бумажной формы электронным документом, но и на обеспечение преемственности помощи и более прозрачного взаимодействия с пациенткой. Такой пример показывает, что цифровизация медицинских данных требует организационно-управленческого подхода: определения

состава данных, интеграции информационных систем, защиты персональной информации и обучения пользователей.

Влияние цифровизации на качество медицинских услуг

Поддержка клинических решений и безопасность лечения

Цифровизация медицинских данных в первую очередь влияет на принятие решений за счёт доступности более полной и структурированной истории пациента. Интегрированные электронные медицинские записи позволяют врачу в одном цифровом профиле видеть анамнез, диагнозы, результаты лабораторных и инструментальных исследований, назначения и сведения об аллергиях, вместо разрозненных бумажных документов. Наличие единой цифровой истории также способствует снижению ошибок и дублирования обследований. Когда результаты лабораторных и инструментальных исследований доступны всем вовлечённым специалистам в электронной форме, уменьшается риск повторного назначения уже выполненных тестов и упущения значимых результатов. Alotaibi и Federico в своём обзоре подчёркивают, что информационные технологии в здравоохранении, в том числе электронные медицинские записи и системы поддержки принятия решений, являются важным инструментом повышения качества и безопасности медицинской помощи. Авторы отмечают, что такие системы позволяют снижать количество медицинских и лекарственных ошибок, улучшать соблюдение клинических рекомендаций при условии их продуманного выбора и корректной стратегии внедрения [6].

Одним из направлений влияния цифровизации медицинских данных на качество медицинских услуг является развитие систем поддержки клинических решений. Sutton и соавторы отмечают, что такие системы предназначены для поддержки клинических решений за счет использования целевых медицинских знаний, данных пациента и иной медицинской информации [7]. В условиях интеграции с электронными медицинскими записями они могут применяться для формирования предупреждений, напоминаний, проверки лекарственных назначений, поддержки диагностики и соблюдения клинических рекомендаций. Следовательно, цифровые медицинские данные становятся не только способом хранения информации, но и основой для более обоснованного, своевременного и безопасного принятия решений медицинскими работниками.

Операционная эффективность и непрерывность помощи

Электронные медицинские записи и цифровые системы обмена данными напрямую связаны с операционной эффективностью и непрерывностью помощи. Исследования показывают, что внедрение ЭМЗ при грамотной реализации сокращает время на документацию в среднем на 22,4 % и снижает количество ошибок при назначении лекарств, что делает процессы работы более устойчивыми и предсказуемыми [4].

Анализ по странам Европейского региона ВОЗ показывает, что электронные медицинские записи и платформы обмена данными между организациями обеспечивают доступность ключевой клинической информации на разных уровнях помощи и в разных учреждениях, тем самым поддерживая непрерывность маршрута пациента и уменьшая фрагментацию помощи [3].

В контексте Казахстана потребность в непрерывном обмене медицинскими данными проявляется в процессе ведения беременности, где медицинская информация одновременно используется для клинического наблюдения, маршрутизации пациентки и

межорганизационного обмена данными. При постановке беременной женщины на учет оформляется обменная карта на бумажном носителе, при этом сведения о состоянии пациентки, результатах обследований, факторах риска и назначениях параллельно вносятся в действующие информационные системы. Такая модель создает двойную нагрузку на медицинских работников, увеличивает время на ведение документации и повышает риск расхождений между бумажными и электронными данными. В этих условиях цифровизация данных обменной карты беременной и родильницы может создать условия для повышения операционной эффективности, поскольку позволяет использовать уже сформированные в информационных системах сведения без повторного ручного заполнения бумажного носителя.

Следовательно, актуальной задачей является не просто перевод обменной карты в электронный вид, а переход к такому формату ведения и предоставления данных о беременности, при котором информация, уже формируемая в информационных системах, становится доступной для использования всеми участниками маршрута пациентки, включая саму беременную женщину. Такой подход позволяет рассматривать электронную обменную карту не как отдельный цифровой документ, а как инструмент устранения дублирования, повышения преемственности медицинской помощи и более прозрачного взаимодействия между медицинской организацией и пациенткой.

Влияние цифровизации медицинских данных на взаимодействие с пациентами

Цифровизация медицинских данных значительно меняет характер взаимодействия между пациентом и системой здравоохранения, прежде всего за счёт расширения доступа к информации. Электронные медицинские записи и пациентские порталы позволяют пациентам видеть результаты анализов, выписки, назначения, план лечения и рекомендации в удобном цифровом формате, а не только через устные объяснения врача или письменные записи в карточке пациента. Исследования показывают, что когда пациент получает доступ к своей электронной медицинской карте, это влияет не только на «прозрачность» информации, но и на его поведение. Систематический обзор Alomar и соавторов показывает, что доступ пациентов к электронным медицинским записям положительно связан с их вовлеченностью в медицинскую помощь, включая повышение приверженности лечению, развитие самоконтроля, улучшение коммуникации с медицинскими работниками и повышение удовлетворенности медицинскими услугами. При этом авторы отмечают и сохраняющиеся барьеры: вопросы конфиденциальности, технические сложности доступа, а также трудности понимания медицинской терминологии пациентами [8].

Использование цифровых сервисов — мобильных приложений, напоминаний о приёме лекарств, онлайн-мониторинга показателей — делает пациента более активным участником лечения. Сходные выводы представлены в систематическом обзоре Han и соавторов, где пациентские порталы рассматриваются как инструмент активного участия пациента в медицинской помощи. Авторы отмечают, что такие порталы могут улучшать информированность пациента, самоэффективность, принятие решений, приверженность лечению и использование профилактических услуг, хотя их влияние на клинические показатели остается неоднозначным [9]. Это позволяет рассматривать цифровой доступ к медицинским данным прежде всего как механизм повышения вовлеченности пациента и качества коммуникации с медицинской организацией.

Ограничения и риски, связанные с цифровизацией медицинских данных

Несмотря на значительные преимущества, цифровизация медицинских данных сопровождается рядом ограничений и рисков, которые необходимо учитывать при проектировании и внедрении информационных систем здравоохранения. Даже при наличии ЭМЗ данные могут быть неполными, дублирующимися или внесёнными с ошибками. Низкое качество данных (пропуски, несогласованные форматы, отсутствие обновления) ограничивает возможность их использования для клинических решений и управления системой здравоохранения. Поэтому международные рекомендации акцентируют необходимость системной работы по обеспечению качества данных и стандартов их ведения.

Одной из ключевых проблем остаётся слабая интероперабельность между разными информационными системами. Недостаток интеграции приводит к фрагментации информации, повторному вводу данных и потере непрерывности маршрута пациента, что снижает качество помощи и ведёт к неэффективному использованию ресурсов.

Также, одним из важных ограничений цифровизации медицинских данных остаётся цифровое неравенство. Не у всех пациентов есть одинаковые возможности пользоваться электронными сервисами: кто-то не имеет стабильного доступа к интернету или современным устройствам, кто-то испытывает трудности с установкой приложений и регистрацией на порталах, а для части людей сами интерфейсы кажутся слишком сложными. Особенно это может относиться к пожилым пациентам, людям с низким уровнем цифровых навыков и проживающим в сельской местности. В итоге те пациенты, кто уверенно пользуется цифровыми технологиями, получают больше преимуществ от новых сервисов, чем те, кто по разным причинам остаётся «в стороне», что может усиливать уже существующие различия в доступе к медицинской помощи.

Наряду с преимуществами цифровизации медицинских данных необходимо учитывать и риски, связанные с ростом документационной нагрузки на медицинских работников. Johnson и соавторы отмечают, что электронные медицинские записи повысили безопасность и надежность многих аспектов медицинской помощи, однако недостатки удобства использования, увеличение объема вводимых данных и несоответствие цифровых инструментов реальным клиническим рабочим процессам могут способствовать профессиональному выгоранию медицинских работников [10]. Следовательно, цифровизация медицинских данных должна сопровождаться оптимизацией процессов, исключением дублирующего ввода информации и учетом пользовательского опыта медицинских работников.

Asgari и соавторы отмечают, что использование электронных медицинских записей связано не только с преимуществами, такими как доступность данных, улучшение коммуникации и поддержка непрерывности помощи, но и с ростом когнитивной нагрузки при сложной навигации, информационной перегрузке, большом количестве уведомлений, дублировании данных и недостаточной интероперабельности систем [11]. В таких условиях цифровизация может не снижать, а увеличивать нагрузку на медицинских работников, что требует продуманного проектирования интерфейсов, оптимизации процессов и устранения повторного ввода информации.

Медицинские данные относятся к чувствительной информации, поэтому их электронное хранение, обмен и использование повышают значимость вопросов конфиденциальности, защиты персональных данных и цифровой безопасности. OECD

подчеркивает, что безопасное использование медицинских данных требует национальных рамок управления данными, прозрачных правил обработки, информирования пациентов, механизмов согласия, разграничения доступа, а также технологических и организационных мер защиты. При отсутствии таких механизмов цифровизация может создавать риски утраты или неправомерного использования данных и снижать доверие пациентов к электронным сервисам здравоохранения [5].

Заключение. Цифровизация медицинских данных является одним из значимых направлений развития современного здравоохранения, поскольку она влияет не только на способ хранения медицинской информации, но и на организацию медицинской помощи, качество принимаемых решений и характер взаимодействия с пациентами. Электронные медицинские записи, системы обмена данными, пациентские порталы и системы поддержки клинических решений позволяют повысить доступность медицинской информации, улучшить преемственность помощи, снизить риск ошибок и сделать пациента более активным участником процесса лечения.

Проведенный анализ показывает, что цифровизация медицинских данных имеет наибольший эффект тогда, когда она не ограничивается простой заменой бумажного документа электронным аналогом. Ее результативность зависит от полноты и качества данных, интероперабельности информационных систем, удобства цифровых решений для медицинских работников и пациентов, а также от наличия прозрачных правил доступа, защиты персональных данных и управления информацией.

На примере ведения беременности видно, что цифровизация медицинских данных может иметь особое значение для процессов длительного наблюдения, где информация формируется на разных этапах и используется несколькими участниками системы здравоохранения. Электронное предоставление данных о беременности способно снизить дублирование записей, повысить преемственность медицинской помощи и обеспечить пациентке более понятный и своевременный доступ к сведениям о собственном наблюдении.

Вместе с тем цифровизация медицинских данных сопровождается рядом ограничений и рисков. К ним относятся низкое качество данных, слабая интеграция информационных систем, цифровое неравенство, рост документационной и когнитивной нагрузки на медицинских работников, а также риски, связанные с конфиденциальностью и цифровой безопасностью. Поэтому цифровизация в здравоохранении должна рассматриваться не только как технологическое обновление, но и как организационно-управленческое изменение, требующее комплексного подхода к проектированию, внедрению и оценке цифровых решений.

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КРИТЕРИИ ТВОРЧЕСКОГО ВКЛАДА ЧЕЛОВЕКА ПРИ СОЗДАНИИ ПРОИЗВЕДЕНИЙ С ПРИМЕНЕНИЕМ СИСТЕМ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА В РЕСПУБЛИКЕ КАЗАХСТАН

Аннотация: В статье рассматривается проблема определения творческого вклада человека при создании произведений с применением систем искусственного интеллекта. Актуальность темы обусловлена тем, что Закон Республики Казахстан «Об искусственном интеллекте» закрепляет общий принцип охраны таких произведений при наличии творческого вклада человека, однако не раскрывает порядок практической оценки данного критерия. В статье анализируется правовое значение промпта, творческого отбора, компоновки, редактирования, переработки результата и цифрового следа. Предлагается система критериев, применимая при регистрации произведений, договорном регулировании и разрешении споров. Отдельное внимание уделяется возможности дополнения Правил внесения сведений и их изменений в Государственный реестр прав на объекты, охраняемые авторским правом, специальными положениями о произведениях, содержащих элементы, созданные с применением систем искусственного интеллекта.

Ключевые слова: искусственный интеллект, авторское право, произведение, творческий вклад, промпт, цифровой след, регистрация произведений, Республика Казахстан.

Введение. Развитие генеративных систем искусственного интеллекта поставило перед авторским правом практический вопрос о том, при каких условиях результат, созданный с применением цифровой системы, может охраняться как произведение и в каком объеме за человеком может быть признано авторство. Современные системы искусственного интеллекта способны генерировать тексты, изображения, музыкальные фрагменты, видеоматериалы и иные объекты, внешне сходные с традиционными результатами творческой деятельности. Такое внешнее сходство само по себе не позволяет сделать вывод о соответствии результата требованиям авторского права.

Для Республики Казахстан проблема имеет особую актуальность. Закон Республики Казахстан «Об авторском праве и смежных правах» сохраняет классическую модель, согласно которой автором признается физическое лицо, творческим трудом которого создано произведение [1]. Закон Республики Казахстан «Об искусственном интеллекте» развивает данный подход и устанавливает, что произведения, созданные с использованием систем искусственного интеллекта, охраняются авторским правом при наличии творческого вклада человека [2]. Следовательно, законодатель уже закрепил

человекоцентричную модель, а основная задача науки и практики состоит в раскрытии критериев ее применения.

Цель настоящей статьи состоит в разработке прикладной системы критериев творческого вклада человека при создании произведений с применением систем искусственного интеллекта. Такая система может иметь значение для уполномоченного органа, экспертной организации, судов и участников договорной практики при регистрации произведений, определении объема охраны и разграничении охраняемых и неохраняемых элементов результата, созданного с применением системы искусственного интеллекта.

1. Законодательная основа и границы исследования

Авторское право традиционно исходит из того, что произведение является результатом интеллектуальной и творческой деятельности человека. Искусственный интеллект не может быть приравнен к автору, поскольку он не является физическим лицом, не обладает личными неимущественными правами и не вступает в личную правовую связь с созданным результатом. В этой части Закон РК «Об искусственном интеллекте» подтверждает уже существующую человекоцентричную основу и переносит центр юридической оценки на установление человеческого творческого участия.

В зарубежной литературе отмечается, что вопросы авторства и охраноспособности результатов, созданных с помощью искусственного интеллекта, особенно остро проявляются в авторском и патентном праве, где человеческая творческая деятельность традиционно выступала условием защиты [4]. U.S. Copyright Office в отчете 2025 года исходит из того, что охрана не распространяется на полностью сгенерированный искусственным интеллектом материал либо на материал, в отношении которого отсутствует достаточный человеческий контроль над выразительными элементами [5]. Европейские исследования также подчеркивают необходимость разграничивать полностью машинно-сгенерированные результаты и произведения, созданные при существенном участии человека [6].

Казахстанская практика также движется в этом направлении. В экспертных материалах по Закону РК «Об искусственном интеллекте» указывается, что фокус правовой оценки смещается с самого факта использования искусственного интеллекта на анализ процесса создания результата. Значение приобретают редакторская переработка, композиция, сценарная структура, художественные и стилистические решения, логика построения текста или изображения [9]. Практический вопрос состоит в определении действий пользователя системы искусственного интеллекта, которые могут подтверждать творческий вклад, и действий, имеющих только технический характер.

Действующие Правила внесения сведений и их изменений в Государственный реестр прав на объекты, охраняемые авторским правом, утвержденные приказом Министра юстиции Республики Казахстан от 28 августа 2018 года № 1315, регулируют подачу заявления, представление экземпляра произведения, выдачу свидетельства и основания отказа [3]. При этом специальный порядок для произведений, содержащих элементы, созданные с применением систем искусственного интеллекта, в них не раскрыт. Указанный пробел имеет процедурный характер и может быть восполнен путем уточнения состава сведений, которые заявитель вправе представить при регистрации произведения, созданного с применением системы искусственного интеллекта.

2. Промпт как элемент творческого процесса

Особое место в оценке творческого вклада занимает промпт, то есть текстовый запрос или система инструкций, адресованных искусственному интеллекту. В практическом обороте именно промпт часто воспринимается как основное действие пользователя, однако его правовое значение зависит от содержания и связи с итоговой формой результата.

Промпт может быть простой технической командой. К таким запросам относятся формулировки вроде «создай изображение города будущего» или «напиши текст о договоре». Они задают общую тему, но не определяют индивидуализированную форму произведения. В подобных случаях участие пользователя обычно ограничивается постановкой общей задачи, тогда как выразительные элементы результата формируются системой искусственного интеллекта.

Иная ситуация возникает, когда промпт представляет собой сложную систему творческих указаний. Он может включать оригинальную концепцию, композиционное построение, характеристики персонажей, стилистические ограничения, последовательность сцен, цветовую палитру, тональность, структуру текста или иные элементы, отражающие замысел человека. В таком случае промпт получает доказательственное значение, поскольку показывает направленность действий пользователя и степень его творческого контроля.

При этом творчески сформированный промпт сам по себе не решает вопрос об авторстве на итоговый результат. Ковалева и Рожкова обращают внимание на двойственную природу промпта. Он может иметь самостоятельную ценность и в отдельных случаях обладать творческим характером, но далеко не каждый запрос является объектом авторского права [7]. U.S. Copyright Office также исходит из того, что сами по себе промпты обычно не обеспечивают достаточного контроля человека над выразительными элементами результата [5]. Поэтому промпт необходимо оценивать вместе с дальнейшим отбором, компоновкой, редактурой и переработкой итогового материала.

3. Критерии творческого вклада человека

Для правоприменения творческий вклад человека целесообразно рассматривать как совокупность обстоятельств. Такой подход позволяет учитывать реальные особенности создания произведений с использованием искусственного интеллекта и избегать формальной оценки по одному признаку.

Первым критерием является самостоятельный творческий замысел. Человек указывает не только тему, но и концепцию произведения, его цель, образную систему, структуру, композиционную задачу или иные элементы, направляющие процесс создания результата. Замысел сам по себе не охраняется как идея, однако он помогает установить активное творческое участие пользователя.

Вторым критерием выступает содержательность промпта. Оценке подлежит не количество слов в запросе, а его качество. Значение имеет способность запроса выражать индивидуальный творческий выбор, структуру, стиль и композиционные параметры результата.

Третий критерий связан с управлением процессом генерации. Пользователь может последовательно уточнять запросы, вводить ограничения, отклонять неподходящие варианты и корректировать направление генерации. Значение имеет не количество итераций, а осознанное воздействие на будущую форму произведения.

Четвертым критерием является творческий отбор. Выбор одного результата из множества предложенных системой имеет правовое значение тогда, когда он связан с формированием целостной композиции, последовательности, смысловой структуры или сочетанием отдельных фрагментов.

Пятый критерий выражается в переработке и редактуре результата. Если человек существенно изменяет сгенерированный материал, дополняет его собственными фрагментами, меняет стиль, структуру, последовательность, художественные детали или выразительные элементы, именно эта переработка может образовывать охраноспособный человеческий вклад.

Элемент участия	Признаки достаточного вклада	Признаки недостаточного вклада
Замысел	Определены концепция, структура и композиционная задача	Указана только общая тема
Промпт	Есть творческие, стилистические и композиционные указания	Использована простая техническая команда
Управление генерацией	Уточнения направляют форму результата и отражают творческий выбор	Имеет место случайный перебор вариантов
Отбор	Формирует композицию, структуру или смысловую целостность	Выбран понравившийся вариант без дальнейшей переработки
Редактура	Существенно изменены форма, стиль, структура или выразительные элементы	Внесены минимальные правки или исправлены технические ошибки
Цифровой след	Подтверждает связь действий человека с итоговой формой	Не позволяет установить характер творческого участия

Предложенные критерии не являются закрытым перечнем. Они образуют ориентиры для практической оценки, при которой учитываются вид произведения, характер используемой системы, объем человеческой переработки и связь между действиями пользователя и итоговой формой результата. Более убедительной представляется совокупная оценка, поскольку отдельный признак редко позволяет полностью определить правовую природу результата, содержащего как элементы, полученные с применением системы искусственного интеллекта, так и элементы, выражающие творческие решения человека.

4. Цифровой след как вспомогательное доказательство

При создании произведений с применением искусственного интеллекта особое значение приобретает цифровой след. Под ним можно понимать совокупность данных, позволяющих восстановить процесс создания результата. К таким данным относятся исходные и уточняющие промпты, промежуточные версии, выбранные и отклоненные варианты, история редактирования, метаданные файлов, параметры генерации, черновики, материалы постобработки и иные сведения.

Цифровой след важен потому, что по внешнему виду итогового результата часто невозможно определить, был ли он создан человеком, системой искусственного

интеллекта или в смешанном процессе. Один и тот же текст или изображение могут выглядеть как результат человеческой работы, хотя фактически быть почти полностью сгенерированными. В обратной ситуации произведение, созданное с активным использованием искусственного интеллекта, может содержать значительный человеческий вклад, который неочевиден без анализа процесса создания.

Цифровой след не следует превращать в обязательную формальность возникновения авторского права. В классической модели авторское право возникает в силу факта создания произведения, а не вследствие регистрации, раскрытия черновиков или предоставления технической истории работы. Поэтому цифровой след должен рассматриваться как вспомогательное доказательственное средство, применимое прежде всего при регистрации, заключении договора, передаче прав или разрешении спора.

Такой подход согласуется с зарубежной практикой. U.S. Copyright Office в Registration Guidance 2023 года указывает на необходимость раскрытия AI-generated material при регистрации и описания человеческого вклада, если произведение содержит материал, созданный искусственным интеллектом [8]. Для Республики Казахстан данную модель целесообразно использовать осторожно. Речь должна идти о возможности подтвердить характер и объем человеческого участия, а не об универсальной обязанности раскрывать весь процесс создания.

5. Практическая модель дополнения правил регистрации

Закон РК «Об искусственном интеллекте» закрепляет общий критерий творческого вклада человека, но не описывает порядок его практической оценки. Поэтому предлагаемые критерии могут быть использованы при подготовке дополнений к Правилам внесения сведений и их изменений в Государственный реестр прав на объекты, охраняемые авторским правом, утвержденным приказом Министра юстиции Республики Казахстан от 28 августа 2018 года № 1315 [3].

Действующие Правила предусматривают подачу заявления и экземпляра произведения, а в отношении составного или производного произведения - дополнительные документы, подтверждающие правомерность использования исходного материала [3]. Для произведений, созданных с применением систем искусственного интеллекта, целесообразно предусмотреть дополнительный информационный блок. Его назначение состоит в обеспечении единообразной оценки заявленного объема охраны и в предоставлении заявителю возможности показать человеческий творческий вклад.

Представление таких сведений следует рассматривать как дополнительную возможность заявителя подтвердить характер человеческого творческого вклада. При наличии спора или необходимости уточнения объема охраны они могут использоваться в качестве вспомогательных доказательств.

При этом предлагаемая модель не предполагает обязательного технического выявления каждого случая использования искусственного интеллекта. На момент подготовки данной статьи происхождение результата на практике не всегда может быть достоверно установлено только по его внешним признакам. Ее назначение состоит в определении порядка оценки человеческого творческого вклада в тех случаях, когда использование системы искусственного интеллекта раскрыто заявителем, следует из представленных материалов либо становится предметом спора.

В таком блоке заявитель мог бы указывать сведения об использовании системы искусственного интеллекта, об элементах результата, сформированных человеком, об

элементах, полученных путем генерации, о характере творческого вклада, а также о материалах, подтверждающих соответствующие обстоятельства. Экспертная организация при рассмотрении таких заявок оценивала бы связь между действиями человека и итоговой формой произведения. Сам по себе факт использования искусственного интеллекта не является достаточным основанием для отказа в регистрации.

В правилах также целесообразно предусмотреть возможность указания элементов результата, в которых выражен творческий вклад человека. Например, если отдельные изображения были получены с применением системы искусственного интеллекта, но человек самостоятельно разработал сюжет, структуру, композицию, последовательность сцен и осуществил редакторскую переработку, охрана может быть связана с композицией, структурой, авторским текстом, подбором и расположением материалов. Такой подход позволяет точнее определить объем заявляемой охраны и отделить технически или автономно сформированные элементы от тех частей результата, которые выражают творческие решения человека.

Элемент процедуры	Предлагаемое дополнение	Практическое значение
Заявление	Отдельное поле о применении системы искусственного интеллекта	Устанавливается технологический контекст создания результата
Описание произведения	Указание элементов, сформированных человеком	Определяется связь результата с творческими действиями заявителя
Сведения о генерации	Краткое описание элементов, полученных с помощью системы искусственного интеллекта	Уточняется объем заявляемой охраны
Материалы заявки	Возможность представить промпты, черновики, версии файлов и историю редактирования	Цифровой след учитывается как вспомогательное доказательство
Результат регистрации	Фиксация охраняемых элементов результата, созданного с применением системы искусственного интеллекта	Снижается риск неопределенности при последующем споре

Предлагаемая модель не меняет природу регистрации и не превращает ее в условие возникновения авторского права. Она конкретизирует процедуру для случаев, когда заявитель сам указывает на использование системы искусственного интеллекта либо когда характер результата требует уточнения объема охраны. Такая модель может применяться как основа для подзаконных изменений, внутренней инструкции экспертной организации или разъяснений уполномоченного органа.

Заключение. Критерий творческого вклада человека является ключевым условием авторско-правовой охраны произведений, создаваемых с применением систем искусственного интеллекта. Его оценка должна учитывать не только факт использования цифрового инструмента, но и характер действий человека, степень его контроля над выразительными элементами и связь таких действий с итоговой формой произведения.

Достаточный творческий вклад может выражаться в самостоятельном замысле, содержательном промпте, управлении процессом генерации, творческом отборе, компоновке, редактировании, переработке и придании итоговому результату индивидуализированной формы. Промпт имеет важное, но ограниченное значение. Он может быть самостоятельным объектом авторского права и доказательством замысла, однако вопрос об охране итогового результата требует дополнительной оценки.

Цифровой след следует рассматривать как вспомогательное доказательство. Его использование оправдано при регистрации, договорном регулировании и разрешении споров, когда необходимо установить характер и объем человеческого вклада. Отсутствие цифрового следа не должно автоматически исключать охрану, если человеческий творческий вклад подтверждается иными материалами.

Таким образом, статья развивает уже закрепленную в законодательстве Республики Казахстан человекоцентричную модель авторского права и предлагает прикладной механизм ее реализации. Предложенные критерии конкретизируют законодательный принцип творческого вклада человека для целей регистрации, договорного регулирования и разрешения споров. Они также могут быть использованы при подготовке дополнений к действующим Правилам внесения сведений в Государственный реестр прав на объекты, охраняемые авторским правом, или при разработке внутренней инструкции экспертной организации.

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ИСКУССТВЕННЫЙ ИНТЕЛЛЕКТ В ОБУЧЕНИИ МАТЕМАТИКЕ В УСЛОВИЯХ ИНКЛЮЗИВНОГО ОБРАЗОВАНИЯ

Аннотация. Настоящая статья посвящена анализу потенциала искусственного интеллекта (ИИ) в обучении математике детей с особыми образовательными потребностями (ООП) в условиях инклюзивного образования. В рамках теоретического исследования, проведенного в 2024–2025 гг., представлен сравнительный анализ адаптивных образовательных систем (Calcularis 2.0, «PL-modified») и современных методов машинного обучения. Было установлено, что специфические когнитивные трудности, возникающие у детей с различными категориями особых образовательных потребностей (ООП) – включая ЗПР, РАС, дискалькулию, нарушения речи, зрения и слуха – оказывают существенное влияние на процесс освоения математики. Исследование выявило дифференцированную эффективность различных моделей машинного обучения: интерпретируемые модели (деревья решений) показали свою пригодность для диагностики когнитивных дефицитов, ансамблевые методы (Gradient Boosting) – для прогнозирования академической успеваемости, а нейронные сети – для мониторинга динамики учебного процесса. На основе полученных данных была разработана концептуальная модель адаптивной системы, состоящая из трёх взаимосвязанных модулей: диагностического, адаптивного и прогностического. Данная модель обеспечивает динамическую персонализацию обучения по темпу, сложности и формату представления материала, а также предусматривает интеграцию с открытыми образовательными ресурсами (OER). Результаты исследования подтверждают потенциал предложенного подхода в преодолении ключевых барьеров в математическом образовании детей с ООП и служат основой для дальнейших эмпирических исследований в условиях реальных инклюзивных образовательных сред.

Ключевые слова: искусственный интеллект, инклюзивное образование, адаптивные обучающие системы, машинное обучение, особые образовательные потребности, обучение математике.

Введение. Современная система образования стремится к тому, чтобы каждый ребенок, независимо от индивидуальных особенностей, мог получить качественное образование. Это и есть инклюзивное образование, и оно имеет большое значение. Однако обучение математике сопряжено с особыми трудностями. Ведь математика требует умения мыслить абстрактно и представлять вещи в уме, а это может быть трудно для многих детей с особыми образовательными потребностями (ООП)[10]. В эпоху

[10] Левшунова Ж.А., Басалаева Н.В., Казакова Т.В. Инклюзивное образование: учеб. пособие. – Красноярск: Сиб. федер. ун-т, 2017. – С. 11–12.

повсеместного распространения цифровых технологий, концепция открытого образования утверждает, что доступность и инклюзивность в сфере образования – это не просто принципы, а базовые права человека.

Целью настоящей работы является теоретически обосновать и представить модель, раскрывающую потенциал технологий искусственного интеллекта, в частности адаптивных обучающих систем, для обеспечения персонализированного обучения математике детей с особыми образовательными потребностями в условиях инклюзивного образования.

Задачи исследования:

1. Оценить адаптивные системы для обучения математике детей с ООП.
2. Сравнить методы машинного обучения для диагностики когнитивных дефицитов и прогнозирования успеваемости
3. Выявить причины низкой успеваемости и предложить пути устранения.

Как показывают исследования, инклюзивное образование сталкивается с рядом проблем. Дело не только в том, что нет пандусов или специального оборудования (это так называемые "физические" барьеры). Есть еще и проблемы с законами, существует дефицит бюджетных средств, а самое главное – люди вокруг не всегда правильно понимают и принимают детей с ОВЗ[11]. В учебнике "Инклюзивное образование" детей с ОВЗ делят на разные группы: те, у кого проблемы со слухом, зрением, речью, интеллектом, кто отстает в развитии, у кого проблемы с движением, и так далее[12]. Каждой такой группе нужен свой особый подход, особенно когда дело доходит до уроков математики.

В данной ситуации значительный потенциал имеет искусственный интеллект (ИИ). ИИ активно интегрируется в нашу жизнь, и сфера образования не является исключением. Как подчеркивают Малинецкий и Смолин, мир вступает в постиндустриальную эпоху, где информационные технологии и самоорганизация играют ведущую роль[13]. Благодаря нейросетевой развития компьютеры теперь способны решать задачи, ранее доступные только людям, такие как распознавание образов, понимание речи и выявление закономерностей[14]. Это открывает новые возможности для индивидуализации образовательного процесса, включая обучение математике.

Реальное внедрение интеллектуальных систем в учебный процесс требует серьезной математической подготовки. Согласно работе Дайзенрота, Фейзала и Она, современные подходы к машинному обучению, такие как нейронные сети и байесовские модели, базируются на таких дисциплинах, как линейная алгебра, математический анализ, теория вероятностей и статистика[15]. Понимание этих фундаментальных концепций открывает путь к непростому применению готовых алгоритмов, но и к их гибкой настройке под специфические педагогические задачи. Это может включать в себя как автоматическое распознавание почерка при проверке письменных работ, так и разработку персонализированных траекторий обучения, основанных на анализе цифрового следа ученика.

[11] Левшунова Ж.А., Басалаева Н.В., Казакова Т.В. Инклюзивное образование. – С. 21–31.
[12] Левшунова Ж.А., Басалаева Н.В., Казакова Т.В. Инклюзивное образование. – С. 9.
[13] Малинецкий Г.Г., Смолин В.С. О развитии прикладной математики, искусственного интеллекта и компьютерных вычислений // Препринты ИПМ им. М.В.Келдыша. 2021. № 69. – С. 6–8.
[14] Малинецкий Г.Г., Смолин В.С. О развитии прикладной математики... – С. 17–18.
[15] Дайзенрот М.П., Фейзал А.А., Он Ч.С. Математика в машинном обучении. – СПб.: Питер, 2024. – С. 15, 20–21, 400–437.

Применение искусственного интеллекта, основанного на точных расчетах, в образовании перестало быть лишь концепцией и стало реальностью. Чтобы интеллектуальные системы стали по-настоящему востребованными, необходимо обеспечить их открытость и доступность. Исследования в области открытого образования убедительно показывают, что бесплатные и свободно распространяемые образовательные ресурсы (OER) являются мощным инструментом для создания равных образовательных возможностей для всех учащихся, включая детей с особыми образовательными потребностями[16]. Открытые платформы предоставляют учителям и родителям возможность не только использовать готовые адаптивные решения, но и вносить в них изменения, а также делиться ценным опытом и лучшими практиками. Это имеет огромное значение для инклюзивного образования, где каждому ребенку требуется индивидуальный подход.

Тем не менее, для того чтобы открытые интеллектуальные системы эффективно работали, необходимо решить как технические, так и методические задачи. Сборник «Цифровая гуманитаристика и технологии в образовании (DHTE 2020)» подчеркивает, что успешная адаптация цифровых инструментов для детей с ООП возможна только при тесном сотрудничестве педагогов, психологов и разработчиков. В качестве примера можно привести компьютерную игровую систему «PL-modified». Изначально предназначенная для диагностики универсальных учебных действий у обычных школьников, она может быть адаптирована для детей с задержкой психического развития путем изменения темпа игры, добавления визуальной поддержки и упрощения инструкций. Это подтверждает, что гибкость цифровых платформ и открытость их исходного кода (принцип OER) являются ключевыми факторами для распространения инклюзивных образовательных практик[17].

Исследования и практика подтверждают, что сочетание искусственного интеллекта и открытых образовательных ресурсов открывает новые возможности для обучения математике детей с особыми образовательными потребностями, помогая преодолеть существующие трудности. Наша модель стремится использовать потенциал машинного обучения (диагностика, адаптация, прогнозирование) в сочетании с гибкостью открытых платформ. Это позволит каждому ребенку двигаться по индивидуальному пути математического развития. Решение задач по оценке адаптивных систем, сравнению алгоритмов машинного обучения и определению причин низкой успеваемости станет фундаментом для практических рекомендаций по внедрению подобных систем в инклюзивном образовании.

Материалы и методы исследования. В период с 2024 по 2025 год было проведено исследование, посвященное изучению потенциала искусственного интеллекта (ИИ) для создания персонализированных математических программ для детей с особыми образовательными потребностями (ООП). Исследование включало теоретический анализ и моделирование. Теоретический этап (сентябрь-декабрь 2024 г.) был посвящен изучению научной литературы по инклюзивному образованию, адаптивным системам обучения и методам машинного обучения. При отборе источников особое внимание

[16] Blessinger P., Bliss T.J. Open Education: International Perspectives in Higher Education. – Cambridge: Open Book Publishers, 2016. – Chapter 1. – P. 11–15.

[17] Марголис А.А., Куравский Л.С., Гаврилова Е.В., Шепелева Е.А., Ермаков С.С., Войтов В.К. Разработка компьютерной игровой системы ‘PL-modified’ как инструмента диагностики универсальных учебных действий младших школьников // Цифровая гуманитаристика и технологии в образовании (DHTE 2020). – М.: МГППУ, 2020. – С. 8–15.

уделялось работам, касающимся инклюзивного образования и классификации ООП (Левшунова и др., 2017; Educație incluzivă, 2017), а также применению машинного обучения в образовании (Дайзенрот и др., 2024; Balaji и др., 2021; Seota и др., 2021). Дополнительные данные об открытых образовательных ресурсах (OER) и теории открытого образования были почерпнуты из работы Blessinger & Bliss (2016), а информация об адаптивных игровых системах диагностики – из сборника DHTE 2020 (Марголис и др., 2020). В результате были собраны сведения о различных типах ООП, когнитивных особенностях, влияющих на изучение математики, алгоритмах машинного обучения для прогнозирования успеваемости и диагностики, а также о реальном опыте использования систем Calcularis 2.0 и «PL-modified».

В ходе работы были получены ценные сведения, касающиеся: разнообразия особых образовательных потребностей (ООП) у учащихся; того, как когнитивные особенности влияют на их способность к изучению математики; использования алгоритмов машинного обучения для предсказания успеваемости и выявления проблем в обучении; а также реальных результатов применения систем Calcularis 2.0 и «PL-modified».

Исследование, основанное на работах Левшуновой и др. (2017) и коллектива авторов Balan V. и др.(2017), выявило, что различные категории особых образовательных потребностей (ООП) порождают уникальные трудности в изучении математики. Например, дети с задержкой психического развития (ЗПР) испытывают проблемы с последовательностью действий и переключением между ними. У детей с расстройствами аутистического спектра (РАС) возникают сложности с абстрактными математическими концепциями. Дискалькулия проявляется в нарушении базовых навыков счета и понимания чисел. Дети с тяжелыми нарушениями речи (ТНР) испытывают трудности с устным объяснением решения задач. Для детей с нарушениями зрения и слуха необходимы альтернативные способы представления информации. Следовательно, образовательная система должна адаптироваться к индивидуальным когнитивным особенностям каждого ребенка, предлагая соответствующие методы обучения.

Для эффективного инклюзивного математического образования, как показал сравнительный анализ (Balaji и др., 2021; Seota и др., 2021), целесообразно использовать различные методы машинного обучения. Интерпретируемые модели, такие как деревья решений и случайный лес, идеально подходят для диагностики нарушений в обучении (ООП) и выявления когнитивных проблем, поскольку они наглядно демонстрируют педагогу процесс принятия решений. Для точного прогнозирования успеваемости и определения учеников, нуждающихся в дополнительной поддержке («группа риска»), лучше всего зарекомендовали себя ансамблевые методы (AdaBoost, Gradient Boosting). Нейросети же эффективны для отслеживания изменений в учебном процессе, например, динамики ошибок, времени выполнения заданий и темпа работы. Комбинирование этих подходов позволяет одновременно решать задачи диагностики (определять причины трудностей) и персонализации обучения (подбирать оптимальные стратегии).

Разработка концептуальной модели адаптивной системы. На основе теоретического анализа была разработана модель, включающая три основных компонента: диагностический модуль (определение типа ООП и уровня математических навыков по цифровым следам), адаптивный модуль (подбор последовательности, темпа и формата подачи математических заданий – от конкретных примеров к абстрактным, от простого к сложному), прогностический модуль (предупреждение учителя о возможных

трудностях и риске отставания). Модель ориентирована на использование в инклюзивных классах и предполагает интеграцию с открытыми образовательными платформами (OER), что обеспечивает доступность и возможность адаптации материалов под конкретного ребенка.

Результаты и обсуждение. Проведенный теоретический анализ и предложенная модель позволяют выявить, как именно ИИ может улучшить преподавание математики детям с ООП. В этом разделе мы представим ключевые выводы нашего исследования, подкрепленные авторитетными источниками и мировыми примерами.

Мы установили, что основное препятствие для успешного обучения детей с ООП кроется в несовпадении стандартной образовательной среды с их индивидуальными когнитивными потребностями. Согласно учебному пособию "Инклюзивное образование" (под ред. Левшуновой и др.), существует целый ряд барьеров – от физических до социально-психологических – которые напрямую ограничивают способность ребенка к пониманию абстрактных математических концепций[18]. В этом контексте адаптивные системы на базе ИИ становятся не просто желательным дополнением, а критически важным решением.

В отличие от статических методов, адаптивные алгоритмы способны в реальном времени изменять сложность, темп и способ представления информации, автоматически подстраиваясь под текущий уровень знаний учащегося[19]. Искусственный интеллект в математике позволяет решать широкий спектр задач: от распознавания почерка при проверке письменных работ до построения персонализированных траекторий обучения на основе анализа цифрового следа ученика[20]. Нейросетевые технологии, в частности глубокие нейронные сети (DNN), успешно применяются для автоматической настройки миллиардов параметров, что делает возможным адаптивное обучение в масштабе[21].

Данный подход полностью соответствует современным педагогическим тенденциям, особенно в контексте работы с детьми, имеющими расстройства аутистического спектра и другие ментальные нарушения. Исследования подчеркивают, что для таких детей критически важна максимальная персонализация и учет их индивидуальных потребностей[22]. Система "PL-modified" служит отличным примером такого комплексного решения. Изначально предназначенная для оценки универсальных учебных действий, она демонстрирует, как интеграция игровых элементов и адаптивных алгоритмов позволяет одновременно решать две ключевые задачи: выступать в роли тренажера для развития навыков и служить точным диагностическим инструментом для определения зоны ближайшего развития ребенка[23].

Представленная технология предоставляет значительные возможности для детей с

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[18] Левшунова Ж.А., Басалаева Н.В., Казакова Т.В. Инклюзивное образование: учеб. пособие. – Красноярск: Сиб. федер. ун-т, 2017. – С. 45-67.

[19] Blessinger P., Bliss T.J. Open Education: International Perspectives in Higher Education. – Cambridge: Open Book Publishers, 2016. – P. 12-14. (О доступе, персонализации и открытости образования)

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нарушениями опорно-двигательного аппарата или когнитивными отличиями в освоении абстрактных математических идей. Разработанный специально для них интерфейс обеспечивает взаимодействие с учебным материалом посредством наглядных или осязаемых репрезентаций числовых понятий и математических операций. Данный подход гармонирует с принципами универсального дизайна в образовании, позиционируя технологию не просто как вспомогательный инструмент, но как фундаментальный компонент доступной образовательной среды[24].

Таким образом, представленные примеры и теоретические положения подтверждают, что инновационные технологии, основанные на искусственном интеллекте и адаптивных алгоритмах, предлагают целый спектр передовых решений для устранения существующих преград в математическом образовании. Для структурирования полученной информации и наглядного представления функционала и преимуществ различных подходов, ниже представлена сводная таблица.

Таблица 1 – Сравнительная характеристика технологий адаптивного обучения математике для детей с ООП

Технология / Программа	Функция в обучении математике	Преимущества для детей с ООП
Адаптивные системы (ITS)	Системы, которые подстраивают уровень сложности заданий в реальном времени, ориентируясь на то, как пользователь справляется с ними.	Уменьшить умственное напряжение и избежать фрустрации, возникающей из-за неудач.
Calcularis 2.0	Программа, направленная на развитие нейронных сетей, отвечающих за числовое восприятие и пространственное мышление.	Оказывать целенаправленную помощь детям, испытывающим трудности с математикой (дискалькулия) или имеющим особенности развития.
Машинное обучение (ML)	Использование алгоритмов для анализа данных о действиях пользователя в цифровой среде с целью предсказания возможных затруднений в обучении.	Заблаговременно определять недостающие знания, опираясь на прогностические модели.
Системы распознавания речи и жестов	Преобразование голосовых команд в математические выражения.	Улучшение доступа к обучению для детей с двигательными нарушениями.
Геймификация (PL-modified)	Применение игровых механик для оценки общих учебных навыков через специально разработанные игровые ситуации.	Стимулировать интерес и повысить вовлеченность учащихся при решении непростых задач.

[24] Шеманов А.Ю. Э-инклюзия, некоторые риски цифровой среды... // DHTE 2020. – С. 184-185. (О расширяющих возможностях цифровых технологий и универсальном дизайне)

Технологии, представленные в таблице, не исключают друг друга. Напротив, их объединение в рамках единой адаптивной платформы открывает возможности для формирования максимально полной и действенной персонализированной образовательной среды, отвечающей разнообразным потребностям детей в изучении математики.

Важным шагом является интеграция диагностического, адаптивного и прогностического модулей в единую систему, где каждый элемент выполняет свою функцию, но при этом усиливает эффективность других.

Рисунок ниже представляет собой концептуальную схему адаптивной системы, которая наглядно показывает, как взаимодействуют ее главные составляющие: от модели, описывающей пользователя, и модели, отвечающей за адаптацию, до блоков, управляющих навигацией и выдающих рекомендации. Учитель и учебный контент тесно связаны с доменной моделью. Эта модель, используя специальный "движок адаптации", обеспечивает индивидуальный подход к подаче материала каждому ученику. Таким образом, представленная визуальная модель подтверждает теоретические положения, лежащие в основе исследования, и служит практическим руководством для внедрения подобных систем в инклюзивное образование.

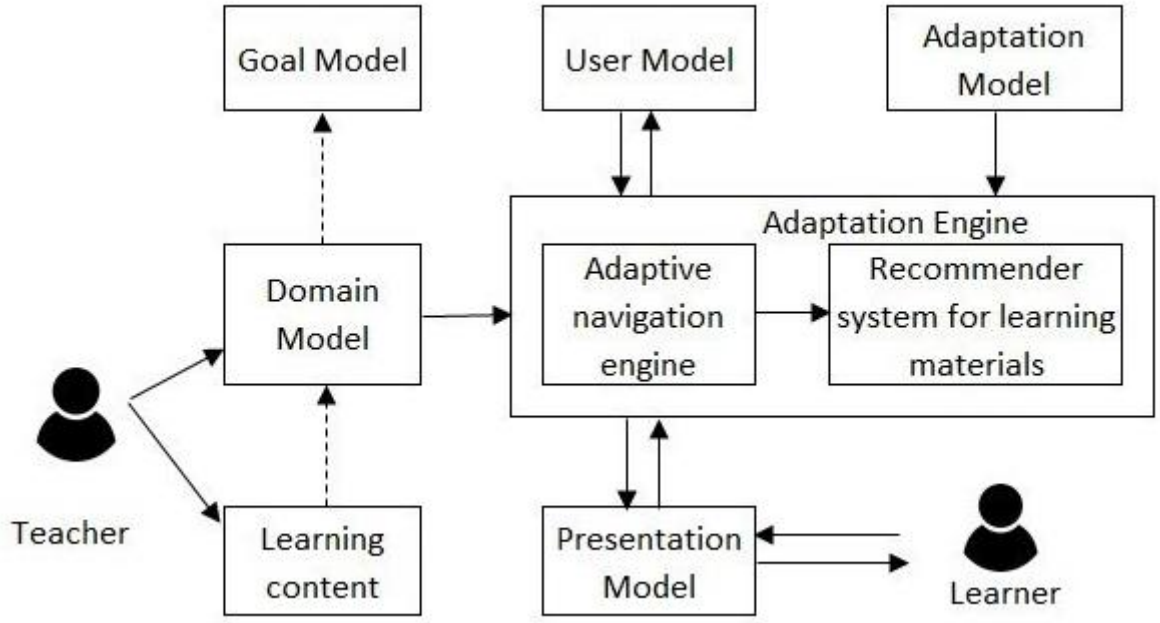


Рисунок 1. Архитектура адаптивной системы обучения (на основе Gupta et al., 2024).

Получается, что представленная визуальная модель служит не только иллюстрацией теоретических основ исследования, но и наглядно демонстрирует практическую реализуемость предложенной концепции. Она подтверждает, что персонализированный подход к обучению достижим посредством интеграции диагностических, адаптивных и прогностических компонентов в рамках единой платформы. Такой подход обеспечивает создание благоприятной и поддерживающей образовательной среды, способствующей успешному освоению математики каждым учащимся, вне зависимости от его индивидуальных особенностей развития.

Заключение. Проведенное теоретическое исследование и разработанная концептуальная модель свидетельствуют о значительном потенциале искусственного интеллекта, в частности адаптивных обучающих систем, в преодолении ключевых барьеров в обучении математике детей с особыми образовательными потребностями. В отличие от традиционных статических методик, предложенная трёхкомпонентная архитектура, включающая диагностический, адаптивный и прогностический модули, обеспечивает динамическое реагирование: она позволяет в режиме реального времени идентифицировать когнитивные дефициты, персонализировать параметры обучения (темп, сложность, формат подачи материала) и проактивно информировать педагога о потенциальных рисках отставания. Данный подход полностью соответствует принципам универсального дизайна в образовании и способствует расширению возможностей для реализации инклюзивной практики.

Результаты сравнительного анализа методов машинного обучения свидетельствуют о том, что максимальная эффективность в контексте инклюзивного математического образования достигается путем интеграции различных подходов. Интерпретируемые модели, включая деревья решений и случайный лес, целесообразно применять для диагностики образовательных дефицитов. Ансамблевые методы, такие как Gradient Boosting и AdaBoost, демонстрируют высокую результативность в прогнозировании академической успеваемости. Нейросетевые подходы, в свою очередь, оптимальны для мониторинга динамики учебной деятельности. Данный гибридный подход обеспечивает синергию между точностью прогнозов, наглядностью представления информации для педагогического состава и способностью к обработке масштабных объемов цифрового следа.

Результаты работы подчеркивают важность синергии адаптивных интеллектуальных систем и открытых образовательных ресурсов (OER). Изучение примеров (Calcularis 2.0, «PL-modified») показало, что открытость кода и свободный доступ к контенту не только устраняют финансовые препятствия, но и создают платформу для совместной работы педагогов, психологов и родителей. Это позволяет им совместно совершенствовать учебные материалы, делая их максимально релевантными для уникальных потребностей каждого ребенка. Данный подход особенно ценен при работе с детьми, имеющими расстройства аутистического спектра, задержку психического развития и дискалькулию, поскольку стандартные цифровые инструменты зачастую оказываются недостаточными.

Полученные результаты исследования убедительно доказывают жизнеспособность предложенной модели адаптивного математического образования. Эта модель, объединяющая возможности машинного обучения с идеями открытого образования, не только теоретически обоснована, но и готова к практическому внедрению. Для дальнейшего развития необходимо провести эмпирические испытания модели в условиях реальных инклюзивных классов, разработать конкретные алгоритмы адаптации для различных групп учащихся с ООП и подготовить методические материалы для педагогов, касающиеся работы с интеллектуальными системами поддержки. Успешное решение этих вопросов позволит перейти от деклараций к реальному воплощению инклюзивного образования, обеспечивая каждому ребенку, вне зависимости от его особенностей, возможность успешного освоения математики.

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