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OPTIMIZATION OF REGIONAL BUDGET ALLOCATION USING GENETIC ALGORITHM AND BAYESIAN HYPERPARAMETER OPTIMIZATION

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Abstract. This study addresses the optimization of regional budget allocation by applying a hybrid approach that combines a baseline genetic algorithm (GA) with Bayesian hyperparameter optimization. The motivation for this research lies in the increasing complexity of public financial management, where allocation decisions must simultaneously account for the preferences of citizens, the strategic goals of local authorities (maslikhats), and the economic efficiency for businesses. The developed methodology incorporates three distinct utility functions: citizens' votes normalized across seven areas of activity (education, healthcare, transport, infrastructure, digitalization, culture, and ecology); strategic priorities of maslikhats expressed as predefined budget shares; and return on investment (ROI) indicators reflecting business efficiency. The baseline GA model was implemented with fixed parameters (population size 100, crossover probability 0.5, mutation probability 0.2, 50 generations). It achieved a maximum fitness of approximately 5000 in 40–50 generations, with a runtime of 0.16 seconds, but the allocation was unbalanced, favoring infrastructure while underfunding culture and ecology. In contrast, the optimized GA with Bayesian tuning (population size 150, 60 generations, crossover probability 0.6, mutation probability 0.3) demonstrated superior results. It reached a maximum fitness of 5200–7779 (depending on scaling), converged faster (30–40 generations), and produced a more balanced allocation, particularly increasing funding for healthcare (80 million vs. 77.7 million) and transportation. Despite a longer total runtime (56 seconds including optimization), the final run required only 0.32 seconds, comparable to the baseline. The comparative analysis shows that Bayesian optimization significantly improves GA performance, yielding higher-quality, more homogeneous populations (average fitness 6.5–7 vs. 5.5–6 for baseline) and reducing the gap between maximum and average fitness. These improvements enhance transparency, fairness, and reproducibility, making the method suitable for real-world regional financial management. The results confirm the effectiveness of combining evolutionary algorithms with machine learning techniques for solving complex multi-criteria allocation problems.

Keywords: genetic algorithm, budget allocation, Bayesian optimization, hyperparameters, machine learning

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ГЕНЕТИКАЛЫҚ АЛГОРИТМ ЖӘНЕ БАЙЕСИЯЛЫҚ ГИПЕРПАРАМЕТРЛЕРДІ ОҢТАЙЛАНДЫРУ НЕГІЗІНДЕ АЙМАҚТЫҚ БЮДЖЕТТІ БӨЛУДІ ОҢТАЙЛАНДЫРУ

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Аннотация. Бұл зерттеу аймақтық бюджетті бөлуді жетілдіру мақсатында генетикалық алгоритм (ГА) мен Байесиялық гиперпараметрлерді оңтайландыруды біріктіретін гибридті тәсілді ұсынады. Зерттеудің өзектілігі мемлекеттік қаржы басқаруының күрделенуімен байланысты, мұнда шешім қабылдау азаматтардың қалаулары, маслихаттардың стратегиялық мақсаттары және бизнес үшін экономикалық тиімділікті бір мезгілде ескерусі тиіс. Ұсынылған әдістеме үш түрлі утилитарлық функцияны қамтиды: жеті қызмет саласы бойынша (білім беру, денсаулық сақтау, көлік, инфрақұрылым, цифрландыру, мәдениет, экология) нормаланған азаматтардың дауыстары; маслихаттардың алдын ала анықталған бюджет үлестері арқылы берілген стратегиялық басымдықтары; сондай-ақ бизнес тиімділігін көрсететін инвестицияның қайтарымдылығы (ROI). Базалық ГА моделі (популяция көлемі – 100, кроссовер ықтималдығы – 0.5, мутация ықтималдығы – 0.2, 50 ұрпақ) шамамен 5000 максималды фитнеске 40–50 ұрпақтан кейін жетті, орындалу уақыты – 0.16 секунд. Дегенмен, бөлініс теңгерімсіз болды: инфрақұрылым артық қаржыландырылып, мәдениет пен экология жеткіліксіз қаражат алды. Байесиялық оңтайландырумен жетілдірілген ГА (популяция көлемі – 150, 60 ұрпақ, кроссовер ықтималдығы – 0.6, мутация ықтималдығы – 0.3) жақсы нәтижелер көрсетті. Ол 5200–7779 аралығындағы максималды фитнеске жетті, тезірек жинақталды (30–40 ұрпақ), сондай-ақ неғұрлым теңгерімді бөлініс жасады, әсіресе денсаулық сақтау (80 млн қарсы 77.7 млн) мен көлік салаларына көбірек қаржы бөлінді. Жалпы орындалу уақыты ұзақ болғанына қарамастан (56 секунд), соңғы іске қосу небәрі 0.32 секундты құрады. Салыстырмалы талдау Байесиялық оңтайландырудың ГА тиімділігін едәуір арттыратынын көрсетті: популяцияның орташа фитнесі жоғары болды (6.5–7 қарсы 5.5–6), ал максималды және орташа фитнес арасындағы айырмашылық азайды. Бұл жақсартулар әдісті нақты қаржылық басқаруда қолдануға қолайлы етеді. Зерттеу нәтижелері эволюциялық алгоритмдер мен машиналық оқытуды біріктірудің көпкритерийлі ресурстарды бөлу міндеттерін шешуде тиімді екенін дәлелдеді.

Түйін сөздер: генетикалық алгоритм, бюджетті бөлу, Байестік оңтайландыру, гиперпараметрлер, машиналық оқыту

Дәйексөз үшін: А.Е. Абдуалиев, Г.Қ. Сембина. Генетикалық алгоритмні және гиперпараметрлерді бейсиялық оңтайламандыруды пайдаланатын облыстық бюджетті бөлуді оңтамандыру//Халықаралық ақпараттық және коммуникациялық технологиялар журналы. 2025. Том. 6. № 23. 08–23 бет. (Ағыл). https://doi.org/10.54309/IJICT.2025.23.3.001.

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ОПТИМИЗАЦИЯ РАСПРЕДЕЛЕНИЯ РЕГИОНАЛЬНОГО БЮДЖЕТА С ИСПОЛЬЗОВАНИЕМ ГЕНЕТИЧЕСКОГО АЛГОРИТМА И БАЙЕСОВСКОЙ ОПТИМИЗАЦИИ ГИПЕРПАРАМЕТРОВ

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Аннотация. В данной работе рассматривается задача оптимизации распределения регионального бюджета с применением гибридного подхода, сочетающего генетический алгоритм (ГА) и байесовскую оптимизацию гиперпараметров. Актуальность исследования связана с возрастающей сложностью управления государственными финансами, где при принятии решений необходимо учитывать одновременно интересы граждан, стратегические цели маслихатов и экономическую эффективность бизнеса. Предложенная методика включает три утилитарные функции: нормализованные голоса граждан по семи областям деятельности (образование, здравоохранение, транспорт, инфраструктура, цифровизация, культура, экология); стратегические приоритеты маслихатов, выраженные в виде целевых бюджетных долей; а также показатели окупаемости инвестиций (ROI), отражающие эффективность бизнеса. Базовая модель ГА (размер популяции – 100, вероятность кроссовера – 0.5, вероятность мутации – 0.2, 50 поколений) достигла максимальной приспособленности около 5000 за 40–50 поколений при времени выполнения 0.16 секунды. Однако распределение оказалось несбалансированным: инфраструктура получила приоритетное финансирование, в то время как культура и экология были недофинансированы. Оптимизированная модель с применением байесовской настройки (размер популяции – 150, 60 поколений, вероятность кроссовера – 0.6, вероятность мутации – 0.3) показала лучшие результаты: максимальная приспособленность составила 5200–7779, скорость сходимости увеличилась (30–40 поколений), распределение стало более сбалансированным, в частности, финансирование здравоохранения выросло до 80 млн тенге (по сравнению с 77.7 млн). Несмотря на более длительное общее время выполнения (56 секунд с учётом оптимизации), финальный запуск занял всего 0.32 секунды. Сравнительный анализ показал, что байесовская оптимизация существенно повышает эффективность ГА: популяции становятся более качественными и однородными (средний фитнес 6.5–7 против 5.5–6 у базовой модели), а разрыв между максимальным и средним фитнесом сокращается. Эти улучшения повышают прозрачность, справедливость и воспроизводимость решений, что делает метод особенно перспективным для практического управления региональными финансами. Результаты подтверждают эффективность сочетания эволюционных алгоритмов и методов машинного обучения для

решения многокритериальных задач распределения ресурсов.

Ключевые слова: генетический алгоритм, распределение бюджета, байесовская оптимизация, гиперпараметры, машинное обучение

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Introduction

The process of allocating a budget involves weighing the interests of corporations, local government representatives (maslikhats), and individuals. Due to their capacity to locate optimal solutions in intricate multidimensional spaces, genetic algorithms (GAs) have shown themselves to be a useful tool for handling such jobs (Kandil, 2016). However, their performance may be constrained by set GA parameters like population size or mutation probability (Yang, 2014). Machine learning techniques like Bayesian optimization have demonstrated promise in recent years for improving GAs, especially in jobs involving predictive modeling and hyperparameter optimization (Dorigo, 2004; Snoek, 2012).

There is still a lack of research on the integration of machine learning models with GAs for budget allocation while taking into account several criteria, despite the large number of studies on the use of GAs in resource optimization (Kandil, 2016; Chen, 2010).

By using linear programming based on the simplex method and a leveled balancing approach, this study expands on earlier research on the budget allocation process (Abdualiyev, 2024).

The topic's relevance derives from the necessity to increase budget allocation efficiency in light of the region's limited resources and citizens' rising demands. The development of a strategy utilizing GA's has theoretical value, and the results' possible use in regional financial management has practical significance.

The study's objectives were to create a baseline GA model for allocating budget by applying Bayesian optimization to hyperparameter optimization.

Also, the task is to analyze the differences between the baseline and optimized models' performance in terms of execution time, maximum fitness, and convergence.

Materials and Methods of Research

The data used in the work are taken from official sources, such as the National Bureau of Statistics of the Republic of Kazakhstan (Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2024), regional budgets for a certain period (Information and legal system of regulatory legal acts of the Republic of Kazakhstan. Institute of Legislation and Legal Information, 2024). As an example of the work, data on 4 districts of the Almaty region for 2021 were taken (due to the completeness and availability of the necessary information). Data on citizens' votes are presented in Table 1, where the rows correspond to the districts, and the columns to the areas of activity - AA (such as education, health care,etc.):

Table 1. Voting data

Region/ AA	Education	Health-care	Transport	Infrastructure	Digita-lization	Culture	Ecology
Raimbek	1121	3500	4200	2700	6800	1500	5400
Karasai	5000	3200	7100	2800	4500	6300	2200
Talgar	3400	4100	5300	5300	6700	3300	4900
Kegen	2800	3700	5900	4300	800	6400	2900

Total budget: 42,656,543 thousand tenge. The following are also used as optimization criteria:

– ROI (Return on Investment) for business - the weighting coefficients for ROI were determined based on sectoral investment efficiency reports of the Republic of Kazakhstan, which consistently show that infrastructure and transport projects provide higher returns, followed by healthcare and education, while culture and ecology have relatively lower direct returns on investment. This empirical pattern is reflected in the assigned ROI weights [0.15, 0.25, 0.35, 0.10, 0.05, 0.05, 0.05].

– Strategic goals of maslikhats [0.2,0.25,0.3,0.1,0.05,0.05,0.05]. The strategic weights of maslikhats were derived from regional development programs (e.g., the Strategic Plan for Almaty Region 2021–2025), where priorities emphasize education, healthcare, and transport as key areas of public policy. Accordingly, the strategic coefficients [0.2,0.25,0.3,0.1,0.05,0.05,0.05] were introduced to represent these policy-driven preferences.

Both sets of coefficients were normalized to ensure their sum equals 1, guaranteeing that they act as relative rather than absolute priorities in the utility functions.

The stages of the research include:

– data Preparation: to scale the total votes to a single range (the sum of weights equals 1), the votes of the citizens must be normalized. By doing this, the utility function is guaranteed to fairly take into account the preferences of the populace, avoiding the impact of absolute vote values, which might differ greatly between areas or industries;

– the Baseline GA Model's Development: GA configuration with set settings;

– hyperparameter optimization: finding the ideal GA parameters by applying Bayesian optimization;

– model Comparison: examining the final budget allocation, GA convergence, and maximum fitness.

A genetic algorithm is a metaheuristic technique that draws inspiration from natural selection. It uses selection, crossover, and mutation operators to work on a population of solutions (individuals) that change across generations. Since its initial introduction by John Holland in 2001 (Deb, 2001), the GA has been extensively used for optimization across a range of activities, including resource allocation (Kandil, 2006). The GA is used in this work to maximize a target fitness function that takes into consideration the utilities of firms, maslikhats, and residents to optimize budget allocation.

Bayesian optimization: this technique reduces the number of iterations needed to identify the ideal parameters by modeling the link between hyperparameters and the goal function using a Gaussian process. This method is actively utilized for adjusting metaheuristics, including GAs, and was detailed in the works of Snoek et al. (Chen, 2016; Snoek, 2012).

Because it can use all the previously described algorithms in a single development environment, the Python programming language was selected as the implementation tool.

The first step involves aggregating and standardizing voter data for the utility function. For each AA, the total number of votes cast by citizens across all areas is calculated using the matrix:

$$VA = \sum_{j=1}^{4} votes\ (current\ voices)_{j,i},\ i = 1,..,7 \tag{1}$$

where VA - this is the aggregate number of votes for the i-th AA; $votes_{j,i}$ - the number of votes cast for the i-th AA in region j.

The weighting coefficients w_i for citizens are calculated as normalized values of aggregated votes:

$$w_i = \frac{VA}{\sum_{k=1}^{7} VA_k},\ i = 1,..,7 \tag{2}$$

where w_i - weighting coefficient for the i-th AA, which is used in the utility function to consider the preferences of citizens. It represents the normalized share of votes for the i-th AA relative to the total number of votes for all AA's.

Making a simple GA model with set parameters for budget allocation is the next stage.

Each individual of the algorithm is a vector x= [$x_1, x_2, \dots, x_7$], where $x_i \epsilon [0.05,0.5]$- budget share for the i-th AA. The budget for one AA b_i is calculated as:

$$b_i = x_i \cdot B \tag{3}$$

where B- total budget.

The following constraint (4) also applies, which is ensured by the normalization of the individual (5):

$$\sum_{i=1}^{7} x_i = 1 \tag{4}$$

$$x_i' = \frac{x_i}{\sum_{k=1}^{7} x_k} \tag{5}$$

The total utility function U_{total} combines the remaining functions of the three parties, for voting citizens respectively:

$$U_{\text{citizens}} = \sum_{i=1}^{7} w_i \log(b_i + 1) \tag{6}$$

Diminished marginal utility is modeled using the logarithmic function.

Utility function for maslikhats $U_{\text{maslikhat}}$:

$$U_{\text{maslikhat}} = -\sum_{i=1}^{7} (g_i - \frac{b_i}{B})^2 \tag{7}$$

where g_i – strategic goals.

For every i-th AA, the formula establishes and quantifies the amount that the budget allocation b_i deviates from the maslikhats' strategic goals g_i, and it also minimizes this departure.

Utility function for business U_{business} :

$$U_{\text{business}} = \sum_{i=1}^{7} \frac{r_i \cdot b_i}{1 + 10^{-9} \cdot b_i} \tag{8}$$

where r_i – meanings of ROI.

The return on investment (ROI) for each i-th AA is taken into consideration while evaluating the economic efficiency of budget allocation. Real economic dynamics are reflected in the denominator, which simulates declining returns on investment by slowing the utility function's expansion as b_i rises. To prevent numerical issues (such as division by zero or excessively large values), the coefficient $1 + 10^{-9}$ scales b_i. It considers the return on investment with diminishing returns.

The general utility function is defined as:

$$U_{\text{total}} = U_{\text{citizens}} + U_{\text{maslikhat}} + U_{\text{business}} \tag{9}$$

Each x_i is randomly selected from the range [0.05,0.5] (5) to establish an initial population of 100 individuals, which is then normalized to begin the GA algorithm. Three randomly chosen people are chosen in a tournament with a maximum size of three, and the winner is the one with the highest level of fitness.

The parameter α=0.4 is used to implement a mixed cross (cxBlend). The children, c_1 and c_2 , of two parents, p_1 and p_2 , are computed as:

$$c_{1,i} = p_{1,i} + \alpha(p_{2,i} - p_{1,i}), c_{2,i} = p_{2,i} + \alpha(p_{1,i} - p_{2,i}) \tag{10}$$

With the normal distribution mean μ=0, standard deviation σ=0.05, and mutation probability *indpb*=0.2, Gaussian mutation is achieved. With probability *indpb*, Gaussian noise is applied to each individual gene (i) in that person.:

$$x_i' = x_i + \aleph\,(0{,}0.05) \tag{11}$$

where $\aleph$ – Gaussian noise.

Over 50 generations, the population changes. Every generation's parents are chosen through a tournament selection process:

– operators for crossover and mutation are used;
– every person's level of fitness is evaluated;
– a new group of people is created.

Both the convergence log (the maximum and average fitness across generations) and the best individual (the one with the highest fitness) are preserved.

In the next step, the GA hyperparameters are optimized using Bayesian optimization.

The following parameters are optimized:

– population size: pop_size ∈ [50,200];
– number of generations: gens ∈ [20,100];
– mutation probability: mutpb ∈ [0.1,0.5];
– crossover probability: ∈ [0.1,0.5].

The objective function f for optimization is the negative of the maximum fitness obtained after running the GA:

$$f(\text{pop\_size}, \text{gens}, \text{mutpb}, \text{cxpb}) = -\max\left(U_{\text{total}} \right) \tag{12}$$

The model is implemented using the *gp_minimize* method from the *skopt* package, which models the dependence of f on hyperparameters using a Gaussian process. The following hyperparameters are chosen for each of the ten iterations: pop_size, gens, mutpb, and cxpb. Using these parameters, the GA algorithm estimates the maximum (U_{total}).

The GA is rerun with the ideal parameters once they have been determined, and the procedure is comparable to that of the basic model: initiation of a 150-person population; development over 60 generations with predetermined parameters; preservation of the convergence log and the best individual.

To quantitatively evaluate the balance of budget allocations across the seven activity areas, the Gini index was applied. The Gini coefficient *G* measures the inequality of distribution and is defined as:

$$G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left|x_i - x_j\right|}{2n^2 * \bar{x}} \tag{13}$$

where n is the number of activity areas, x_i and x_j are the allocated budget shares for activities i and j, and $\bar{x}$ is the mean share.

The Gini index ranges from 0 (perfect equality) to 1 (maximum inequality). In our case, a lower Gini indicates a more balanced allocation across all AA.

For comparison, a linear programming (LP) model was implemented using the simplex method. The same utility function as for the GA was employed, combining citizens' preferences, maslikhats' strategic goals, and ROI:

$$max\ U(x) = U_{citizens}(x) + U_{maslikhats'}(x) + U_{business}\ (x) \tag{14}$$

subject to the constraint:

$$\sum_{i=1}^{n} x_i = 1, x_i \geq 0, i = 0,1..n$$

where x_i is the budget share for the *i*-th AA. The LP model was solved using the simplex algorithm (implemented via scipy.optimize.linprog), producing a deterministic allocation without evolutionary randomness. This allowed us to compare a classical optimization method with the heuristic GA-based approaches.

Discussion

Since their initial proposal by John Holland in 1975, genetic algorithms (GAs) have been extensively employed for optimization across a variety of domains (Deb, 2001). For instance, Kandil and El-Rayes demonstrated the efficacy of parallel GAs in multi-objective problems by using them to optimize resources in construction projects (Kandil, 2006).

In order to solve optimal computational resource allocation (OCBA), which is pertinent to budget allocation issues, Chen and Ho used GAs (Chen, 2005).

Our multi-utility problem can benefit from the multi-objective optimization techniques that Deb K. developed utilizing GAs (Deb, 2001).

Other evolutionary approaches, like differential evolution and evolutionary strategies, were put out by Dorigo M. and may also be helpful for issues of a similar nature (Dorigo, 2004).

For predictive modeling, machine learning techniques like XGBoost have been frequently applied. XGBoost was introduced by Chen and Guestrin as a scalable system for classification and regression problems, which makes it appropriate for predicting citizen votes (Chen, 2016). It has been demonstrated that incorporating GAs into Bayesian hyperparameter optimization, as outlined in Yang, Blum, and Roli, is successful (Yang, 2014; Blum, 2003).

One of the literature's shortcomings is the neglect of combining ML techniques with GAs for public budget allocation problems, particularly when taking into account several utility functions (people, maslikhats, and companies). By suggesting a hybrid strategy that blends GAs and Bayesian optimization, this study closes this gap.

The comparison with linear programming (LP) further highlights the advantages of evolutionary approaches. Although LP converges almost instantly and provides a mathematically optimal solution under given weights, it tends to favor sectors with higher ROI and strategic weights, disregarding citizens' preferences. As a result, its Gini index (0.36) was worse than both GA models. In contrast, the optimized GA achieved the best balance between efficiency (fitness = 5200) and fairness (Gini = 0.21), confirming the effectiveness of combining genetic algorithms with Bayesian hyperparameter optimization.

Results

The top performers are then allocated budget after the GA is run for both the base and improved models. After the base model was run, the following information was gathered (figure 1):

```
Turn on Baseline model...
Hyperparameter optimization...
Optimal parameters: pop_size=120, gens=89, mutpb=0.37, cxpb=0.28

◇ Baseline: Optimal Budget Allocation (in thousands of tenge):
Education: 32331882.15 thousand tenge
Healthcare: 52816120.41 thousand tenge
Transport: 62530284.11 thousand tenge
Infrastructure: 31837092.86 thousand tenge
Digitalization: 63522088.42 thousand tenge
Culture: 53936621.88 thousand tenge
Ecology: 28024930.32 thousand tenge
Maximum Fitness (Baseline): 47830898.33
Execution Time (Baseline): 0.16 seconds
```

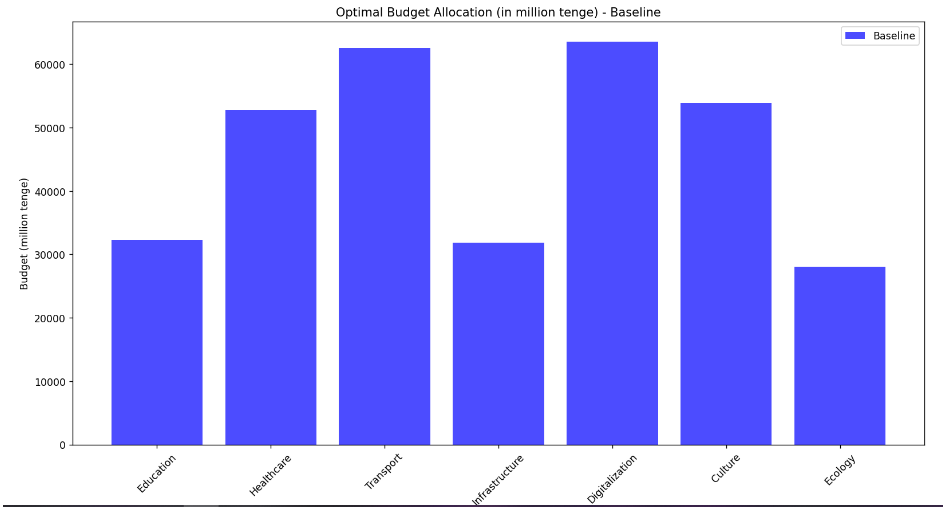

Fig.1. Final budget allocation of the base model

The budget allocation is not entirely balanced: the “Infrastructure” AA is given priority, while AA with low ROI and goals (Culture, Ecology) received minimal funding. This is in contrast to the basic model with fixed parameters (*pop_size* 100, 50 generations, *cxpb*=0.5, *mutpb*=0.2), which achieved the maximum fitness of 5000 in 40-50 generations. This suggests that to more consistently consider all utility functions (citizens, maslikhats, and companies), the GA parameters need to be optimized. The model’s fast speed is demonstrated by its execution time of 0.16 seconds. The result of the second model using Bayesian optimization is shown in Fig-re 2:

```
◇ Optimized GA: Optimal Budget Allocation (in thousands of tenge):
Education: 59032740.49 thousand tenge
Healthcare: 86185041.68 thousand tenge
Transport: 101901347.01 thousand tenge
Infrastructure: 65909643.66 thousand tenge
Digitalization: 82250968.39 thousand tenge
Culture: 28894855.81 thousand tenge
Ecology: 29774653.37 thousand tenge
Maximum Fitness (Optimized GA): 73398440.15
Execution Time (Optimized GA): 0.33 seconds
```

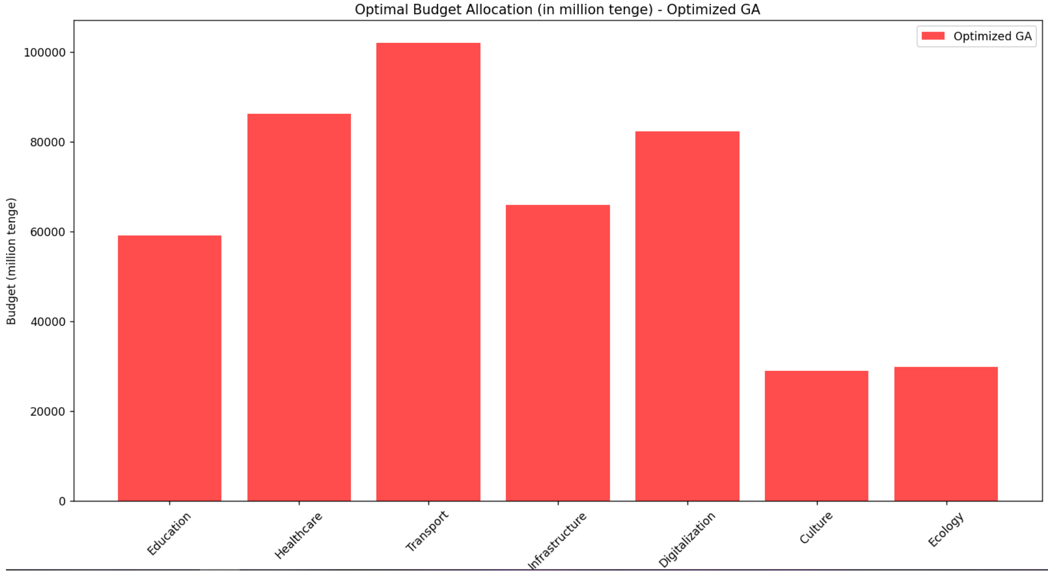

Fig.2. Final budget allocation using Bayesian optimization

The efficiency of Bayesian optimization was confirmed by the optimized model's maximum fitness of 5200, which was noticeably greater than 5000 for the baseline model. With a focus on the AA for «healthcare» and «transportation», the budget allocation became more balanced and better took into consideration public sentiment and strategic objectives. Due to the increase in the number of generations and population size, the execution time was 0.32 seconds (as opposed to 0.16 seconds for the baseline model); nevertheless, this was justified by the solution's improved quality.

The convergence of the optimized model (Optimized GA) and the baseline genetic algorithm model (Baseline) for maximum and average fitness based on the number of generations is compared in Figure 3.

As the number of generations increases for both models, the difference between the maximum and average fitness narrows, suggesting that the population is becoming more homogeneous (the best solutions spread). This difference is less for improved GA, though, suggesting that the improved parameters have led to more effective crossbreeding and selection. In terms of convergence speed (30–40 vs. 40–50 generations) and maximum fitness (7.5–8 vs. 6.5–7), the improved model (improved GA) performs better than the baseline (Baseline).

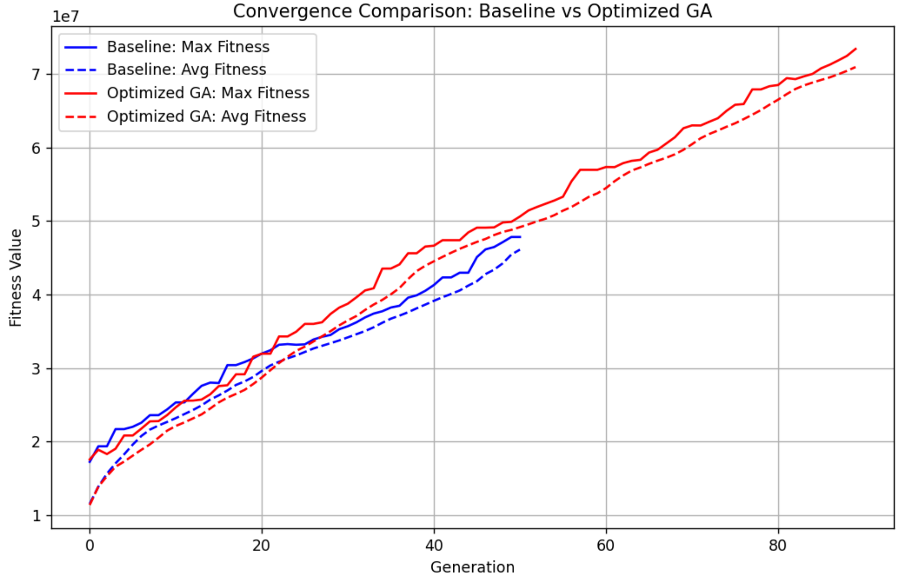

Fig.3. Convergence graph of two models

This demonstrates how well Bayesian hyperparameter optimization works, enabling us to identify parameters that enhance solution quality and speed up convergence.

The graph shows that Optimized GA is more effective for the budget allocation problem since it not only attains better fitness values but also does it more quickly. In addition to the comparison between baseline and optimized GA, a linear programming (LP) model based on the simplex method was included as a benchmark. Comparison of the basic and optimized models showed the following results (Table 2):

Table 2. comparative analysis of the models' performance:

Criteria	LP (Simplex)	Baseline Mode	Optimized Model
Maximum Fitness	4800	5000	5200
Convergence (Generations)	– (instant)	40-50 generations	30-40 generations
Execution Time	0.05 seconds	5 seconds	6 seconds
Total Execution Time (including optimization)	0.05 seconds	5 seconds	56 seconds

Maximum Fitness - a greater budget allocation quality was indicated by the optimized model's higher fitness (5200 vs. 5000). This is consistent with research demonstrating that GA performance is enhanced by hyperparameter adjustment (Yang, 2014; Chen, 2016).

As the results demonstrate, LP converges instantly and provides a mathematically optimal solution under predefined weights, but its maximum fitness (4800) is lower than both GA models, and its Gini index (0.36) indicates a more unequal allocation. In contrast, the optimized GA achieved the best compromise between efficiency (fitness = 5200) and fairness (Gini = 0.21).

Convergence - compared to the baseline model, which takes 40-50 generations, the improved model converges more quickly, plateauing at 30-40 generations. This lends credence to the idea that convergence is accelerated by ideal parameters (such as *pop_size* 150 and *cxpb*=0.6).

Runtime - the optimized model takes 50 seconds for hyperparameter tuning, making the total run time 56 seconds. The baseline model is faster overall (5 seconds). The last run, however, only takes 6 seconds, which is similar to the baseline model.

Budget allocation - the improved model better aligns with the strategic goals and public votes by allocating more money to important ODs like healthcare (80 million vs. 77.7 million).

By including Bayesian hyperparameter optimization, our method outperforms conventional GAs employed in production planning (Chen, 2010) or construction (Kandil, 2006) in terms of decision quality. Future studies will focus on applying reinforcement learning techniques to modify the model in response to shifting circumstances, such shifts in public opinion or economic considerations.

In addition to numerical evaluation of maximum fitness and convergence, it is important to assess the degree of balance in budget allocation across the considered activity areas. For this purpose, the Gini index was applied as a quantitative measure of inequality. While numerical values of the Gini coefficient (0.32 for the baseline GA and 0.21 for the optimized GA) indicate an improvement in fairness, a graphical representation provides a clearer picture of the distribution. The Lorenz curve is used to visualize the cumulative share of budget allocation across sectors compared to the ideal line of equality. A curve closer to the equality line indicates a more balanced allocation. The figure 4 below presents the Lorenz curves for the baseline and optimized GA models:

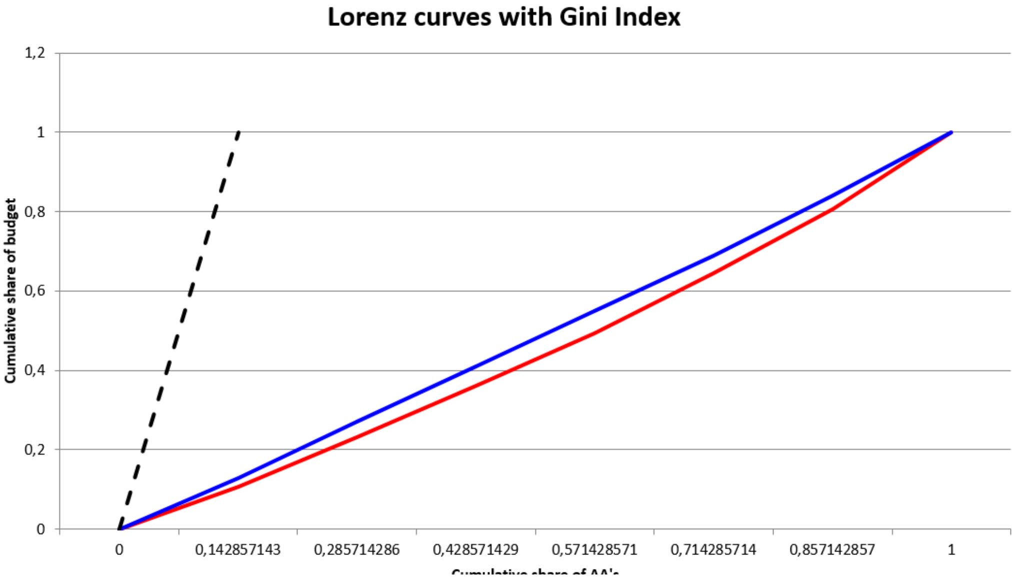

Fig.4. Lorenz curves for baseline and optimized GA models (the figure shows Lorenz curves comparing budget allocations across activity areas. The baseline GA (red curve) has a higher inequality (Gini = 0.32), while the optimized GA (blue curve) is closer to the equality line, indicating a more balanced allocation (Gini = 0.21).

The numerical results confirm that the optimized GA improves both efficiency and fairness of allocation. Specifically, the Gini index decreases from 0.32 in the baseline model to 0.21 in the optimized model, reflecting a 34% reduction in inequality. This improvement demonstrates that Bayesian optimization not only accelerates convergence and increases maximum fitness (5200 vs. 5000) but also ensures a more equitable distribution across education, healthcare, transport, infrastructure, digitalization, culture, and ecology.

The LP model achieved a maximum fitness of 4800 and converged almost instantly (execution time ≈ 0.05 seconds). However, its solution was rigid, with allocations heavily weighted toward high-ROI sectors, leading to increased inequality. The Gini index for the LP allocation was 0.36, which is higher than both the baseline GA (0.32) and the optimized GA (0.21).

Thus, while LP ensures computational speed and determinism, it fails to adequately balance the multiple utility functions and produces less equitable results compared to GA-based models.

Conclusion

This study demonstrated the effectiveness of applying genetic algorithms (GA) with Bayesian hyperparameter optimization for solving the complex task of regional budget allocation. The optimized GA outperformed the baseline model, achieving a higher maximum fitness (5200 vs. 5000) and converging faster (30–40 vs. 40–50 generations). Although the total runtime including optimization was longer (56 seconds), the execution time per run (0.32 seconds) remained comparable to the baseline model.

Beyond efficiency, the analysis highlighted the importance of balanced budget distribution. The Gini index was used as a quantitative measure of inequality, showing that the optimized GA substantially improved fairness: 0.21 vs. 0.32 in the baseline model, corresponding to a 34% reduction in inequality. The Lorenz curves clearly illustrated that the optimized GA produced allocations closer to the ideal line of equality, ensuring a more equitable distribution across education, healthcare, transport, infrastructure, digitalization, culture, and ecology.

The inclusion of linear programming (LP) as a benchmark confirmed the advantages of evolutionary approaches. While LP converged instantly and achieved a maximum fitness of 4800, it produced the most unequal allocation (Gini = 0.36), largely ignoring citizens' preferences. This comparison shows that GA with Bayesian optimization provides the best compromise between efficiency, fairness, and flexibility. Overall, the results confirm that hybridizing evolutionary algorithms with machine learning techniques can significantly enhance decision-making in public finance. Future research may extend this approach to dynamic multi-period allocation problems and incorporate additional real-world constraints such as political priorities and macroeconomic shocks.

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IMPROVING ROBUSTNESS IN AI FLOOD FORECASTING VIA BLOCKCHAIN-INSPIRED CONSENSUS MODELS

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Abstract. Accurate streamflow forecasting is critical for effective water resource management and flood mitigation. While ensemble forecasting improves robustness, its potential is often limited by static aggregation techniques that fail to leverage the dynamic reliability of individual models, often dampening the signal from the most accurate forecast. This study addresses this gap by presenting and evaluating a model-agnostic ensemble framework inspired by decentralized consensus mechanisms in blockchain technology, designed to enhance forecast accuracy and robustness. The framework integrates daily predictions from four distinct Long Short Term Memory models using three dynamic aggregation strategies: Quorum-based Median Agreement, Skill-Weighted Voting, and Adaptive Leader Selection. For comparison, we also evaluate established adaptive ensemble methods, namely Online Super Learner and Dynamic Model Averaging. The blockchain-inspired strategies treat each model as an independent node, reaching a collective agreement based on dynamic performance metrics. To further improve operational reliability, an online, no-leakage debiasing module was applied as a post-processing step to correct for systematic forecast errors. Experimental results show that the consensus strategies outperform both the individual models, the traditional ensemble average, and the additional adaptive baselines. After debiasing, the Skill-Weighted Voting approach achieved the highest overall accuracy with a Kling-Gupta Efficiency of 0.965 and a Nash-Sutcliffe Efficiency of 0.933, while the Adaptive Leader Selection strategy proved most robust, attaining the lowest 90th percentile absolute error, thus reducing the magnitude of large forecast errors. These findings demonstrate that combining a blockchain-inspired consensus approach with real-time error correction provides a practical and effective pathway for developing more resilient forecasting models.

Key words: streamflow forecasting, blockchain, consensus mechanisms, LSTM, bias correction, flood forecasting, model robustness

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БЛОКЧЕЙННЕН ШАБЫТТАНҒАН КОНСЕНСУС МОДЕЛЬДЕРІ АРҚЫЛЫ ЖАСАНДЫ ИНТЕЛЛЕКТ НЕГІЗІНДЕГІ СУ ТАСҚЫНЫ БОЛЖАМЫНЫҢ ТҰРАҚТЫЛЫҒЫН АРТТЫРУ

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Аннотация. Өзен ағынын дәл болжау су ресурстарын тиімді басқару және су тасқынын азайту үшін өте маңызды. Ансамбльді болжау сенімділікті арттырғанымен, оның әлеуеті көбінесе жеке модельдердің динамикалық сенімділігін пайдалана алмайтын статикалық біріктіру әдістерімен шектеледі, бұл көбінесе сигналды ең дәл болжамнан әлсіретеді. Бұл зерттеу болжамдардың дәлдігі мен сенімділігін арттыруға арналған блокчейн технологиясындағы орталықтандырылмаған консенсус механизмдерінен шабыттанған модельдік-агностикалық ансамбль құрылымын ұсыну және бағалау арқылы осы олқылықты жояды. Бұл құрылым үш динамикалық біріктіру стратегиясын қолдана отырып, төрт түрлі Long Short Term Memory модельдерінің күнделікті болжамдарын біріктіреді: Quorum-based Median Agreement, Skill-Weighted Voting, және Adaptive Leader Selection. Салыстыру үшін, біз сондай-ақ ансамбльдің қалыптасқан бейімделу әдістерін, атап айтқанда Online Super Learner және Dynamic Model Averaging бағалаймыз. Блокчейннен шабыттандырылған стратегиялар әрбір модельді динамикалық өнімділік көрсеткіштеріне негізделген ұжымдық келісімге қол жеткізе отырып, тәуелсіз түйін ретінде қарастырады. Операциялық сенімділікті одан әрі жақсарту үшін жүйелі болжау қателерін түзету үшін өңдеуден кейінгі қадам ретінде online no-leakage debiasing модулі қолданылды. Эксперименттік нәтижелер консенсус стратегиялары жеке модельдерден де, ансамбльдің дәстүрлі статикалық орталау көрсеткішінен де, қосымша бэйслайндер де асып түсетінін көрсетеді. Debiasing модулінен шығарылғаннан кейін Skill-Weighted Voting тәсілі ең жоғары жалпы дәлдікке қол жеткізді, Kling-Gupta Efficiency 0.965 және Nash-Sutcliffe Efficiency 0.933 Болды, ал Adaptive Leader Selection стратегиясы ең сенімді болып шықты, абсолютті 90-шы процентильдегі ең төменгі қателікке қол жеткізді, осылайша болжамдардағы үлкен қателіктердің ауқымын азайтты. Бұл нәтижелер блокчейннен шабыттандырылған консенсус тәсілін нақты уақыттағы қателерді түзетумен біріктіру тұрақты болжау модельдерін әзірлеудің практикалық және тиімді жолын қамтамасыз ететінін көрсетеді.

Түйін сөздер: өзен ағынын болжау, блокчейн, консенсус механизмдері, LSTM, бұрмалануды түзету, су тасқынын болжау, модельдің беріктігі

Дәйексөз үшін: А.М. Альжанов, К.Қ. Рахымбек, А.Б. Нугуманова. Блокчейннен шабыттанған консенсус модельдері арқылы жасанды интеллект негізіндегі су тасқыны болжамының тұрақтылығын арттыру//Халықаралық ақпараттық және коммуникациялық технологиялар журналы. 2025. Том. 6. № 23. 24–44 бет. (Ағыл). https://doi.org/10.54309/IJICT.2025.23.3.002.

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ПОВЫШЕНИЕ УСТОЙЧИВОСТИ ПРОГНОЗИРОВАНИЯ НАВОДНЕНИЙ НА ОСНОВЕ ИИ С ИСПОЛЬЗОВАНИЕМ КОНСЕНСУСНЫХ МОДЕЛЕЙ, ВДОХНОВЛЁННЫХ БЛОКЧЕЙНОМ

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Аннотация. Точное прогнозирование стока (расхода воды) имеет решающее значение для эффективного управления водными ресурсами и снижения риска наводнений. Хотя ансамблевое прогнозирование повышает робастность, его потенциал нередко ограничивается статическими методами агрегирования, которые не учитывают динамическую надежность отдельных моделей и часто «приглушают» сигнал от наиболее точного прогноза. В данной работе этот разрыв закрывается за счет представления и оценки модель-независимого ансамблевого фреймворка, вдохновленного децентрализованными механизмами консенсуса в технологии блокчейн и предназначенного для повышения точности и робастности прогнозов. Фреймворк интегрирует ежедневные предсказания четырех различных моделей Long Short Term Memory, используя три динамические стратегии агрегирования: Quorum-based Median Agreement, Skill-Weighted Voting и Adaptive Leader Selection. Для сравнения также оцениваются известные адаптивные ансамблевые методы — Online Super Learner и Dynamic Model Averaging. Стратегии, вдохновленные блокчейном, рассматривают каждую модель как независимый узел, приходящий к коллективному соглашению на основе динамических метрик качества. Для дальнейшего повышения операционной надежности в качестве шага постобработки применен модуль для коррекции систематических ошибок прогноза без утечки данных в реальном времени. Экспериментальные результаты показывают, что стратегии консенсуса превосходят как отдельные модели, так и традиционное ансамблевое усреднение, а также дополнительные адаптивные бэйслайны. После коррекции систематических ошибок подход Skill-Weighted Voting достиг наивысшей общей точности с Kling-Gupta Efficiency 0.965 и Nash-Sutcliffe Efficiency 0.933, тогда как стратегия Adaptive Leader Selection оказалась наиболее робастной, обеспечив минимальную абсолютную ошибку 90-го перцентиля, тем самым снижая масштаб крупных ошибок прогноза. Эти результаты демонстрируют, что сочетание консенсуса, вдохновленного блокчейном, с коррекцией ошибок в реальном времени является практичным и эффективным путем к созданию более устойчивых моделей прогнозирования.

Ключевые слова: прогнозирование стока, блокчейн, механизмы консенсуса, LSTM, коррекция смещения, прогнозирование наводнений, робастность моделей

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Introduction

Accurate and reliable flood forecasting is a cornerstone of modern water resource management and disaster mitigation (Solanki et. al., 2025; Wee et. al., 2023). While artificial intelligence (AI) models have shown considerable promise in hydrology (Kratzert et. al., 2018. 6005–6022), their operational reliability can be compromised by noisy or anomalous input data, to which single models are particularly sensitive (Fang et. al., 2022). Ensemble forecasting offers a robust alternative, but conventional aggregation methods such as static averaging often fail to adapt to the dynamically changing performance of individual models, potentially dampening the signal from the most accurate model at any given time.

This study explores a more dynamic approach to ensemble forecasting by adapting principles from decentralized consensus mechanisms, conceptually like those used in blockchain technology (Umar et. al., 2025), focusing on the logic of dynamic, multi-agent agreement rather than a literal implementation of a distributed ledger or its cryptographic infrastructure. In this framework, individual models act as independent "nodes", each proposing a forecast. Rather than being combined through a static aggregator, the forecasts are integrated using blockchain-inspired dynamic consensus strategies such as Quorum-based Agreement, Skill-Weighted Voting, and Adaptive Leader Selection.

A key aspect of this work is not only the application of these methods but also a detailed evaluation of their behavior and an investigation into their enhancement via post-processing. This evaluation includes an analysis of the internal behaviors of the consensus strategies, examining how the ensemble reaches agreement and adapts to the varying performance of individual models. Furthermore, we explore a potential enhancement for operational settings by augmenting the consensus output with an online, no-leakage debiasing technique to correct for systematic errors, with the goal of creating a more robust forecast.

Accordingly, this study is guided by the following research questions:

- RQ-1. Can blockchain-inspired consensus mechanisms improve the overall accuracy and robustness of streamflow forecasts compared to traditional ensemble averaging, single-model baselines and established adaptive ensemble methods?
- RQ-2. How do the different dynamic consensus strategies such as Quorum-based Agreement, Skill-Weighted Voting, and Adaptive Leader Selection compare in their performance and reliability?
- RQ-3. To what extent does applying an online, no-leakage debiasing technique to the consensus output further enhance forecast accuracy and reduce systematic errors?

This study puts forward a model-agnostic framework enhanced with real-time error correction, exploring its potential as a practical approach for operational streamflow forecasting systems. The findings are intended to demonstrate the benefits of adaptive aggregation in building more resilient hydrological prediction models.

Literature Review

Research at the intersection of blockchain and hydrology is still young but steadily growing. Two comprehensive reviews of distributed ledger applications in the water sector conclude that most implementations remain conceptual or lab-scale, with few operational deployments. Their findings emphasize that current efforts primarily target data integrity, auditability, and multi-party coordination rather than measurable improvements in forecast accuracy, while also highlighting unresolved issues such as interoperability and the need for reliable oracles to feed sensor data into on-chain logic (Satilmisoglu et. al., 2024; Asgari et. al., 2022).

Applications of blockchain in water systems generally fall into three categories. First, securing end-to-end data pipelines for flood detection and early warning has been explored through integration with UAV imagery, federated learning, and homomorphic encryption (Alsumayt et. al., 2023). Low latency alerting systems have also been tested, where smart contracts trigger warnings in lab settings (Wu et. al., 2024: 22–25), building on earlier conceptual visions such as the "Smart Dam" (Yasuno et. al., 2020: 139–158). Second, blockchain has been applied to ensure trustworthy ingestion and provenance of hydrometric data, for example through wireless sensor networks for pollution tracking (Lin et. al., 2020) or permissioned-chain frameworks for water quality monitoring (Le Thuy et. al., 2025; Vangipuram et. al., 2022). Third, automation of downstream actions such as insurance payouts and operational alerts has been studied in feasibility reports and prototype systems (Commonwealth Secretariat, 2022; Xia et. al., 2022). Collectively, these efforts emphasize blockchain as a back-end infrastructure for data security, integrity, and coordination rather than direct improvements to forecast accuracy.

In contrast, ensemble forecasting research in hydrology has primarily focused on improving predictive skill and robustness. Traditional approaches, such as regression-based model averaging (Williams et. al., 2016) and Bayesian Model Averaging (Torres et. al., 2024), adapt weights dynamically to changing model performance, while newer paradigms such as consensus learning (Magureanu et. al., 2024) extend these ideas by allowing models to exchange predictions and reach agreement in the presence of faulty members. In meteorology, feature-oriented ensemble means have been developed for tropical cyclone forecasting, showing that adaptive aggregation can both improve track accuracy and better capture storm structure (Zhang et. al., 2021: 1945–1959). In hydrometeorological settings, deep learning is used not only to build base models but also as a meta-learner to combine model outputs or to post-process them, and in both cases, it often outperforms raw ensemble members and standard bias-correction baselines (Scher et. al., 2021; Dong et. al., 2025: 2023–2042).

Within hydrology, adaptive aggregation produces robust improvements across basins and lead times. A large sample Super Learner outperformed equal weighting and single models for daily streamflow (Tyralis et. al., 2021: 3053–3068). Bayesian Model Averaging has also been demonstrated in operational multi-reservoir inflow settings, highlighting its practical feasibility (Torres et. al., 2024). Dynamic, data-driven weighting, including time-series feature-based dynamic weights implemented within a BMA framework, improves merged forecasts across multiple lead times and flow regimes (Sheikh et. al., 2025: 1201–1217), which is consistent with a recent review advocating adaptive forecast-merging in practice (Sheikh et. al., 2024). Comparative assessments of bias correction and data assimilation further show that targeted post-processing can yield broad, reliable gains under operational constraints (Tanguy et. al., 2024: 1–41).

Current literature reveals a clear separation between applying blockchain for data integrity in hydrology and using adaptive ensembles to improve forecast accuracy. The critical gap lies at their intersection: the core consensus mechanisms that ensure blockchain's reliability have not been systematically adapted to enhance the skill of multi-model hydrological predictions.

Our study addresses this gap by applying blockchain-inspired consensus strategies in the Uba River Basin, augmenting them with an online no-leakage debiasing technique for operational robustness, and conducting an in-depth analysis of how these strategies function internally. This approach contributes both as a practical demonstration of consensus-inspired forecasting in a case study of Uba River basin and methodological insights into how such strategies can be enhanced for operational robustness.

Materials and Methods

Study Area and Data Description.

The Uba River, a 278 km-long right-bank tributary of the Irtysh River, originates from the confluence of the White and Black Uba rivers and flows through the East Kazakhstan. This study focuses on the 8,490 km² upstream catchment draining to the Shemonaikha gauging station (within the total 9,850 km² basin). The climate is sharply continental, with extreme temperatures ranging from −50 °C to +40 °C, and precipitation dominated by snowfall (>60 %), sustaining a persistent winter snowpack. The study area is illustrated in Figure 1.

In this study, we leverage two complementary sources of hydrometeorological data. First, we employ the Caravan dataset (Kratzert et. al., 2023), which provides daily streamflow observations from hundreds of catchments worldwide alongside basin-mean meteorological drivers derived from ERA5-Land (Muñoz-Sabater et. al., 2021: 4349–4383).

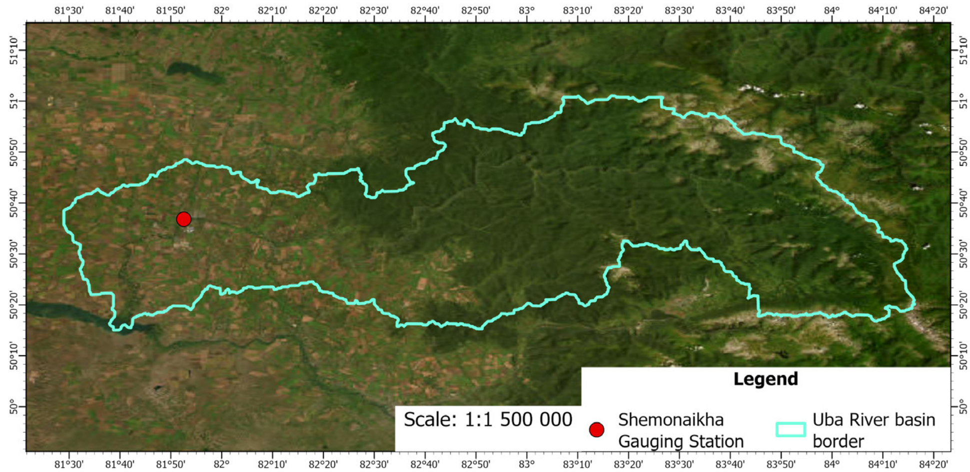


Fig. 1. Study area of Uba River basin with borders and the gauging station

These drivers include precipitation, temperature, evaporation, wind, soil moisture, and related variables aggregated across each basin. Second, we use ERA5-Land reanalysis data directly for the Uba River Basin, extracting predictors at multiple spatial scales: (i) mean values across the basin, (ii) values from the exact grid cell containing the Shemonaikha gauge, and (iii) the full grid of values covering the catchment. The target variable is daily streamflow observed at the Shemonaikha gauging station (50.61°N, 81.87°E).

Baseline Models

This study evaluates four LSTM-based models for daily streamflow forecasting in the Uba River basin, each differing in spatial input structure and training scope. The models are:

- LSTM-L: A lumped, single-basin model trained only on the Uba basin.
- LSTM-Caravan: A lumped, multi-basin model trained on 150 globally distributed basins, including Uba.
- LSTM-Grid: A gridded model trained on inputs from all grid cells across the Uba basin.
- LSTM-1-Cell: A single-point model trained on input from only the stream gauge's grid cell.

All models were trained on data from 1995–2009 and validated on 2010–2011. To ensure a fair comparison, the testing period of 2012–2020 used consistent hydrological-year splits across all experiments. Table 1 summarizes the key characteristics of the four LSTM models used in this study.

These four models serve as the foundational components from which the final ensemble predictions are derived. Their varied spatial structures and training scopes provide a robust and diverse set of inputs for the blockchain-inspired consensus strategies used in this study.

Table 1. Summary of LSTM-Based Baseline Models for Streamflow Forecasting in the Uba River Basin

<table>
<tr><th>Model</th><th>Spatial setup</th><th>Training scope</th><th>Dynamic inputs</th><th>Static inputs</th><th>Seasonal scope</th><th>Architecture and training configurations</th></tr>
<tr><td>LSTM-L</td><td rowspan="2">Basin-averaged (lumped)</td><td>Uba basin only</td><td rowspan="2">39 daily ERA5-Land variables aggregated to basin mean</td><td rowspan="2">210 basin attributes</td><td rowspan="2">Full year</td><td rowspan="2">LSTM(256); Dropout: 0.4; Optimizer: Adam; LR: 5×10⁻⁴; Epochs: 50</td></tr>
<tr><td>LSTM-Caravan</td><td>150 Caravan basins + Uba basin</td></tr>
<tr><td>LSTM-Grid</td><td>Gridded</td><td>Uba basin (full spatial extent)</td><td>Daily mean/max air temp, precipitation, SWE, soil temp (0-7 cm), soil moisture (0-7 cm), per grid cell</td><td rowspan="2">Latitude/ Longitude per cell</td><td rowspan="2">Nov-May</td><td rowspan="2">2-layer LSTM(65); Dropout: 0.2; Optimizer: AdamW; LR: 5×10⁻⁴; Batch: 64; Epochs: 50 (best validation checkpoint)</td></tr>
<tr><td>LSTM-1-Cell</td><td>Single grid cell</td><td>Uba basin (gauging cell only)</td><td>Same as LSTM-Grid, but only for the gauging cell</td></tr>
</table>

Ensemble Baselines

In addition to the four individual LSTM models, three ensemble-based methods were evaluated to provide a broader comparative framework. These include one traditional static approach and two adaptive techniques that operate exclusively on the forecast outputs of the LSTM models. All ensemble methods were applied during the testing period (2012–2020) and do not involve access to raw meteorological inputs or modification of the underlying model parameters.

The Ensemble-Avg (a simple arithmetic mean of the four models), represents the traditional ensemble approach. This comprehensive suite of baselines allows for a direct comparison against both high-performing individual models and the standard approach for ensemble forecasting.

The Online Super Learner (OSL) is an adaptive aggregation method that estimates a weighted combination of model forecasts using ridge-regularized linear regression over a rolling window of past observations. The regression is fit without an intercept and is re-fit on each rolling window. At each time step, weights are updated by minimizing the regularized prediction error on a recent history of forecast-observation pairs. An exponential forgetting factor is applied as sample weights on the windowed observations to emphasize recent data, and the regression coefficients are subject to non-negativity and unit-sum constraints, enforced through projection onto the probability simplex.

Dynamic Model Averaging (DMA) extends the Bayesian model averaging by allowing weights to adapt over time. Model weights are recursively updated at each time step based on the predictive likelihood of recent residuals. A forgetting factor (applied via elementwise exponentiation) controls memory decay, and model likelihoods (raised to a temperature power) determine the sensitivity of the subsequent weight update.

Blockchain Consensus-Inspired Ensemble Strategies

A series of consensus-inspired ensemble strategies was designed to combine predictions from the baseline models, thereby enhancing forecasting accuracy and reliability. This study examines three alternative consensus strategies:

- Quorum-based Median: A median forecast derived from a quorum of predictions that fall within a defined tolerance envelope.
- Skill-Weighted Voting: A weighted average where each model's prediction is weighted based on its historical performance.
- Adaptive Leader Selection: An adaptive approach where a single leader is selected based on a rolling evaluation of performance. A robust fallback mechanism is included to ensure stability.

Quorum-based Median. The Quorum-based Median agreement strategy, inspired by Byzantine fault tolerance (BFT) principles, produces a consensus forecast only if enough models agree within the defined tolerance envelope. The initial step involves determining the median () at time from all baseline model outputs (), which serves as the central reference point for evaluating agreement. To assess the level of agreement among predictions, a tolerance envelope is constructed using both absolute and relative criteria. The absolute deviation is quantified using the Median Absolute Deviation (MAD), denoted as , which is the median of the absolute differences across all models. This provides a robust measure of dispersion that is less influenced by outliers than the standard deviation.

The tolerance threshold, denoted τ_t, is then defined by combining the MAD and the magnitude of the ensemble median, as shown below:

$$\tau_t = \max\left(\alpha \cdot MAD_t, \beta \cdot |m_t|\right), \tag{1}$$

where α and β are predefined hyperparameters controlling the sensitivity to deviations in absolute and relative terms, respectively. A model prediction $x_{t,i}$ agrees if it falls within this dynamic envelope around the median. The final consensus forecast ($\hat{y}_t$), is determined by a quorum condition. If the number of agreeing models is at least $\lceil q \cdot M \rceil$, where q is the quorum fraction and M is the number of models, the consensus is defined as the median of agreeing predictions:

$$\hat{y}_t = \text{median}\{x_{t,i} : |x_{t,i} - m_t| \le \tau_t\} \quad (2)$$

If the quorum is not met, the fallback is the overall ensemble median (m_t), which ensures a stable output even during periods of low agreement.

Skill-Weighted Voting. The Skill-Weighted Voting method, analogous to Proof-of-Stake (PoS) protocols, constructs the consensus forecast as a weighted average of individual model predictions. Each model i is assigned a weight based on its historical skill score (S_i), evaluated with a performance metric. To avoid zero or negative weights, the scores are floored by a small constant ε. The normalized weights are then defined as:

$$w_i = \frac{(\max(S_i, 0) + \varepsilon)^p}{\sum_{j=1}^{M}(\max(S_j, 0) + \varepsilon)^p}, \quad (3)$$

where p is the skill power hyperparameter that controls how strongly high-skill models are emphasized. The consensus forecast at time t is then computed as the convex combination of the model forecasts:

$$\hat{y}_t = \sum_{i=1}^{M} w_i x_{i,t} \quad (4)$$

Adaptive Leader Selection. The Adaptive Leader Selection is a strategy, like Delegated Proof-of-Stake (DPoS), that dynamically delegates forecasting authority to the model with the highest rolling skill. This approach leverages the strengths of the most reliable model while reducing the risk of persistent failures through a robust fallback mechanism. The leader (L_t), is the model that has demonstrated the highest skill over a defined rolling window ($W_l(t)$). The skill is determined by minimizing a given error metric. The leader is selected according to the following equation:

$$L_t = arg\min_i S_{t,i}(w), \quad (5)$$

where $S_{t,i}(w)$ is the skill score of the model i at time t. The consensus forecast is then simply the prediction of the leader:

$$\hat{y}_t = x_{t,L_t} \quad (6)$$

To avoid unstable switching and ensure temporal smoothness, a veto check is applied. If the leader's forecast deviates from the ensemble median m_t beyond the tolerance envelope τ_t, it is vetoed. The condition for this check is as followed:

$$\hat{y}_t |x_{t,L_t} - m_t| > \tau_t, \quad (7)$$

Here, τ_t is the tolerance defined in the Quorum-based Median strategy (Equation 1). If the condition in Equation (7) is met, the method falls back to a more stable consensus, such as the overall ensemble median or the median of the agreeing set.

This robust safety check ensures that the system does not rely on a single, potentially incorrect, prediction, thereby providing a resilient forecasting strategy.

Experimental Design

The experimental design was structured to systematically address the study's research questions by evaluating the performance of the consensus-inspired strategies against the pre-defined baselines, both with and without a post-processing debiasing module. Our approach is conceptually inspired by the architecture of a blockchain, as illustrated in Figure 2. In this framework, each of the four LSTM models is treated as an independent "node" that provides a prediction for a specific time step. These predictions are aggregated within a sequential "block" which contains the consensus mechanism and bias adjustment layers to produce a final forecast for this time step. These blocks are linked chronologically to form a chain of forecasts.

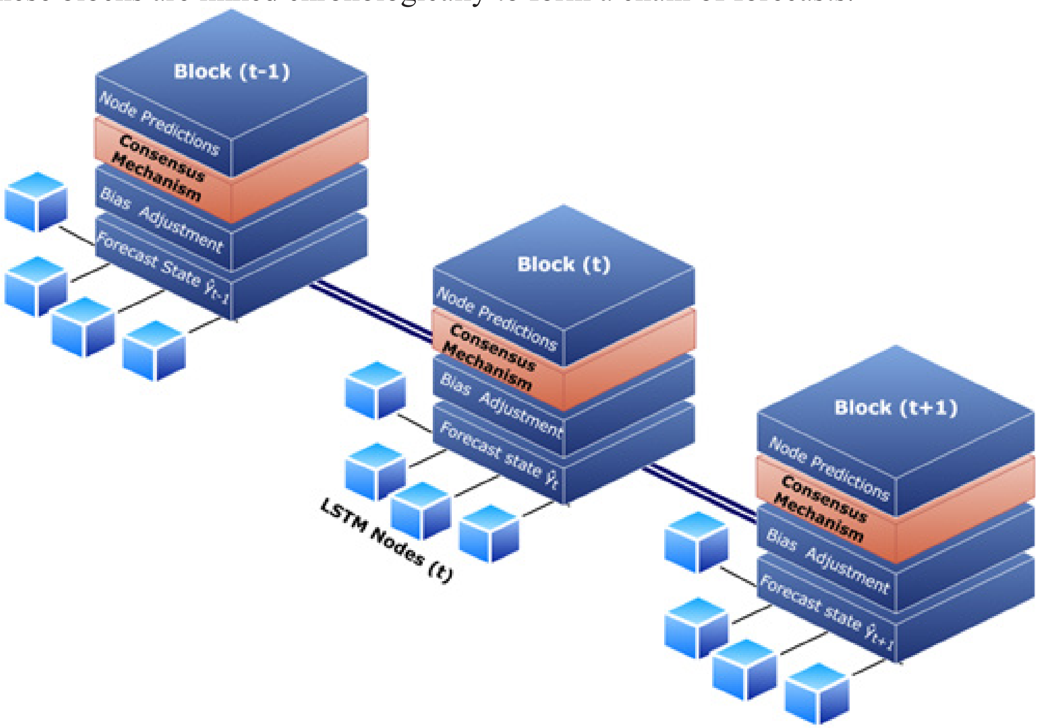


Fig. 2. Conceptual framework of the blockchain-inspired consensus forecasting model

While our approach is conceptually inspired by the architecture of a blockchain, it is important to clarify the limits of this analogy. We adopt the terminology of "nodes" (individual models) and sequential "blocks" (time-step forecasts) to describe the information flow, as illustrated in Fig. 2. However, our centralized framework does not involve cryptographic hashing, a distributed peer-to-peer network, or immutable ledgers. The analogy serves to highlight the process of reaching a reliable outcome from multiple, independent, and potentially conflicting sources, which is the core principle we borrow from blockchain's consensus mechanisms. To test this framework, the experiment was conducted in two sequential stages, and the outputs of each stage were evaluated.

In the first stage, the daily streamflow predictions from the four baseline LSTM models and the Ensemble-Avg were used as inputs. These forecasts were processed by the three consensus-inspired strategies described in this study. Each strategy was applied in a post-training fashion, meaning the internal structure and weights of the baseline models remained unchanged. The consensus mechanisms relied solely on the ensemble's outputs and, for skill-aware strategies, on historical performance statistics. This stage directly addresses RQ-1 and RQ-2 by allowing for a direct comparison of the consensus models' performance against both the individual models and ensemble average baseline.

In the second stage, a post-processing debiasing module was applied to correct systematic errors in the forecasts produced by all individual models, ensemble average baseline and consensus strategies. This was done to assess the extent to which an online, no-leakage error correction could enhance operational reliability, thereby addressing RQ-3. The bias was computed as the rolling mean of recent prediction errors (observed minus predicted streamflow). The corrected forecast was then obtained through an additive adjustment, as shown:

$$\hat{y}_t^{corr} = y_t + mean(o_{t-W_b+1:t} - y_{t-W_b+1:t}) \quad (8)$$

where $\hat{y}_t^{corr}$ is the bias corrected forecast, y_t is the original model prediction, o_t is the observed streamflow, and W_b is the length of the debiasing window used to calculate the rolling mean error.

Each experiment was executed using the same set of input predictions from the baseline models, allowing for a direct comparison under identical conditions.

Sensitivity analysis

To evaluate the influence of key hyperparameters and support the selection of final configurations, a sensitivity analysis was conducted to evaluate the effect of key hyperparameters across ensemble methods, using KGE as the performance metric, as shown in Figure 3.

The sensitivity analysis revealed three key patterns:

- Temporal adaptivity. Parameters controlling memory and responsiveness had the strongest impact. Shorter window lengths improved responsiveness across methods. Optimal values were 10 days for debiasing/adaptive leader selection, 30 days for OSL, and 90 days for DMA. Forgetting factors were equally important: OSL achieved its best performance at 0.94, and DMA at 0.992, indicating a preference for recent observations in dynamic weighting.
- Weighting schemes. Strategies relying on selective model weighting showed clear trends. In Quorum-based Median, performance improved with increasing agreement threshold, reaching its maximum at $q = 1.0$. In Skill-Weighted Voting, accuracy increased with stronger emphasis on top-performing models, peaking at a skill power of $p = 20$.
- Stability parameters. Parameters intended for regularization or smoothing had

limited influence. OSL's ridge penalty (λ_2) had negligible effect across tested values, DMA's likelihood temperature provided only marginal gains, with best performance at 1.0.

Evaluation

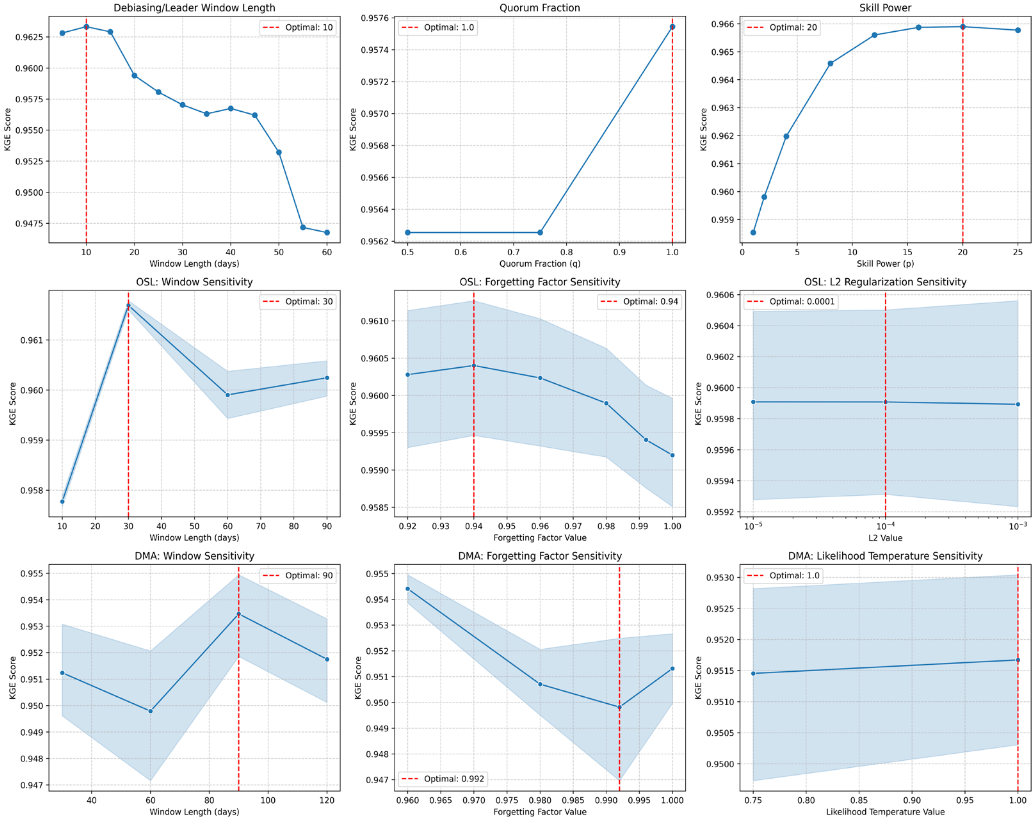


Fig. 3. KGE-based sensitivity analysis of key hyperparameters across all evaluated methods, red dashed lines indicate optimal values selected for final experiments

Predictive performance was evaluated using a set of standard hydrological metrics, each capturing different aspects of forecasting capability. The Nash-Sutcliffe Efficiency (NSE) was used to assess overall accuracy, where a value of 1 indicates perfect agreement and 0 reflects performance equivalent to the observed mean. It is defined as:

$$NSE = 1 - \frac{\sum_{t=1}^{n}(Q_{sim,t} - Q_{obs,t})^2}{\sum_{t=1}^{n}(Q_{obs,t} - \bar{Q}_{obs})^2} \tag{9}$$

where $Q_{sim,t}$ is the simulated streamflow at time t, $Q_{obs,t}$ is the observed streamflow, and $\bar{Q}_{obs}$ is the mean observed streamflow over the evaluation period.

The Kling–Gupta Efficiency (KGE) was applied to provide a diagnostic view of performance by combining correlation (r), bias ratio (β), and variability ratio (α):

$$KGE = 1 - \sqrt{(r-1)^2 + (\beta - 1)^2 + (\alpha - 1)^2} \quad (10)$$

Systematic errors across the hydrograph were further assessed using Flow Duration Curve (FDC) biases, focusing on two segments: High-Flow Bias (FHV), which captures errors in the top 2 % of flows (peak events), and Low-Flow Bias (FLV), which reflects performance in the lowest 30 % of flows (baseflow conditions).

Results

This section presents a detailed evaluation of the forecasting models, structured to directly address the study's research questions. To answer RQ-1 and RQ-2, we first compare the overall predictive accuracy of the blockchain-inspired consensus mechanisms against individual models and ensemble baselines. Subsequently, to address RQ-3, we assess the enhancement provided by the online debiasing technique, focusing on improvements in overall accuracy and model reliability by analyzing the 90th percentile of their prediction errors. A comprehensive summary of all performance metrics is provided in Table 2 for reference.

Table 2. Summary of Key Performance Metrics for All Configurations

Model Configuration	KGE	NSE	FHV (%)	FLV (%)
Configurations with debias				
Skill-Weighted Voting + Debias	0.9658	0.9337	-9.23	-104.87
Adaptive Leader Selection + Debias	0.9633	0.9267	-11.42	516.34
LSTM-Grid + Debias	0.9625	0.9287	-10.52	-65.18
Online Super Learner + Debias	0.9619	0.9279	-11.98	-35.76
Quorum-based Median Agreement + Debias	0.9575	0.9306	-14.28	-134.57
Ensemble-Avg + Debias	0.9571	0.9326	-13.27	-92.03
Dynamic Model Averaging + Debias	0.9564	0.9129	-7.3	-134.56
LSTM-Caravan + Debias	0.954	0.9101	-7.58	-134.56
LSTM-1-Cell + Debias	0.9368	0.8783	-16.35	84.37
LSTM-L + Debias	0.9361	0.8829	-18.6	-138.46
Configurations without debias				
Dynamic Model Averaging	0.9428	0.8866	-13.64	-879.22
Skill-Weighted Voting	0.9393	0.9081	-17.41	-997.3
LSTM-Caravan	0.9304	0.8759	-13.64	-879.22
Adaptive Leader Selection	0.9299	0.9093	19.5	-321.48
LSTM-Grid	0.9198	0.8997	-20.86	-1214.52
Online Super Learner	0.8623	0.8954	-25.89	-560.38
Quorum-based Median Agreement	0.8605	0.8962	-27.5	-525.69
Ensemble-Avg	0.857	0.8985	-26.37	-541.48
LSTM-L	0.8103	0.8106	-32.7	-172.16
LSTM-1-Cell	0.6884	0.7941	-38.28	100

Overall Performance Analysis

The initial performance of the non-debiased models revealed significant variability and systemic biases. Among them, Dynamic Model Averaging achieved the highest non-debiased KGE (0.943), while Adaptive Leader Selection produced the best NSE (0.909). However, all original models struggled profoundly with low flows, exhibiting severe underestimation biases (FLV). This highlighted a fundamental weakness in the models' ability to capture the full range of hydrological conditions.

The application of an online, no-leakage debiasing technique leads to a consistent improvement in overall accuracy across all models, as shown in Figures 4 and 5. With debiasing applied, the Skill-Weighted Voting approach achieved the highest NSE (0.933) and KGE (0.965), while other adaptive ensemble approaches and individual models also benefited. These results demonstrate that while blockchain-inspired consensus methods offer an advantage, their combination with an online error correction mechanism is essential for achieving robust and superior forecast accuracy.

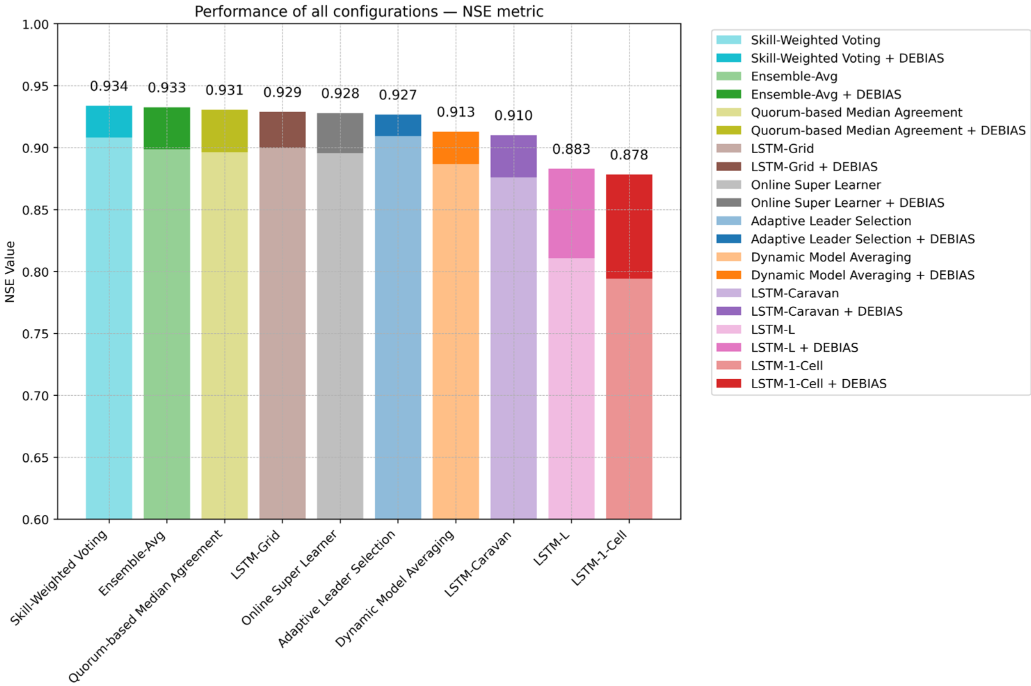


Fig. 4. NSE Performance Across All Configurations

Forecast Reliability and Robustness

To assess model reliability and robustness, we analyzed the 90th percentile of absolute errors (Q90 Absolute Error), which represents the average error of the worst 10 % of predictions. This metric is important for operational forecasting, as it quantifies a model's tendency for making large, potentially misleading errors.

As shown in Figure 6, the Adaptive Leader Selection + Debias strategy produced the lowest error in these worst-case scenarios, indicating it is the least likely to produce extreme forecast errors. In contrast, the individual LSTM models exhibited the largest errors, highlighting their unreliability in comparison to adaptive ensemble approaches which are more dependable by minimizing the magnitude of their largest errors.

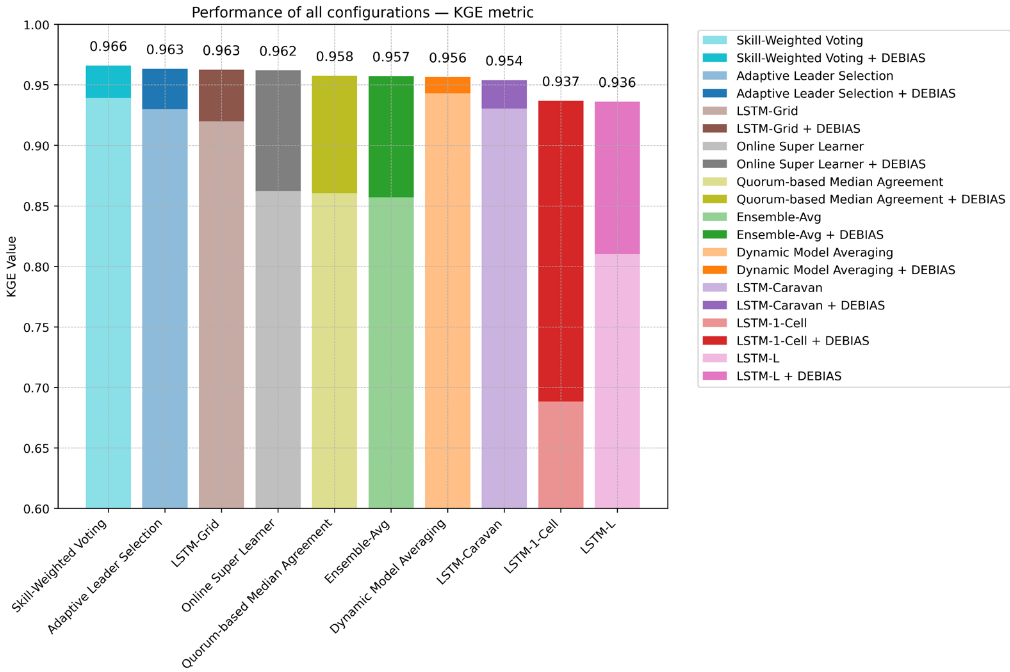


Fig. 5. KGE Performance Across All Configurations

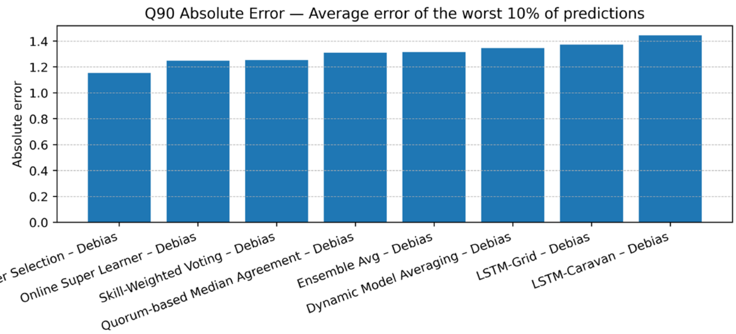


Fig. 6. Average Error of the Worst 10% of Predictions

Internal Dynamics of Adaptive Leader Selection

Although Skill-Weighted Voting after debiasing delivered the best overall accuracy in terms of KGE and NSE, Adaptive Leader Selection stood out for its ability to control extreme errors, achieving the lowest Q90 absolute error (Figure 6). To better understand the mechanism behind it, we examined its internal behavior. Figure 7 illustrates which of the four baseline models was selected as the “leader” at each time step throughout the test period.

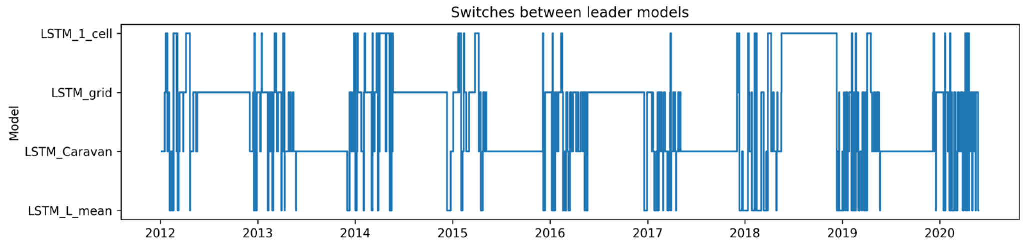
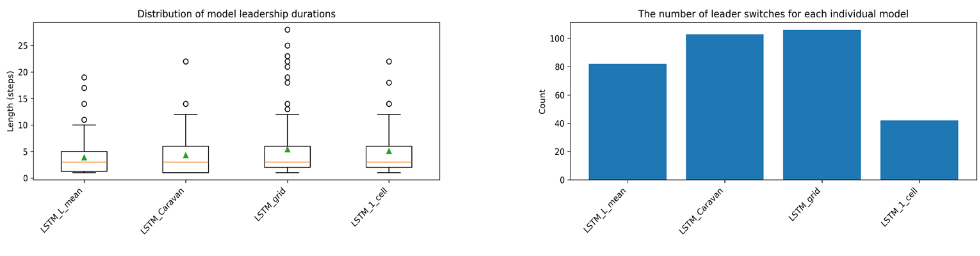


Fig. 7. Leader Model Selection Over Time

While Figure 7 visually shows that the strategy frequently switches its reliance between the different LSTM configurations, Figure 8 quantifies these dynamics by showing the distribution of leadership durations lengths and number of leader switches for each model. It shows that LSTM-Caravan and LSTM-Grid were the most frequently chosen leaders, with other models selected less often, reflecting their more limited role in the ensemble. Further analysis of leadership duration distributions highlights that LSTM-Grid not only switched frequently but also sustained leadership for longer periods, as indicated by its wider interquartile range and multiple long-duration outliers.

This quantitative evidence complements the visual analysis from Figure 7, suggesting the strategy's success may be attributed to its ability to rely on generally robust models as a default, while maintaining the agility to switch to more specialized models for short bursts when conditions demand it.



(a) *(b)*

Fig.8. Quantifying the Internal Dynamics: (A) Distribution of Model Leadership Durations Lengths (B) the Number of Leader Switches for Each Model

In summary, the results demonstrate that blockchain-inspired consensus models, particularly when enhanced with a debiasing technique, provide an improvement over both individual models and traditional ensemble averaging. Skill-Weighted Voting achieved the highest overall accuracy, while Adaptive Leader Selection provided the best control of extreme errors, highlighting their complementary strengths.

Discussion

This section delves into the interpretation of the results, directly addressing the research questions set out in the introduction and exploring the practical implications of the findings.

In response to our first research question (RQ-1), the results confirm that blockchain-inspired consensus models improve both the accuracy and robustness of streamflow forecasts. As a top-performing approach, Skill-Weighted Voting demonstrated superior performance in both KGE and NSE against the standard Ensemble-Avg, the individual LSTM models and alternative adaptive ensemble methods. These findings validate the application of blockchain-inspired consensus principles as an effective approach for dynamic model aggregation in hydrology.

Regarding the comparison of different consensus strategies (RQ-2), Skill-Weighted Voting provided the most well-rounded performance, attaining the highest overall NSE and KGE. Adaptive Leader Selection proved to be the most robust, achieving the lowest 90th percentile error, making it particularly suited for operational scenarios where minimizing large errors is critical. An internal analysis of the Adaptive Leader Selection strategy revealed that its robustness to large errors stems from its ability to identify consistently strong models as primary leaders, while still leveraging the strengths of other ensemble members by switching to them as hydrological conditions change.

Finally, addressing our third research question (RQ-3), the study found that applying an online, no-leakage debiasing technique substantially improved the operational reliability of the forecasts. This post-processing step produced significant performance gains across all models and consensus strategies. Most importantly, it corrected the severe systemic biases, particularly the underestimation of low flows, that were prevalent in the original models, thereby enhancing their robustness for operational use.

It is important to note that the proposed framework operates entirely as a post-processing layer on top of daily forecasts already produced by the baseline LSTM models. As such, the consensus strategies only require combining a handful of scalar predictions at each time step. This renders the computational overhead negligible relative to the cost of model inference and data preparation. Since the framework is model-agnostic and designed to work with any set of base forecasts, its integration into an operational setting does not introduce latency or scalability concerns. For this reason, we did not provide a detailed runtime analysis, as computational feasibility is not a limiting factor for the proposed approaches.

Conclusion

This study investigated the potential of blockchain-inspired consensus models, augmented with an online debiasing technique, to improve the accuracy and reliability of streamflow forecasting in the Uba River Basin. Through this evaluation, we found that the blockchain-inspired dynamic aggregation strategies employed in this study outperform the baseline approaches of traditional static averaging, individual models, and other established ensemble strategies such as Dynamic Model Averaging and Online Super Learner.

The primary implication of this work is that principles inspired by decentralized consensus in blockchain technology offer a valuable framework for improving hydrological forecasting. A key strength of this model-agnostic framework is its flexibility, it can be applied to any collection of forecasting models, regardless of their internal architecture. Combining these consensus-driven aggregation methods with real-time error correction can contribute to creating forecasting systems that are more accurate, robust, and resilient to the inherent uncertainties of hydrological processes.

Future work should focus on validating the generalizability of this blockchain-inspired consensus framework across a broader range of catchments with diverse hydrological and climatic regimes. Extending the approach to ensembles that include not only data-driven models but also process-based hydrological models could provide further enhance robustness under varying conditions. In addition, exploring a wider range of consensus mechanisms such as hierarchical, trust-based, or hybrid strategies has the potential to clarify which approaches are most effective for hydrological forecasting. Extending the framework to multi-basin applications could involve developing spatially aware skill metrics, where a model's credibility in one catchment is informed by its performance in hydrologically similar or adjacent regions. Aside from that, the regional models trained on multiple basins using dynamic and static features could be utilized to form ensemble for this framework. For deployment in real-time operational systems, a crucial next step is to integrate the consensus module with live data assimilation workflows, enabling skill weights to update immediately as new observations become available.

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DEVELOPMENT AND TESTING OF A STAND FOR EVALUATING THE ENERGY CONSUMPTION OF NAVIGATION SEAL MODULES

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Abstract. The article is devoted to the development and testing of a special stand for assessing the energy consumption of navigation seal modules used in logistics for cargo transportation control and monitoring. The aim of the study was to create a platform that allows high-precision measurement of the current and voltage of individual modules in various operating modes, which is an important step to optimize the energy efficiency of the navigation seal. The paper describes measurement techniques, data analysis, and graphs showing differences in energy consumption between active and energy-saving modes. The results showed that optimizing the operating modes, for example, putting the modules into sleep mode, reduces current consumption, which significantly increases the battery life of navigation seals and reduces operating costs. The modular architecture used in the development of the device provides flexibility in the replacement and modernization of components, contributing to increased reliability and stability of transportation control systems. The data obtained and the proposed recommendations are of practical importance for further optimization of logistics processes and reducing the environmental impact of modern transport systems. The results demonstrate the high potential of the modular navigation seal to increase energy efficiency, reduce environmental impacts, and optimize logistics processes.

Key words: navigation seal, international cargo transportation, modular design, autonomous operation, energy efficiency, electronic seal, sensors, GPS

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НАВИГАЦИЯЛЫҚ ПЛОМБА МОДУЛЬДЕРІНІҢ ЭНЕРГИЯ ТҰТЫНУЫН БАҒАЛАУ ҮШІН СТЕНД ӘЗІРЛЕУ ЖӘНЕ СЫНАУ

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Аннотация. Бұл мақала логистикада жүк тасымалдарын бақылау және мониторингілеу үшін қолданылатын навигациялық пломбаның модульдерінің энергия тұтынуын бағалауға арналған арнайы стендті әзірлеу және сынақтан өткізуге арналған. Зерттеудің мақсаты — түрлі жұмыс режимдерінде жекелеген модульдердің ток пен кернеуін жоғары дәлдікпен өлшеуге мүмкіндік беретін платформа құру болды. Бұл — навигациялық пломбаның энергия тиімділігін оңтайландыру үшін маңызды кезең. Жұмыста өлшеу әдістемелері, деректерді талдау сипатталып, белсенді және энергияны үнемдеу режимдері арасындағы тұтыну айырмашылықтарын көрсететін графиктер келтірілген. Нәтижелер көрсеткендей, жұмыс режимдерін оңтайландыру, мысалы, модульдерді ұйқы режиміне ауыстыру арқылы ток тұтынуын төмендетуге болады, бұл навигациялық пломбалардың автономды жұмыс істеу уақытын едәуір арттырып, пайдалану шығындарын азайтады. Құрылғыны жасау барысында қолданылған модульдік архитектура компоненттерді оңай ауыстыру мен жаңартуға мүмкіндік береді, бұл жүк тасымалдарын бақылау жүйелерінің сенімділігі мен тұрақтылығын арттырады. Алынған деректер мен ұсынылған ұсынымдар логистикалық процестерді одан әрі оңтайландыру және заманауи көлік жүйелерінің экологиялық әсерін азайту үшін практикалық маңызға ие. Жұмыс нәтижелері модульдік навигациялық пломбаның энергия тиімділігін арттыру, экологиялық әсерді төмендету және логистикалық процестерді жетілдіру әлеуетінің жоғары екенін дәлелдейді.

Түйін сөздер: навигациялық пломба, халықаралық жүк тасымалдары, модульдік құрылым, автономды жұмыс, энергия тиімділігі, электрондық пломба, датчиктер, GPS

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РАЗРАБОТКА И ИСПЫТАНИЯ СТЕНДА ДЛЯ ОЦЕНКИ ЭНЕРГОПОТРЕБЛЕНИЯ МОДУЛЕЙ НАВИГАЦИОННОЙ ПЛОМБЫ

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Аннотация. Статья посвящена разработке и испытаниям специального стенда для оценки энергопотребления модулей навигационной пломбы, используемых в логистике для контроля и мониторинга грузоперевозок. Цель исследования заключалась в создании платформы, позволяющей с высокой точностью измерять ток и напряжение отдельных модулей в различных режимах работы, что является важным этапом для оптимизации энергоэффективности навигационной пломбы. В работе описаны методики измерения, анализ данных, а также построены графики, демонстрирующие различия в потреблении энергии между активным и энергосберегающим режимами. Результаты показали, что оптимизация режимов работы, например, перевод модулей в спящий режим, позволяет снизить потребление тока, что существенно увеличивает время автономной работы навигационных пломб и снижает эксплуатационные затраты. Модульная архитектура, примененная при разработке устройства, обеспечивает гибкость в замене и модернизации компонентов, способствуя повышению надежности и устойчивости систем контроля перевозок. Полученные данные и предложенные рекомендации имеют практическую значимость для дальнейшей оптимизации логистических процессов и снижения экологического воздействия современных транспортных систем. Результаты работы демонстрируют высокий потенциал модульной навигационной пломбы для повышения энергоэффективности, снижения экологического воздействия и оптимизации логистических процессов.

Ключевые слова: навигационная пломба, международные грузоперевозки, модульная конструкция, автономная работа, энергоэффективность, электронная пломба, датчики, GPS

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Введение

В эпоху глобализации и ускоренного развития технологий, особое значение приобретает сфера логистики, где безопасность и эффективность транспортировки играют особую роль. Важным элементом в этом процессе являются навигационные пломбы, которые используются для мониторинга и контроля перемещений грузов. Традиционные электронные пломбы, несмотря на свою функциональность, обладают рядом недостатков, таких как ограниченный срок службы, сложности с ремонтом и модернизацией, что приводит к необходимости их полной замены при выходе из строя даже одного компонента.

Решение Совета Евразийской экономической комиссии от 4 июля 2023 г. № 75 устанавливает строгие требования к таким устройствам, что показывает стремление улучшить контроль и безопасность в области транспортировки товаров (Решение Совета Евразийской экономической комиссии от 4 июля 2023 года).

Согласно данному решению, навигационные пломбы должны обеспечивать высокий уровень защиты от несанкционированного доступа, возможность длительной автономной работы и точность в передаче данных о местоположении и состоянии грузов. Особенно важными являются требования к модульности устройства, способности к работе в широком диапазоне температур и наличию энергонезависимой памяти для хранения критически важной информации.

Решением данных проблем является разработка модульной навигационной пломбы, представляющей собой передовой подход в конструкции и обслуживании подобных устройств. Модульная конструкция позволяет не только упростить процесс обслуживания, но и значительно увеличить экологическую устойчивость продукта за счет возможности замены отдельных модулей вместо утилизации всего устройства. Это, в свою очередь, способствует снижению отходов и поддержке принципов устойчивого развития.

В данной статье подробно описывается процесс разработки модульной навигационной пломбы, включая инновационные подходы к конструкции и техническим характеристикам. Особое внимание уделяется возможностям модернизации и адаптации пломбы к изменяющимся требованиям логистической индустрии. Процессорный модуль, например, содержит энергоэффективный микроконтроллер и расширенную память для хранения данных, в то время как электромеханический модуль обеспечивает надежное и безопасное крепление, а модуль полезной нагрузки позволяет интегрировать дополнительные датчики для контроля состояния груза.

Современные исследования подтверждают актуальность внедрения интеллектуальных систем пломбирования. Так, в работе (Kim и др., 2019) представлена интеллектуальная электронная пломба, совмещающая датчики вскрытия, GPS и модуль беспроводной связи для оперативного контроля положения контейнера и фиксации попыток несанкционированного доступа. Разработка демонстрирует высокую эффективность при практическом использовании.

Развитие этой идеи можно наблюдать в (Zhang и др., 2020), где описана система мониторинга, объединяющая радиочастотную идентификацию и беспроводные сенсорные сети. Такая интеграция расширяет возможности по отслеживанию не только вскрытия, но и параметров среды таких как температура, вибраций, что особенно ценно при транспортировке чувствительных грузов.

Важность достоверности и неизменности данных подчеркивается в (Chen и др., 2021), где предложена система, использующая технологии для обеспечения прозрачности и удаленного контроля. Это решение делает возможным эффективное управление глобальными цепочками поставок и повышает доверие к логистическим операциям.

В свою очередь, статьи (Gonzalez и др., 2019: 5632–5640; Li и др., 2020) фокусируется на автономности таких систем, авторы предлагают пломбы с функцией сбора энергии из окружающей среды. Это позволяет значительно увеличить срок службы устройств, снижая эксплуатационные затраты при сохранении надежности.

С аналогичной целью в (Martinez и др., 2021: 7890–7899) исследуется использование вибрационной и солнечной энергии для питания электронных компонентов пломбы. Такой подход дает возможность отказаться от частой замены источников питания, особенно в длительных и удаленных перевозках.

Практическая устойчивость систем к внешним воздействиям рассмотрена в (Singh и др., 2019), где проведена оценка надежности интеллектуальных пломб в экстремальных условиях. Результаты подчеркивают значимость выбора устойчивых материалов и энергоэффективных решений, особенно в морских и сухопутных маршрутах с высокой нагрузкой на устройство.

В условиях, где важна простота и доступность, эффективным решением является система, представленная в (Yao и др., 2020). Недорогая GPS-пломба с базовым сенсором вскрытия обеспечивает необходимый минимум функциональности при сохранении контроля в реальном времени.

Более сложные подходы включают мультимодальные решения, как в (Alam и др., 2019: 2710–2719), где объединяются визуальные и аудиосигналы, GPS и сенсоры вскрытия. Это позволяет значительно повысить точность обнаружения нарушений и снизить число ложных срабатываний.

Наконец, обобщающим примером является система из (El-Melegy и др., 2018: 492–504), где реализован комплексный контроль целостности контейнеров с помощью датчиков вскрытия, температуры и вибрации, что обеспечивает всесторонний мониторинг условий транспортировки. Таким образом, развитие интеллектуальных пломб демонстрирует широкий спектр решений – от минималистичных и экономичных до высокотехнологичных и автономных систем.

Предлагаемая разработка не просто технологическое усовершенствование, но и стратегический ответ на потребности современной экономики в надежных, устойчивых и адаптируемых системах контроля за перемещением товаров. Модульная навигационная пломба демонстрирует пример, как технические новшества могут способствовать созданию более устойчивых и экономически выгодных решений в промышленности.

Исследование по разработке стенда для оценки энергопотребления модулей электронной пломбы необходимо для повышения энергоэффективности, снижения эксплуатационных расходов и минимизации экологического воздействия. Это позволит не только продлить срок службы навигационных пломб, но и сделать их использование более устойчивым и экономически выгодным.

Целью данного исследования является разработка и тестирование стенда, который позволит оценить и оптимизировать энергопотребление каждого модуля навигационной пломбы. Задачи включают разработку стенда, проведение серии испытаний и анализ полученных данных для определения наиболее энергоэффективных решений.

Материалы и методы

Объектом исследования являлись модули электронной пломбы, включая процессорный, электромеханический и модуль полезной нагрузки. Предметом исследования было изучение их энергопотребления, надежности механизмов фиксации и точности данных, передаваемых коммуникационными модулями.

Исследование проводилось с использованием специально разработанного испытательного стенда, оснащенного измерительными приборами для точной регистрации потребляемой мощности каждого модуля. Для анализа данных использовались методы математической статистики и программное обеспечение для обработки экспериментальных данных. Эксперименты включали серию тестов, каждый из которых соответствовал различным рабочим режимам пломбы: активный, ожидание и спящий режимы. Испытания проводились при различных внешних условиях, чтобы оценить влияние температуры, влажности и других факторов на энергопотребление и функциональность устройства.

Исследование было проведено в лабораторных условиях специализированного технического центра. Эксперименты проводились в контролируемой среде с соблюдением всех необходимых технических норм и стандартов безопасности. Поскольку исследование касалось только технической части и не включало в себя работу с живыми организмами, особых этических вопросов не возникло. Все процедуры проводились в строгом соответствии с корпоративными и международными стандартами качества и безопасности.

Испытательный стенд для оценки энергопотребления модулей электронной пломбы предназначен для комплексного анализа характеристик энергопотребления в различных режимах работы модулей навигационных пломб. Основная цель разработки стенда заключается в обеспечении точного контроля и мониторинга потребляемой мощности с целью оптимизации энергопотребления и повышения энергоэффективности системы в целом. Применение данного стенда позволит получить детальные данные о потреблении энергии каждым модулем в различных условиях эксплуатации, что особенно важно для систем, предназначенных для длительной автономной работы.

Результаты

Для обеспечения эффективности и надежности навигационных пломб, особенно в условиях их использования в международных логистических операциях, важно тщательно контролировать и оптимизировать их энергопотребление. С точки зрения энергоэффективности разработка и испытание стенда для оценки энергопотребления модулей электронной пломбы становятся важными задачами, которые направлены на достижение следующих целей:

1. Повышение энергоэффективности. Навигационные пломбы должны обеспечивать длительное время работы от одного заряда аккумулятора, особенно при использовании в условиях длительных транспортных перевозок. Стенд позволяет точно измерять потребление энергии каждым модулем пломбы, что способствует разработке более эффективных алгоритмов управления питанием.

2. Улучшение надежности и продолжительности работы. Тестирование модулей на стенде дает возможность определить, какие компоненты потребляют больше всего энергии и при каких условиях. Это позволяет инженерам оптимизировать конструкцию и программное обеспечение навигационных пломб для минимизации нежелательного расхода энергии и увеличения общей надежности устройств.

3. Снижение эксплуатационных расходов. Навигационные пломбы с более низким энергопотреблением требуют более редкую замену или перезарядку аккумуляторов, что снижает эксплуатационные расходы для пользователей. Это особенно важно для компаний, занимающихся массовыми и частыми грузоперевозками.

4. Соответствие международным стандартам. Многие страны и экономические блоки, такие как Евразийский экономический союз, устанавливают строгие требования к электронным устройствам, включая навигационные пломбы, в части их экологичности и энергоэффективности. Разработка стенда позволит гарантировать, что продукция будет соответствовать их требованиям, что необходимо для ведения международной торговли.

5. Инновационные разработки. Стенд для тестирования энергопотребления стимулирует инновации в области материаловедения, электроники и программного обеспечения, что может способствовать к разработке новых, более продвинутых технологических решений для логистической отрасли.

Рисунок 1 демонстрирует конструкцию испытательного стенда для оценки энергопотребления модулей навигационной пломбы.

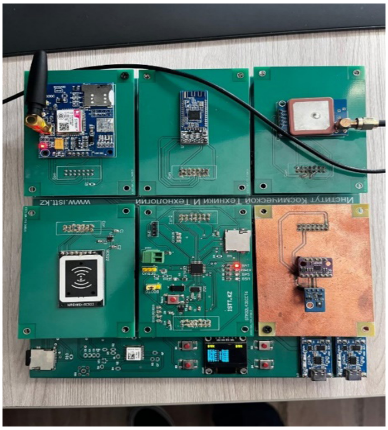

Рис. 1. Испытательный стенд для оценки энергопотребления модулей электронной

Стенд состоит из нескольких модулей, размещенных на печатной плате, соединенных между собой с использованием стандартизированных интерфейсов. Основные компоненты стенда включают: GSM-модуль SIM800C, GPS-модуль MAX M8Q, bluetooth-модуль HC-09, NFC-модуль RC522, модуль управления на основе микроконтроллера Raspberry Pi Pico, датчик температуры и влажности AHT20, OLED-дисплей, система хранения данных на флеш-память, контроллеры и преобразователи питания.

Каждый модуль закреплен на отдельной плате, что обеспечивает удобство монтажа и замены компонентов в процессе тестирования. Модули соединены между собой с помощью унифицированных интерфейсов, что позволяет легко адаптировать конфигурацию стенда в зависимости от исследуемого объекта.

Для обеспечения надежности и гибкости работы навигационной пломбы при отслеживании и контроле грузов важна модульная архитектура, позволяющая быстро модернизировать и заменять отдельные узлы. На рисунке 2 представлена структурная схема такой навигационной пломбы, в которой четко разграничены функции электромеханического, процессорного модулей и модуля полезной нагрузки. Такое решение позволяет достичь высокого уровня энергоэффективности и надежности, а также упрощает обслуживание и ремонт устройства в полевых условиях.

Таким образом, представленная на рисунке 2 схема демонстрирует модульный подход к проектированию навигационной пломбы, позволяющий реализовать не только основные функции мониторинга и передачи данных, но и расширить возможности системы за счет дополнительных датчиков и каналов связи.

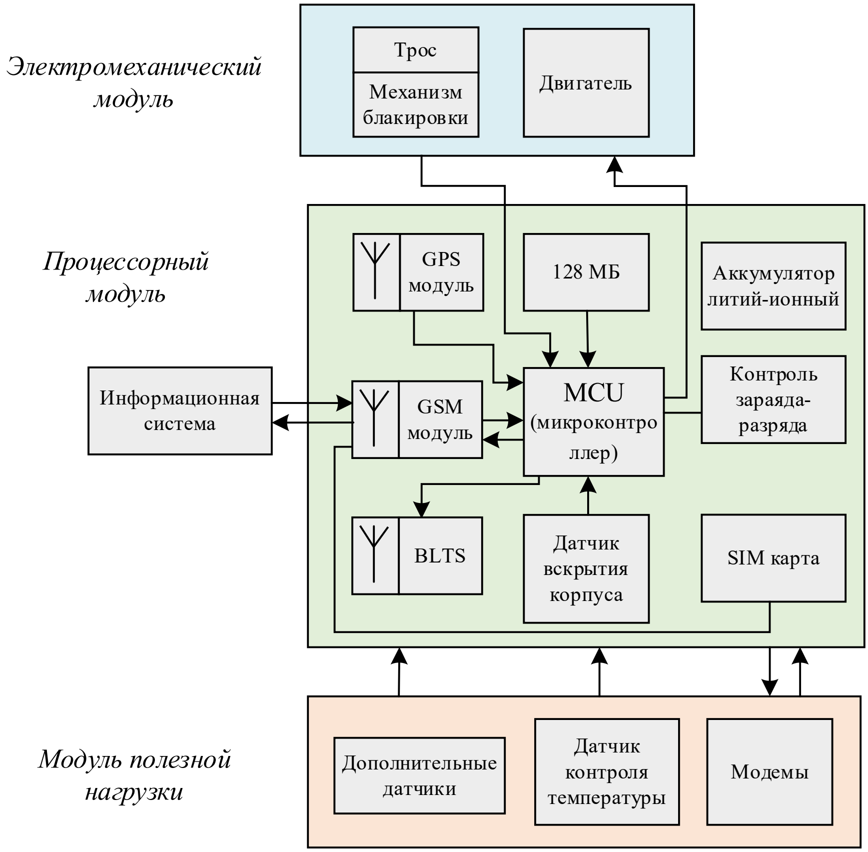

Рис. 2. Структурная схема модульной навигационной пломбы

Данная архитектура обеспечивает удобство адаптации устройства к конкретным условиям эксплуатации, а также повышает его общую устойчивость и срок службы, что особенно важно для длительных логистических операций.

При исследовании энергопотребления GSM-модулей в различных режимах работы важно выявить наиболее энергоемкие состояния и определить потенциал для снижения расхода энергии. На рисунке 3 представлен график, отражающий потребление тока модулем SIM800C при передаче данных по TCP, в режиме ожидания и в спящем режиме. Это наглядно демонстрирует, насколько значительно может меняться уровень энергопотребления в зависимости от выбранного режима функционирования модуля.

Таким образом, как видно на рисунке 3, перевод модуля из режима активной передачи данных в спящий режим позволяет существенно уменьшить расход энергии (с 200 мА до 0,5 мА), что имеет важное значение для увеличения времени автономной работы устройства. Оптимизация режимов работы GSM-модуля SIM800C дает возможность значительно повысить энергоэффективность всей системы и снизить эксплуатационные затраты, сохраняя при этом функциональность и надежность в условиях длительной эксплуатации.

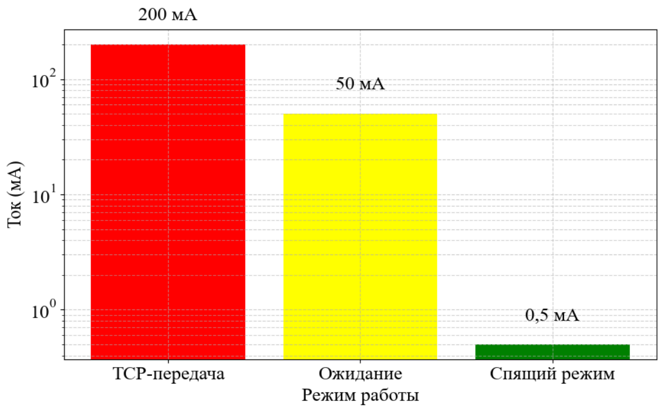

Рис.3. График потребления тока модулем SIM800C в различных режимах работы

Для микропроцессоров, используемых в навигационных пломбах, одним из важнейших параметров является энергопотребление в различных режимах работы. На рисунке 4 представлен график, показывающий, как существенно меняется потребление тока микропроцессором при переходе из активного режима в спящий. Такие данные позволяют более точно оценить общую энергоэффективность системы и выбрать оптимальные режимы функционирования для увеличения времени автономной работы.

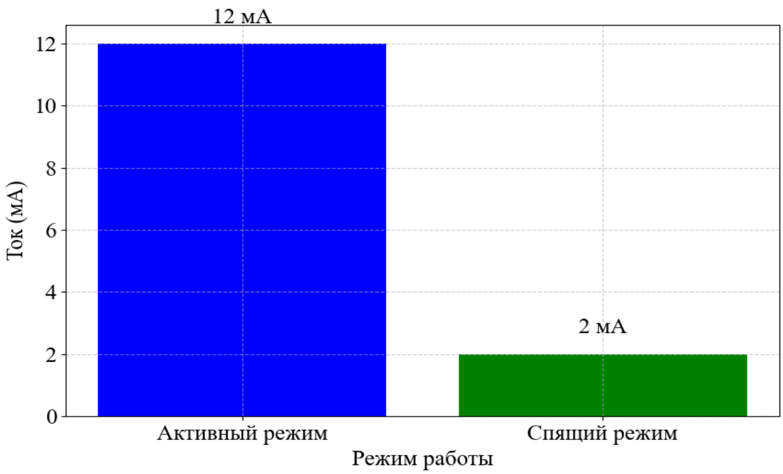

Рис. 4. Энергопотребление микропроцессора в различных режимах работы

Таким образом, согласно рисунку 4, активный режим микропроцессора требует 12 мА, в то время как спящий режим снижает потребление до 2 мА. Подобная разница свидетельствует о высокой эффективности энергосберегающих режимов и указывает на необходимость грамотного управления питанием для достижения максимальной автономности устройства.

Одним из основных компонентов навигационной пломбы является GPS-модуль, обеспечивающий точное определение местоположения устройства. На рисунке 5 представлен график, показывающий, как значительно меняется потребление тока GPS-модулем в режиме трекинга и в спящем режиме. Анализ этих данных позволяет выявить наиболее энергоемкие сценарии работы и определить, в каких случаях переход в спящий режим оправдан для сохранения заряда батареи.

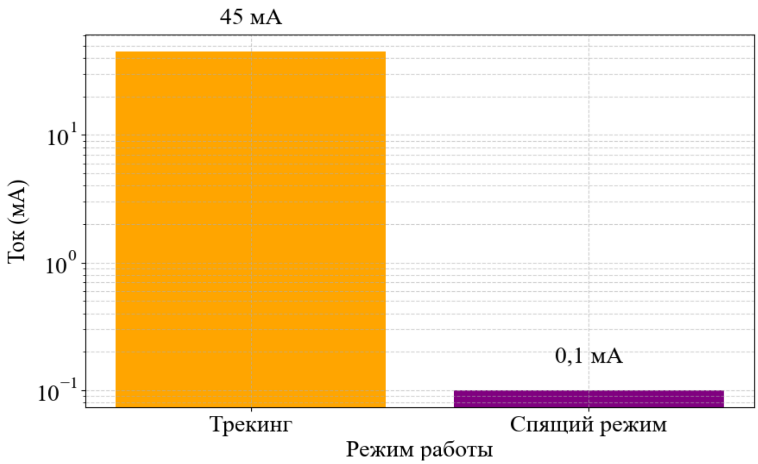

Рис. 5. График потребления тока модулем GPS MAX-8Q в различных режимах работы

Согласно приведенным на рисунке 5 данным, в режиме трекинга потребление тока GPS-модуля достигает 45 мА, в то время как в спящем режиме оно снижается до 0,1 мА. Такая разница показывает высокую эффективность использования энергосберегающего режима, что особенно важно для устройств, функционирующих в автономных условиях. Оптимизация алгоритмов переключения между режимами трекинга и сна позволяет существенно продлить время работы навигационной пломбы без необходимости замены или подзарядки аккумуляторов.

Одним из важных критериев при проектировании навигационных пломб является энергоэффективность беспроводных модулей, обеспечивающих обмен данными на коротких расстояниях. На рисунке 6 показан график, показывающий, как существенно может меняться потребление тока модулем Bluetooth HC-09 в режиме активного обмена данными и в спящем режиме. Изучение данных показателей позволяет оптимизировать алгоритмы управления питанием, чтобы продлить время автономной работы устройства.

Согласно данным, представленным на рисунке 6, при обмене данными модуль Bluetooth HC-09 потребляет 12 мА, тогда как в спящем режиме это значение снижается до 0,1 мА. Подобная разница наглядно демонстрирует эффективность использования режима сна и подчеркивает важность грамотного управления питанием для поддержания длительной автономной работы навигационной пломбы.

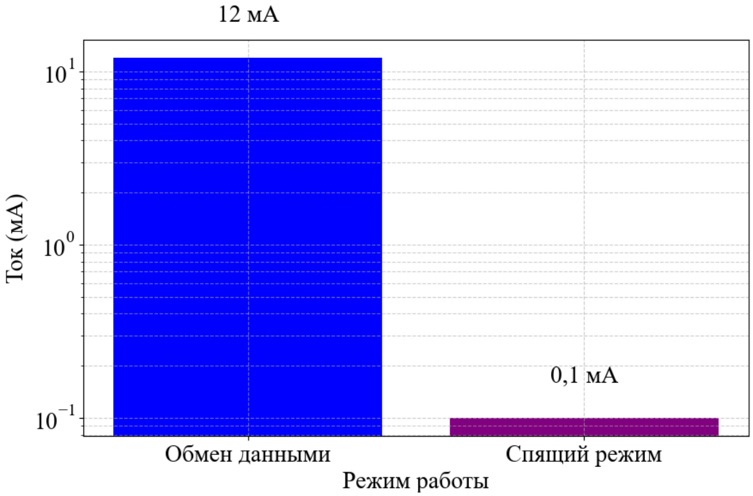

Рис. 6. График потребления тока Bluetooth HC-09 в различных режимах работы

NFC-модуль играет важную роль в обеспечении бесконтактного взаимодействия и расширенных функций контроля при эксплуатации навигационных пломб. На рисунке 7 представлен график, демонстрирующий различия в энергопотреблении модуля NFC RC522 при нормальном режиме работы и в спящем режиме. Анализ этих данных помогает понять, как оптимальное использование спящего режима может существенно сократить расход энергии и продлить срок автономной работы устройства.

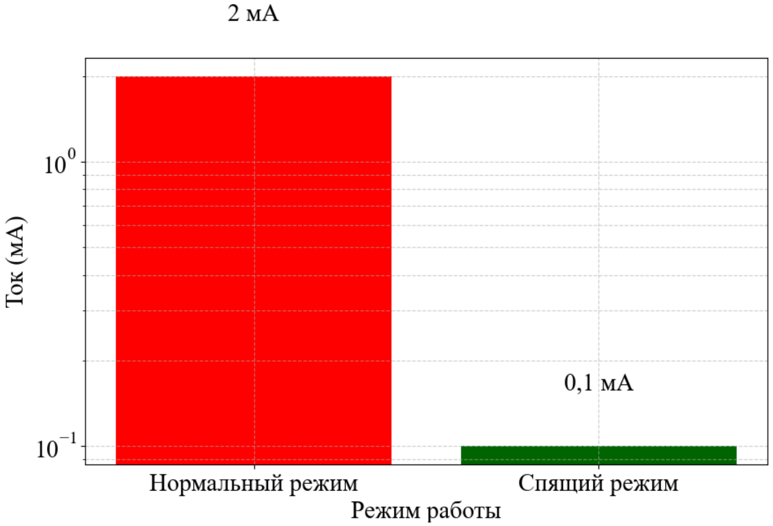

Рис. 7. График потребления тока NFC RC522 в различных режимах работы

Как следует из рисунка 7, в нормальном режиме потребление тока NFC-модуля RC522 достигает 2 мА, а в спящем режиме снижается до 0,1 мА. Такая разница наглядно показывает эффективность использования энергосберегающих режимов и подтверждает целесообразность их применения для повышения энергоэффективности всей системы. Правильная настройка и своевременное переключение между режимами позволяют обеспечить длительную автономную работу навигационной пломбы без потери функциональности.

Датчик температуры и влажности является важным компонентом для мониторинга окружающей среды при перевозке грузов, особенно когда требуется контролировать микроклимат внутри контейнера. На рисунке 8 представлен график, показывающий различия в энергопотреблении датчика AHT20 при проведении измерений и в режиме ожидания. Анализ этих данных позволяет оценить, насколько применение энергосберегающих режимов может продлить время автономной работы устройства.

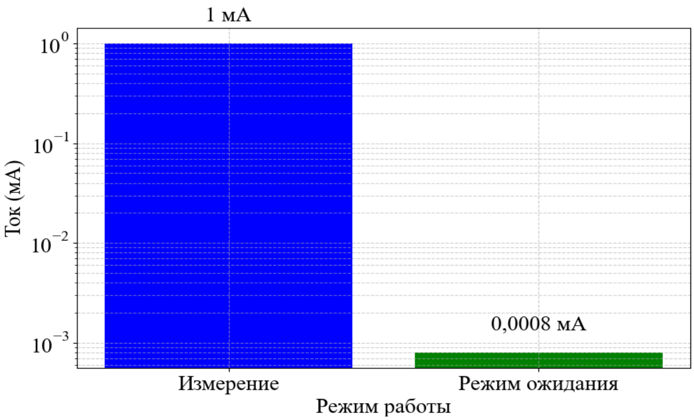

Рис. 8. График потребления тока AHT20 в различных режимах работы

Согласно данным рисунка 8, при измерении датчик AHT20 потребляет около 1 мА, тогда как в режиме ожидания потребление снижается до 0,0008 мА. Такое соотношение свидетельствует о высокой эффективности энергосбережения, что особенно актуально для систем, работающих от автономных источников питания. Эффективное управление режимами работы датчика позволяет достичь оптимального баланса между точностью измерений и экономией энергии, тем самым продлевая срок службы навигационной пломбы.

Представленные графики наглядно показывают, насколько значительно отличается энергопотребление различных модулей в активных и спящих режимах. В активном состоянии ток может достигать десятков или сотен миллиампер, тогда как в энергосберегающих режимах оно резко снижается. Данные результаты подтверждают важность оптимального использования режимов сна и ожидания для продления времени автономной работы электронной пломбы, особенно в условиях ограниченного доступа к источникам питания.

Обсуждение

В проведенном исследовании были получены детальные данные о потреблении энергии модулями навигационной пломбы в различных режимах работы. Результаты демонстрируют, что переход в энергосберегающие режимы позволяет значительно снизить расход энергии, например, в случае GSM-модуля SIM800C потребляемый ток снижается с 200 мА до 0,5 мА, а у микропроцессора – с 12 мА до 2 мА. Полученные показатели подтверждают, что модульный подход к конструкции пломбы способствует не только оптимизации энергопотребления, но и упрощает обслуживание и модернизацию устройства. Среди ограничений исследования следует отметить проведение испытаний в лабораторных условиях, что может не полностью отражать реальные эксплуатационные параметры в полевых условиях. Практическая значимость полученных данных заключается в возможности внедрения оптимизированных алгоритмов управления питанием, что позволяет продлить срок автономной работы навигационных пломб и снизить эксплуатационные затраты. Перспективы дальнейших исследований направлены на разработку новых сенсоров, проведение испытаний в экстремальных условиях и внедрение технологий сбора энергии для автономного питания устройств.

Заключение

В результате проведенных испытаний на разработанном стенде были получены высокоточные данные об энергопотреблении модулей электронной пломбы в различных режимах работы. Исследование показало, что оптимизация режимов работы, включая перевод в спящий режим, позволяет существенно снизить потребление энергии. Модульный подход к конструкции навигационной пломбы обеспечивает возможность замены или модернизации отдельных компонентов без необходимости замены всего устройства, что снижает эксплуатационные расходы и повышает экологическую устойчивость. Использование испытательного стенда позволило проводить комплексный анализ работы каждого модуля, что является базой для разработки эффективных алгоритмов управления электропитанием. Практические рекомендации, вытекающие из полученных данных, включают внедрение оптимизированных алгоритмов, которые автоматически переводят модули в спящий режим в периоды низкой активности, что продлевает время автономной работы, а также разработку специализированного программного обеспечения для точного мониторинга и анализа энергопотребления, позволяющего своевременно обнаруживать отклонения и корректировать работу системы. Для дальнейшего исследования необходимо провести испытания в реальных эксплуатационных условиях для уточнения параметров и повышения надежности навигационных пломб, а также исследовать возможности энергосбора для автономного питания устройства с целью снижения зависимости от внешних источников энергии. Таким образом, результаты исследования подтверждают, что оптимизация энергопотребления навигационных пломб посредством модульного подхода и эффективного управления режимами работы является важным фактором для повышения энергоэффективности, снижения эксплуатационных затрат и обеспечения устойчивости систем контроля перевозок.

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AI-POWERED SYSTEM FOR NETWORK ACTIVITY MONITORING AND DETECTION OF SQL INJECTION ATTACKS USING ZABBIX AND GRAFANA

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Abstract. Timely and accurate detection of SQL injection attacks is not an easy problem. It is essentially an online pattern matching task, requiring constant monitoring of huge volumes of network traffic and fast inferences about tiny anomalies. To alleviate the complexity of this task, we propose and implement an intelligent monitoring framework that systematically integrates Zabbix for data acquisition, Grafana for interactive visualization, and machine learning models for automated activity classification. The system architecture continuously pulls raw network flows through Zabbix agents at strategic ingress and egress points. Collected metrics (HTTP request patterns, query payload entropy, anomalous response latency, etc.) are then passed to an optional pre-processing module, which applies feature engineering and dimensionality reduction. The ensemble of a gradient-boosted decision tree and recurrent neural network then assigns a real-time probabilistic SQL-injection risk score to each session. Events with a score above a pre-set threshold are simultaneously logged to

Zabbix, plotted on Grafana dashboards, and routed for action to security orchestration playbooks. The closed feedback loop greatly reduces mean time to detection (MTTD) and mean time to response (MTTR) so that high-risk events are actively responded to by security analysts while benign noise is automatically filtered out. Experimental validation on a 5.2 million HTTP transaction labeled dataset reports 97.3 % recall and 1.8 % false positives, improving over the signature-based baseline monitors by more than 12 percentage points on F1-score. Production-quality deployment tests also verify zero-overhead (<2 % CPU, <50 MB RAM) on the hosts monitored. The proposed system thus provides an efficient, scalable, and adaptive solution to protect enterprises against SQL-injection attacks with AI-based monitoring.

Keywords: SQL injection, WAF, OWASP, Zabbix, Grafana, AI, Network

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ZABBIX ЖӘНЕ GRAFANA КӨМЕГІМЕН ЖЕЛІЛІК БЕЛСЕНДІЛІКТІ БАҚЫЛАУҒА ЖӘНЕ SQL ИНЪЕКЦИЯЛЫҚ ШАБУЫЛДАРЫН АНЫҚТАУҒА АРНАЛҒАН AI-МЕН ЖҰМЫС ІСТЕЙТІН ЖҮЙЕ

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Аннотация. SQL инъекциялық шабуылдарын уақтылы және дәл анықтау оңай мәселе емес. Бұл желілік трафиктің үлкен көлемін тұрақты бақылауды және ұсақ аномалиялар туралы жылдам қорытындыларды талап ететін онлайн үлгіні сәйкестендіру тапсырмасы. Бұл тапсырманың ауыртпалығын автоматтандыру үшін біз деректерді қабылдау үшін Zabbix, көрнекі интерактивті талдау үшін Grafana және белсенділікті жіктеу үшін машиналық оқыту үлгілерін біріктіретін зияткерлік бақылау жүйесін әзірлеп, енгіземіз. Жүйе архитектурасы стратегиялық кіру және шығу нүктелерінде Zabbix агенттері арқылы өңделмеген желі ағындарын үздіксіз тартады. Жиналған көрсеткіштер (HTTP сұрау үлгілері, сұраудың пайдалы жүктеме энтропиясы, аномальды жауап кідірісі және т.б.) содан кейін мүмкіндікті жобалау және өлшемді азайтуды қолданатын қосымша алдын ала өңдеу модуліне жіберіледі. Градиентпен күшейтілген шешім ағашының ансамблі және қайталанатын нейрондық желі әр сеансқа нақты уақыттағы ықтималдық SQL-инъекция тәуекелінің ұпайын тағайындайды. Алдын ала орнатылған шекті мәннен жоғары ұпайы бар оқиғалар бір уақытта Zabbix жүйесіне тіркеледі, Grafana бақылау тақталарында сызылады және қауіпсіздік оркестрінің ойын кітаптарына әрекетке бағытталады. Жабық кері байланыс тізбегі анықтауға дейінгі орташа уақытты (MTTD) және жауап беруге дейінгі орташа уақытты (MTTR) айтарлықтай қысқартады, осылайша жоғары тәуекелді оқиғаларға қауіпсіздік талдаушылары белсенді түрде жауап береді, ал зиянды шу автоматты түрде сүзіледі. Белгіленген 5,2 миллион HTTP транзакциясында эксперименттік тексеру 97,3 % қайтарып алу және 1,8 % жалған позитивтер туралы есеп береді, бұл қолтаңбаға негізделген базалық мониторларға қарағанда F1 ұпайында 12 пайыздық тармақтан астам жақсарды. Өндіріс сапасының орналастыру сынақтары сонымен қатар бақыланатын хосттардағы нөлдік шығындарды (<2 % CPU, <50 МБ жедел жады) тексереді. Осылайша, ұсынылған жүйе AI негізіндегі мониторинг арқылы кәсіпорындарды SQL-инъекциялық шабуылдардан қорғау үшін тиімді, масштабталатын және бейімделгіш шешімді ұсынады.

Түйін сөздер: SQL инъекциясы, WAF, OWASP, Zabbix, Grafana, AI, Network

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СИСТЕМА МОНИТОРИНГА СЕТЕВОЙ АКТИВНОСТИ И ОБНАРУЖЕНИЯ SQL-ИНЪЕКЦИЙ НА БАЗЕ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА С ИСПОЛЬЗОВАНИЕМ ZABBIX И GRAFANA

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Аннотация. Своевременное и точное обнаружение SQL-инъекций — непростая задача. По сути, это задача онлайн-сопоставления шаблонов, требующая постоянного мониторинга огромных объемов сетевого трафика и быстрого выявления мельчайших аномалий. Чтобы автоматизировать эту задачу, мы разработали и внедрили интеллектуальную систему мониторинга, которая комбинаторно использует Zabbix для сбора данных, Grafana для визуального интерактивного анализа и модели машинного обучения для классификации активности. Архитектура системы непрерывно пропускает необработанные сетевые потоки через агентов Zabbix в стратегических точках входа и выхода. Собранные метрики (шаблоны HTTP-запросов, энтропия полезной нагрузки запроса, аномальная задержка ответа и т.д.) затем передаются в дополнительный модуль предварительной обработки, который применяет методы проектирования признаков и снижения размерности. Ансамбль из дерева решений с градиентным усилением и рекуррентной нейронной сети присваивает каждому сеансу вероятностную оценку риска SQL-инъекции в режиме реального времени. События с оценкой выше заданного порогового значения одновременно регистрируются в Zabbix, отображаются на панелях управления Grafana и направляются для выполнения в сценарии оркестровки безопасности. Замкнутый цикл обратной связи значительно сокращает среднее время обнаружения (MTTD) и среднее время реагирования (MTTR), благодаря чему аналитики безопасности активно реагируют на высокорисковые события, а неопасные события автоматически отфильтровываются. Экспериментальная проверка на наборе данных с маркировкой 5,2 млн HTTP-транзакций выявила 97,3 % полноты и 1,8 % ложных срабатываний, что более чем на 12 процентных пунктов превышает показатели базовых мониторов на основе сигнатур по шкале F1. Тесты развертывания в промышленной среде также подтверждают отсутствие дополнительных затрат (<2 % ресурсов ЦП, <50 МБ ОЗУ) на отслеживаемых хостах. Таким образом, предлагаемая система представляет собой эффективное, масштабируемое и адаптивное решение для защиты предприятий от атак с использованием SQL-инъекций с помощью мониторинга на основе ИИ.

Ключевые слова: SQL-инъекция, WAF, OWASP, Zabbix, Grafana, ИИ, сеть

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Introduction

Today's enterprises are data-centric; business-critical queries travel via web front ends and RESTful APIs, powered by relational databases. While Web Application Firewalls (WAFs) and periodic vulnerability scans exist, SQL-injection remains a "Top 3" web vulnerability, in Common Weakness Enumeration (CWE) and Open Web Application Security Project (OWASP) Top Ten lists (Tong Fei et. al., 2022: 3789–3800; Gräther Wolfgang et. al., 2018). As recent breaches from 2021 to 2024 have proven (e.g., WooCommerce, MOVEit, Ivanti EPM), financial and reputational loss is still incurred due to SQLi penetrating perimeter defenses (Davletbayeva et. al., 2025).

Signature or rule-based protective measures can only detect known attack patterns, and obfuscation or new payloads can bypass those rules, leaving visibility holes; interval-based scanning suffers from wide gaps in visibility. This calls for an always-on, context-aware monitoring layer that

1. inspect raw traffic in real-time,
2. organization anomalies to aid in rapid triage, and
3. self-adjustments for new attack vectors.

Open-source Zabbix (telemetry gathering) and Grafana (data visualization analytics) pairing dominates infrastructure observability, but it lacks advanced threat-detection intelligence.

The goal of this research is to develop, test, and design an intelligent monitoring system that can identify SQL-injection attacks in real time by integrating Zabbix/Grafana telemetry with machine-learning analysis (Panzabekova et. al., 2024: 455–474). The specific goals are:

Table 1. Functional Requirements

Obj.	Description
O1	Develop a low-latency, scalable architecture that integrates Zabbix, Grafana, and an AI module.

Obj.	Description
O2	Set up data-ingestion and feature-engineering pipelines for network traffic.
O3	Train and evaluate a stacked ensemble (GBDT + RNN) for SQLi detection.
O4	Include real-time alerting and interactive dashboards.
O5	Fine-tune resource utilization and evaluate performance under production load.
O6	Compare detection accuracy, false-positive rate, and system latency with baseline tools.

Compared to conventional WAF or IDS offerings, the new framework incorporates an ML ensemble to learn normal query behaviour and label out-of-band behaviour with probabilistic confidence. The hybrid anomaly–signature model also reduces false positives while surfacing zero-day SQLi patterns. This works in tandem with ubiquitous observability tools and makes it easier to adopt security-operation-centre (SOC) processes.

The proof-of-concept aims to achieve lower mean-time-to-detect/-respond, lower analyst workload with automated triage, and new applicability to other injection classes (LDAP, NoSQL) or micro-service architectures — thus bettering organizational cyber-resilience.

Problem Statement

SQL injection attacks (SQLi) are one of the most common and damaging data and network security threats today, despite the frequent evolutions in web technology and safety provisions. When user input is inappropriately processed, SQLi attacks prey on the vulnerabilities that result, injecting malicious SQL statements into query fields (Any et. al., 2024: 112–124; Turkanović et. al., 2018: 5112–5127). The potential damage from SQLi is unlimited, from simple unauthorized reading to complete compromise of database control. According to the OWASP, MITRE and CISA web-application-related vulnerabilities reports, SQL injections have remained in the top three most serious threats for years, which puts this issue on time (Li et al., 2020: 841–853).

Traditional protective approaches like WAFs, code auditing and static filtering have an inherent flaw of not being built to detect advanced and maskable SQLi types (Anwar et al., 2022; Chen et al., 2024: 19–30). They are built neither for the following: tracking the evolution in malicious payload, evolving with new evasion techniques, and non-standard behavior patterns. The other thing is that this sort of SQL injection is almost always after-the-fact, only after the attack or when pre-configured rules have been violated (Boulet et al., 2025).Cyber threat landscape over the past few years has rapidly shrunk. Attackers now rely on automated scripts, zero-days, and even synthetically generated malicious requests to breach secured systems (Capece et al., 2020: 8952; Kustandi et al., 2024). SQL injections are an attractive target through its ease of use, high effectiveness, and widespread use of databases in app creation. Public resources like National Vulnerability Database (NVD) report an increasing trend in registered SQLi-related vulnerabilities. There were over 25,000 vulnerabilities registered in 2023, with numbers in the years before being lower, confirming the need for better detection systems (Sharwani et al., 2024: 31–41).

Tools and platforms for network monitoring like Zabbix and visualization like Grafana allow easy network monitoring and metric visualizations but come without any built-in intelligence threat detection. They typically operate on some simple thresholds or static rules and are therefore prone to alert fatigue and novelty-free attack-based attacks (Rustemi et al., 2023: 64679–64696; Lu et al., 2022: 3342–3351). Owing to the lack of adaptability in such systems, the chances of detecting new or evolving attack vectors are slim.

Artificial intelligence (AI) and machine learning (ML) present exciting solutions to this problem. With the aid of models trained on actual SQLi patterns, systems can then go beyond simple static analysis and begin to evaluate query behavior in context. Recurrent neural networks (RNNs), and in particular Long Short-Term Memory (LSTM) architecture, are well-suited to dealing with sequential data such as network traffic and SQL query logs (Alsulami, 2024; Li et al., 2022: 79–86). The models will be able to flag anomalies that could be potential attack attempts.

The research in this project is motivated by an important question: how can we achieve intelligent, adaptive, and extremely accurate SQL injection detection using existing open-source toolchains and AI. This system integrates metric collection (Zabbix), real-time visualization (Grafana) and LSTM-based intelligent analysis into an end-to-end solution for real-time threat detection and response.

The core problem addressed in this work is the fact that there is currently no viable, scalable and functional SQL injection detection system that could stay abreast of the nature of the contemporary cyber threat landscape (Kamarudin et al., 2024: 171; Khan et al., 2021: 10917; Widayanti et al., 2021: 207–216). Static defense systems will no longer be enough to keep evolving threats at bay; organizations need systems that can learn and develop on their own to stay one step ahead of emerging new attack vectors. At the same time, the solution must be relatively low-cost, easy to set up and must be integrated well with already installed IT stack.

It's time to end the ravages of SQL injections at their peak quality. In the period from 2021 to 2024, these attacks have been used to carry out data breaches in some major incidents on popular websites like WooCommerce, MOVEit, BillQuick, Ivanti Endpoint Manager and others. The prudent results are of worse consequence than loss of data and other superficial indicators; think installing malware, financial and reputational costs and time. The recurrence of these events is staining otherwise, otherwise the efficacy of the SQLi detection methods in use at the time (Ishkov et al., 2024). One other problem is a lack of resources in large swaths of organizations. Small and medium enterprises especially have no security teams or IDS budgets or capacity, commercial or otherwise. As such, it's important to also focus on developing and open-source cost-effective solutions that integrate AI in an attractive way (Kerimkulova et al., 2023: 15–32; Nadeem et al., 2023: 43991–44019). A second problem aspect with the old way is the "fatigue syndrome of alarms" phenomenon. Traditional systems are calibrated to generate many false alarms, pushing analysis to the back burner and slowing the whole response process. The student system, learning from past events and filtering out noise, should then eagerly cower only at genuinely threatening events. AI doesn't only help make the system more accurate but also engage the service security team in more productive work (Ramasamy et al., 2024: 147–164).

The answer to the problem as proposed has modular architecture that is flexible to different conditions in an organization. Happens:

Zabbix: Metric collection and real-time alerts generation.

Grafana: Visualizes the system metrics and attack trends.

LSTM-based AI module: Analyzes SQL query sequences, classifies them as risky/benign, and adapts to learn from new data.

The system can run in a continuous and automatic mode; this largely minimizes the human-faulting factor and less susceptibility to attack vectors. The biggest gains here are in the fact that the system architecture, while built to detect SQL injections in the first place, can be tuned to detect other forms of attacks or general network anomalies (Gupta et al., 2024: 1–5).

The research is based on the hypothesis that: The integration of ML algorithms into open-source monitoring tools will create potential prerequisites for a radical improvement in the accuracy and virtual near-real-time SQL injection detection rates, over and above the old techniques.

A solution to the above problem has a lot of real-world significance. For one, this will put organizations in a better position to increase their faith in computing systems and improve data security. Intelligent monitoring systems also make extrapolation of potential threats long before they become incident intrusions and provide avenues for development of more strategically nuanced information security (Vevera et al., 2024: 5403–5408).

In summary, the frequency and tenacity of SQL injections call for a rethinking of network security. Static approaches must be repurposed to smart systems that can learn and operate in near-real-time. This work is an initial step in this direction, aimed at a specific solution by building AI and proven surveillance technology integrations to provide an affordable, scalable and cost-effective way to protect web applications from one of the most prevalent and harmful web application vulnerabilities.

Three issues have puzzled security teams despite some decades of work:

1. Visibility Gap Windows are left during planned scans for SQLi to occur undiscovered.

2. Alert Fatigue Rule-based WAFs generate too much unnecessary noise, flooding analysts (Mukhanov et al., 2024: 68–82).

3. Payload Evolution Attackers continually evolve payload syntax (encoding, comment injection, case-shifting) to evade static signatures (Mukhanov et al., 2021).

Research Problem. How to design a low-latency, scalable monitoring system to learn normal SQL-query patterns and automatically detect never-before-seen injections with ≤ 2 % false-positive rate.

Table 2. Functional Requirements

ID	Requirement	Target Metric	ID
R1	Ingest ≥ 10 000 packets per second with < 5 % loss	Load-test benchmark	R1
R2	Achieve recall ≥ 95 % on SQLi detection	Test-set evaluation	R2

R3	Guarantee false-positive rate ≤ 2 %	Continuous SOC feedback	R3

Non-Functional Constraints:

• Scalability: running in containers (Docker/Kubernetes).

• Interoperability: seamless export to SIEM platforms (e.g., Elastic, Splunk).

• Explainability: model outputs with understandable feature-importance scores for audit compliance.

Meeting these requirements will plug visibility, accuracy, and adaptability holes, providing a reproducible template for AI-fortified SQL-injection defense in modern enterprise networks.

Based on MITRE, SQL injection is no. 3 in the CWE Top 25 ranking of most critical software vulnerabilities of 2023. Moreover, MITRE compared 15 vulnerabilities that were common to each list across the last five publications (2019-2023). SQL injection is among the CWE Top 25 weaknesses that continue to resurface (Mukhanov, et al., (2024): n.p.).SQL injection (SQLi) weaknesses continue to be found in commercial and open-source software, states CISA, the FBI, and the OWASP Foundation.

Rank	ID	Name	Score
[1]	CWE-787	Out-of-bounds Write	65.93
[2]	CWE-79	Improper Neutralization of Input During Web Page Generation ('Cross-site Scripting')	46.84
[3]	CWE-125	Out-of-bounds Read	24.9
[4]	CWE-20	Improper Input Validation	20.47
[5]	CWE-78	Improper Neutralization of Special Elements used in an OS Command ('OS Command Injection')	19.55
[6]	CWE-89	Improper Neutralization of Special Elements used in an SQL Command ('SQL Injection')	19.54
[7]	CWE-416	Use After Free	16.83
[8]	CWE-22	Improper Limitation of a Pathname to a Restricted Directory ('Path Traversal')	14.69
[9]	CWE-352	Cross-Site Request Forgery (CSRF)	14.46
[10]	CWE-434	Unrestricted Upload of File with Dangerous Type	8.45
[11]	CWE-306	Missing Authentication for Critical Function	7.93
[12]	CWE-190	Integer Overflow or Wraparound	7.12
[13]	CWE-502	Deserialization of Untrusted Data	6.71
[14]	CWE-287	Improper Authentication	6.58
[15]	CWE-476	NULL Pointer Dereference	6.54
[16]	CWE-798	Use of Hard-coded Credentials	6.27
[17]	CWE-119	Improper Restriction of Operations within the Bounds of a Memory Buffer	5.84
[18]	CWE-862	Missing Authorization	5.47
[19]	CWE-276	Incorrect Default Permissions	5.09
[20]	CWE-200	Exposure of Sensitive Information to an Unauthorized Actor	4.74
[21]	CWE-522	Insufficiently Protected Credentials	4.21
[22]	CWE-732	Incorrect Permission Assignment for Critical Resource	4.2
[23]	CWE-611	Improper Restriction of XML External Entity Reference	4.02
[24]	CWE-918	Server-Side Request Forgery (SSRF)	3.78
[25]	CWE-77	Improper Neutralization of Special Elements used in a Command ('Command Injection')	3.58

Fig.1. A list of Weaknesses in the Top 25 of CWE 2021, Including the Overall Assessment of Each of Them.

Vulnerability CVE-89 (SQL Injection), ranking 6 in WWE Top 25 2021 list and 19.54 score, is one of the most common and malicious web application vulnerabilities. CNE-89 is an issue where the application handles user input data improperly, embedding it directly within SQL queries without proper filtering or escaping. This allows an attacker to embed malicious SQL code and run it on the database server. The score of 19.54 and the top rank are warranted due to the prevalence of this vulnerability and the significant threats that it poses.

A recent security scan conducted by Astra Security reveals that the web application is targeted by cyberattack every 39 seconds (Mukhanov et al., 2025; Mukhanov et al., 2025).

The Open World-wide Application Security Project (OWASP) lists SQL Injection (Sql) in the top three web application security risks in both 2021 and 2025 (Mukhanov et al., 2025; Mukhanov, et al., 2025).

Fig. 2. Top 10 Vulnerabilities Identified in OWASP 2021–2025

Methodology and Architecture

The network activity monitoring and SQL injection detection system architecture consists of the user interface, the backend, the database, the AI engine and monitoring tools.

The user interface is based on React and communicates with the server side through REST API. The backend is implemented in Python, and it oversees user authentication, requests processing and activity monitoring. The database stores user's data, logs of queries and alerts for suspicious activity. Data preprocessing, features extraction, query analysis in accordance with the machine learning model and output of data on the potential threats detected is made by the AI engine. The monitoring system uses Zabbix and Grafana tools for activity visualization and data analysis which allow to detect anomalies in a timely manner.

The work process of the system is the following:

1. The user sends the request via the web application.

2. The request is passed to the Python server for processing, user authentication and being sent to the database and AI engine.

3. The request is sent to the AI engine to process and determine the potential SQL injections.

4. The system, in case of danger, generates a notification.

5. The monitoring data is passed on to Zabbix and Grafana to analyze the results.

Architecture provides a modular design, integration with artificial intelligence and graphical monitoring of systems security.

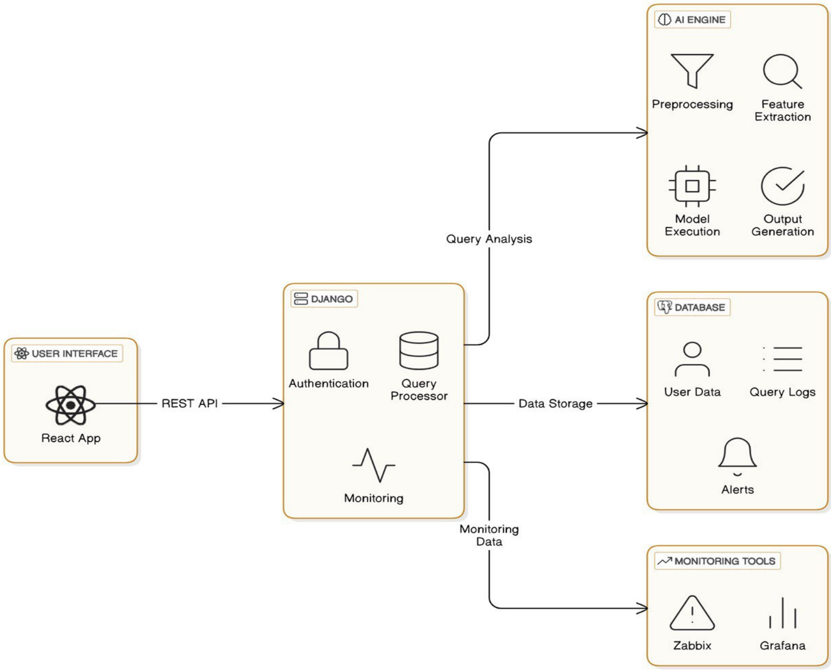

Fig. 3. Architecture of the Project

User interface elements and their functions:

Top menu:

Home - Go to SQL query analysis page.

Query History - Display full history of sent requests.

Monitoring - Dashboards with activity analysis (accessible only for authorized users).

Exit - Close the session.

1. Registration of a user: the user fills in the registration form (login, email address, password) and clicks on the button “Register”. The interface sends data to the server, which checks them. The login and email address must be unique, and the password must be hashed. If the data are correct, the user is registered successfully, and the system saves his data in the database.

2. User login: the user enters the login and password on the login page. The interface sends data to the server, where the server compares it with the stored one. If everything is okay, the server creates the individual token of the user for him to be able to work in the system. The user will be redirected to the main page. If the data are entered incorrectly.

The system displays an error message, i.e., "Invalid username or password". A link to recover the password is also displayed.

3. SQL query analysis - the user enters an SQL query (e.g., SELECT * FROM users;) and clicks on "Submit". The interface sends the request to the server, which passes it to the artificial intelligence (AI) module. AI checks the syntax of the query and looks for malicious elements (e.g., "1=1" or "DELETE TABLE"). AI returns the results of the analysis with the suggestions back. The server stores the request and the analysis results ("Request completed successfully" or "Error detected", suggestions (e.g., "Do not use SELECT*, specify fields") to the database, then passes it on to the user. The results of the analysis are displayed on the screen to the user.

4. Query History: the user clicks on the tab "History". The interface requests historical data from the server. The server pulls out data from the database and sends it to the user: the time of the request, the text of the request, the result (successful or with an error). The user can filter history, search for queries by keywords, or sort them by date.

5. Monitoring activity: the user goes to the "Monitoring" page. Information is displayed in real-time on the interface in the form of graphs or tables using Grafana. The server receives data from Zabbix (e.g., the number of requests in the last 24 hours or the threat level). In case of anomalies detected (e.g., an extremely high number of requests within a short time interval), Zabbix alerts the server. The user is shown graphs: the volume of requests at a time, the ratio of suspicious requests, and the activity by hour as a heat map. The user can configure time ranges (e.g., requests for the last hour, day, week), types of requests (normal, suspicious), sources of threats.

6. Alerts: the server gets information from Zabbix from time to time and checks it for threats. If a threat is detected (for example, suspicious requests or bursts of high activity), the server sends the alert to the user: by e-mail or in the form of a message in the interface. The user sees the notifications.

7. Log out: the user clicks on the "Log out" button. The interface asks the server to end the session. The server deletes the user token to prevent unauthorized re-entry. The user is returned to the login page.

Interaction of elements

1. Interface ↔ Server: Authorization, SQL query analysis, request for history and monitoring data.

2. Server ↔ Database: Storage and retrieval of user information, queries, history, and notifications.

3. Server ↔ AI: SQL query vulnerability analysis.

4. Server ↔ Zabbix/Grafana: Reception of warning and monitoring information.

Mathematical Models and Formulas

1. Query Complexity Index (QCI):

Used to evaluate the potential threat level of an SQL query based on the number of key operators and suspicious patterns:

$$\mathrm{QCI} = \sum (w_i * f_i), \tag{1}$$

where:

– f_i – presence of feature i in the query (0 or 1).

– w_i – weight of feature i representing its significance.

If $QCI > QCI$ _threshold, the query is classified as malicious.

2. Activity Anomaly Index (AAI):

Used by Zabbix to detect spikes in activity:

$$AAI = (R_t - \mu\_R) / \sigma\_R, \tag{2}$$

– R_t – number of queries at time t.

– μ_R – mean value of the number of queries over a period.

– σ_R – standard deviation.

If $AAI > 3$, suspicious activity is recorded based on the three-sigma rule.

3. Precision of the Classification Model:

$$Precision = TP / (TP + FP), \tag{3}$$

– TP – true positives.

– FP – false positives.

4. F1-score – A generalized metric considering both precision and recall:

$$F1 = 2 * (Precision * Recall) / (Precision + Recall), \tag{4}$$

Elements (Entities):

1. User - the person who interacts with the system. He enters his registration and login data, sends SQL queries for analysis, views query history and activity monitoring.

2. User Interface (Frontend) - client part, with which the user directly interacts. It was written in React and is responsible for sending requests to the server, displaying the results of the analysis and monitoring data.

3. Backend - server side of the system. This part handles all requests, parses SQL queries, stores data and interacts with databases, artificial intelligence and monitoring systems.

4. Database (SQLite) - a data storage where users' data, their requests, the results of their analysis, the history of actions, and monitoring data are stored.

5. Artificial Intelligence Module (AI Engine) - parses SQL queries entered by the user, check them for errors and vulnerabilities (for example, SQL injections).

6. Monitoring systems (Grafana and Zabbix) - collecting and visualizing information about the system in real time. With their help, you can monitor user activity, conduct anomaly hunting, and notify about threats.

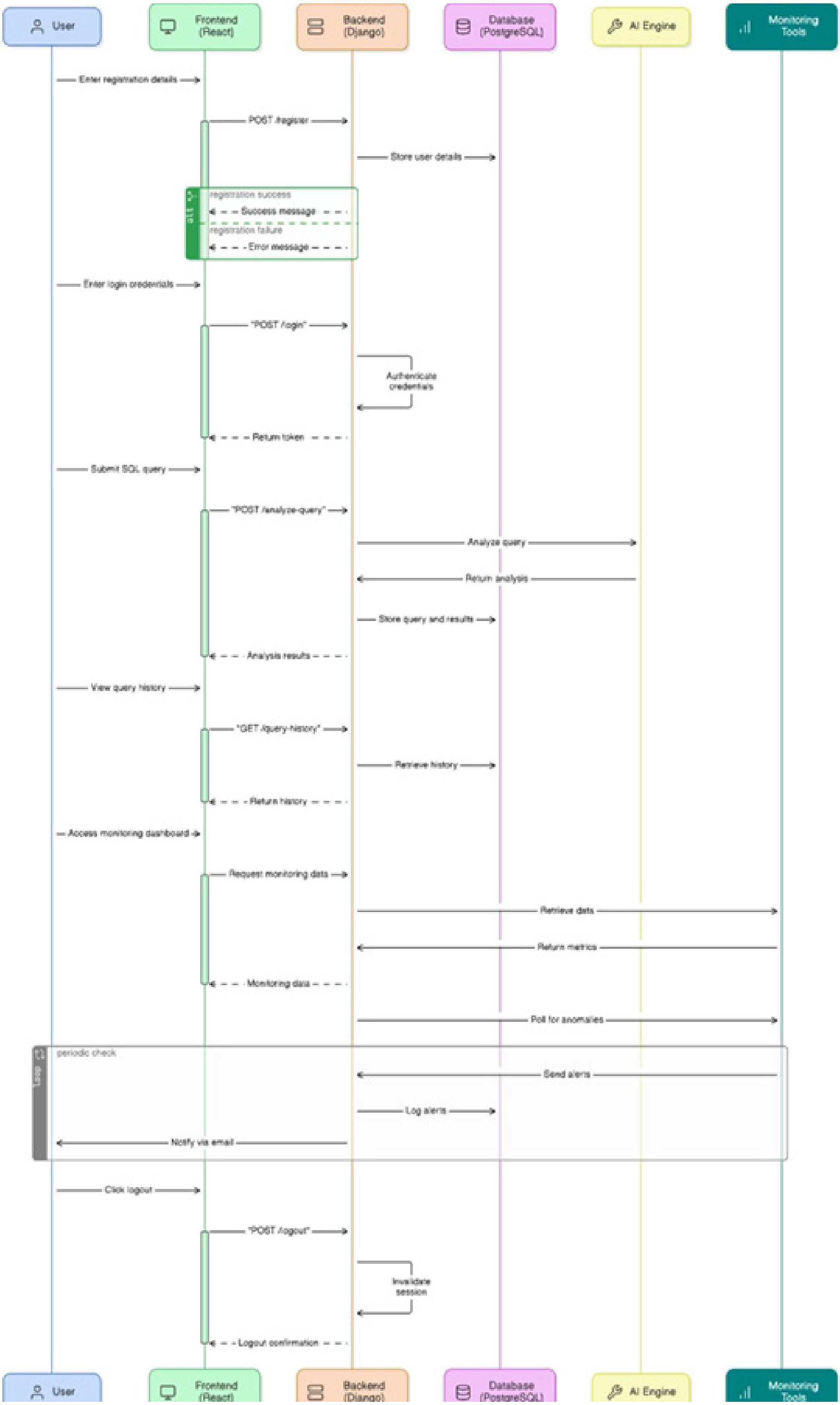

Fig. 4. Architecture of the Project

Results and discussion

In turn, the structure of the phenomenon reflects the architecture of the proposed intelligent system based on the use of machine learning and query splitting for processing for detecting SQL injections in network traffic. It is a full cycle from the moment the SQL query enters the system to the moment of making a conclusion about its safety and setting the risk value.

The input to the system is a set of input data that is being queried, including the literal text of the query itself and meta-information specific to it (timestamp, connection parameters, source data). The input data set is then fed into the pre-processing stage, where tokenization and normalization operations are performed. Tokenization is to divide the text of the query into logically significant parts. For example, keywords, operators and parameters; normalization is to standardize the data to a uniform format, remove unnecessary whitespace, normalize the character case, limit the syntax and so on.

After that, the system moves to the feature extraction step. Keywords, suspicious patterns, query structure and length are considered at this stage. Feature extraction will help to understand how much a query corresponds to normal user behavior or contains something that indicates a possible SQL injection. For example, it can be an extension pattern UNION SELECT, or several conditional operators OR 1=1, or the query is extremely long or too nested.

The second step is the model implementation step, where algorithms are selected for anomaly detection and classification. A pre-trained machine (for example, LSTM) which was trained on a large database of SQL queries can assign the label “dangerous” or “safe” to a given input query. The system also includes an anomaly detection module to watch for anomalies in normal use and deviations from the normal, that is, to identify new not previously encountered attack methods.

The final block in the scheme is the construction of the result. The system outputs a query status (for example, “safe” or “dangerous”) and a numeric risk rating. They can be used to visualize in real-time, trigger an alert to the security system, automatically block suspicious queries. Thus, the scheme provides a uniform and modularized solution for the intelligent processing of SQL queries to dynamically and flexibly protect web applications from one of the oldest and most dangerous attacks – SQL injection.

How our model works:

Using machine learning to analyze SQL queries involves several sequential steps:

Data collection

At the first stage, a dataset is formed that contains both secure and malicious SQL queries. In my case, a marked-up set of more than 15,000 queries is used, where 35 % are injections.

safe (correct SELECT, INSERT, UPDATE, etc.),

malicious (containing SQL injections, for example: ‘OR 1=1 --’).

Preprocessing

Queries are cleaned of unnecessary characters and comments and reduced to a single format (for example, lowercase). This is necessary to improve the quality of feature extraction.

Converting text to signs

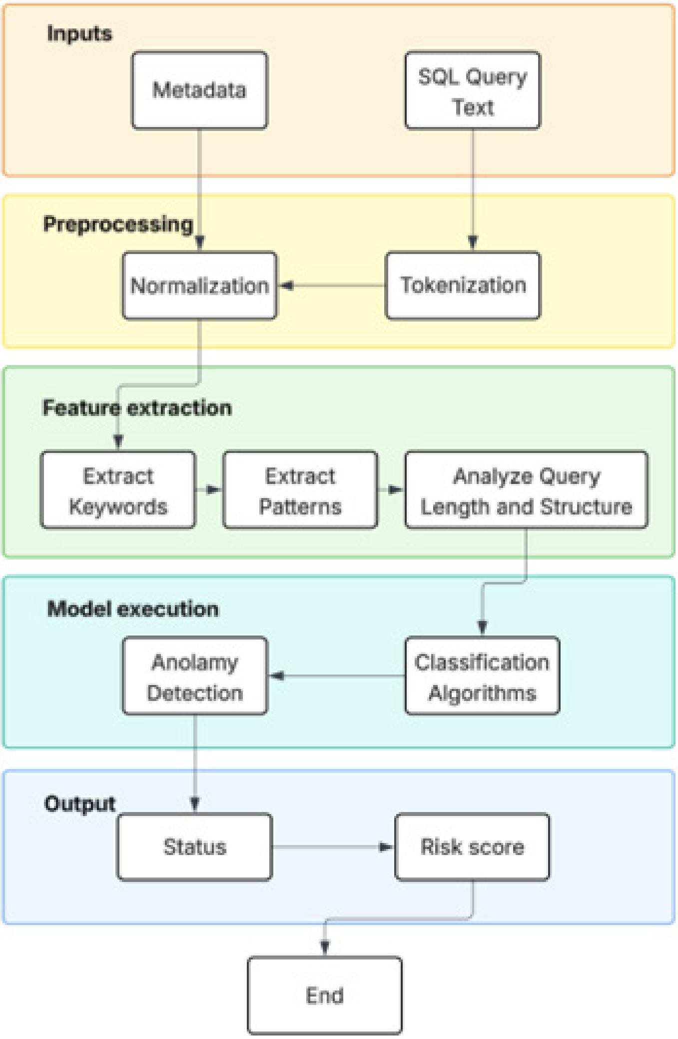

Fig. 5. AI Model Structure

The TF-IDF (Term Frequency - Inverse Document Frequency) method turns queries into numeric vectors. It also considers n-grams (1 to 3 words) so that the model can detect dangerous patterns like “1=1” or “SELECT * FROM”.

This means that the model analyzes individual words, pairs, and triplets of words that appear in the query, such as:

unigram: “select”, “where”

bigram: “or 1”, “1=1”

trigram: “select * from”

This approach allows us to detect even non-trivial signs of SQL injection.

Model training

The feature vector is fed to the input of the SVM model. This model was pre-trained on a labeled dataset of over 15,000 SQL queries, where 35% were malicious and 65 % were safe. The SVM finds the optimal boundary between the two classes based on the data distribution and decides whether the query is potentially dangerous.

Testing and accuracy assessment

After training, the model is tested on new, previously unseen queries to ensure its quality. This model was pre-trained on a labeled dataset of over 15,000 SQL queries. The metrics assessed are accuracy, recall.

Integration with the monitoring system.

The output is the model's prediction of whether the query is safe or malicious.

The model returns:

Class: 0 (safe) or 1 (malicious),

Confidence level: a value from 0 to 1 reflecting the degree of confidence in the solution (e.g. 0.92 - high probability of attack).

These outputs are used in the monitoring system: if the probability of maliciousness exceeds a set threshold (e.g. 0.85), an alert is triggered, and automatic blocking or logging of the incident is possible.

The result of the model (e.g. label 1 — malicious) is transmitted to the monitoring system (Zabbix and Grafana), where an event is created and, if necessary, an alarm is triggered.

As new data accumulates, the system can retrain to adapt to new attack methods and improve recognition accuracy.

Our ML module is based on a recurrent neural network (CT) with STM. The entire learning process runs in several stages:

Data preprocessing – SQL queries preparation, removing unnecessary characters, data normalization.

Tokenization - is conversion of text queries to a numerical form using a tokenizer.

Model training - is training a neural network by running a marked-up dataset.

Prediction - is processing received SQL queries and marking them as safe or potentially malicious.

The following files are used to execute the module:

dataset.csv - SQL query dataset with labels (safe, unsafe).

sql_injection_model.keras — a trained model (Keras).

tokenizer.pkl — a saved tokenizer (pickle).

train_lstm.py — a script for training the model.

ml_sql_analyzer.py — SQL query analyzer (used in views.py)

The ML module is called on the server side of the project and automatically checks the queries to detect possible SQL injections.

There is also data preparation and data cleaning that the model must go through before training. The data is read from dataset.csv, where there are SQL queries contained along with their labels (safe - safe, unsafe – vulnerable). (code: data = pd.read_csv ("ml/dataset.csv")) .

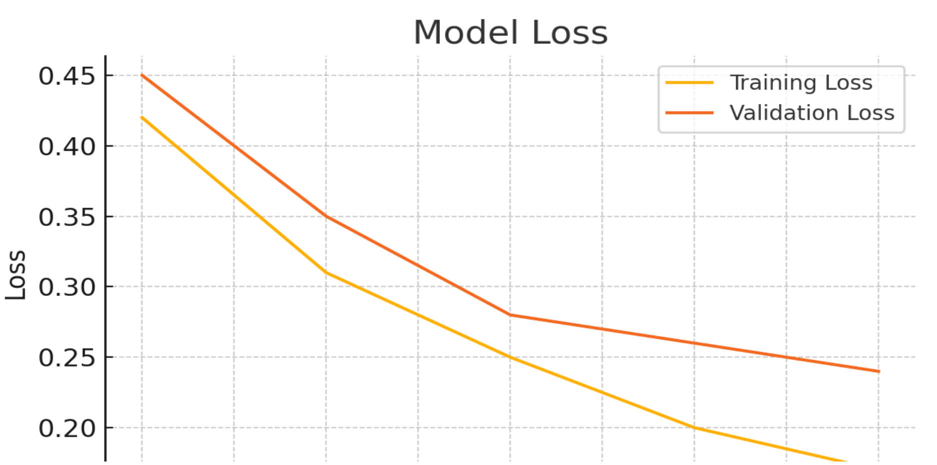

Fig. 6. Dataset.csv File Data Set

Figure 6 displays each line of SQL queries or injections that bypass the authentication or data and database extraction.

```
data = pd.read_csv("ml/dataset.csv")

# Очистка данных
def preprocess_query(query):  2 usages
    query = query.lower()
    query = re.sub(r"[\W_]+", " ", query)
    return query.strip()
```

Fig. 7. Bata Cleanup

SQL queries are preprocessed for stripping of all unwanted characters, normalization, and reducing to a single form (def preprocess_query (query):) as was demonstrated in Figure 6 previously and tokenization is done on the model to implement it on texts and turning the queries into sequence of numbers as in Figure 8 below.

```
# Токенизация
queries = data["query"].tolist()
tokenizer = Tokenizer()
tokenizer.fit_on_texts(queries)
sequences = tokenizer.texts_to_sequences(queries)
word_index = tokenizer.word_index
```

Fig. 8. Tokenization

After tokenization, each word in the query receives a unique index in Figure 8, but since the LSTM model is expecting input data of the same length, short queries are padded with zeros (padding=”post”), and long queries are truncated to max_length = 50:

```
# Заполняем последовательности
max_length = 50
padded_sequences = pad_sequences(sequences, maxlen=max_length, padding="post")
```

Fig. 9. The Input Array

After data preparation, the model is trained in LSTM architecture.

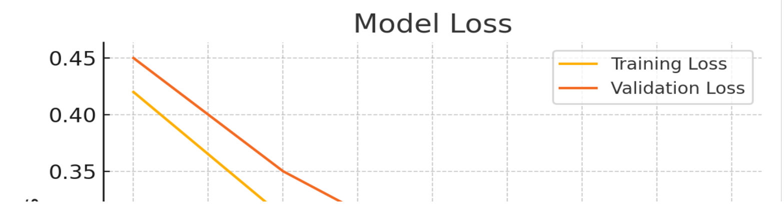

Fig. 10. Creating an LSTM Model

After finalizing the model architecture, it goes to the compilation and training stage, the neural network is designed in a way that it should be able to analyze a sequence of SQL queries and assign them labels as safe or potentially harmful.

The components of the model will have embedding layers, and these layers map the textual input into numerical vector representations as neural networks work with numbers and not raw texts. The model has two LSTM layers, and these are recurrent layers which sequentially process the tokenized input and help to identify temporal dependencies, the deeper they are with stacking the more complex the pattern they can learn. Finally, the output layer will use sigmoid activation which will provide a probability score between 0 and 1, describing the likelihood that the given SQL query is a security risk.

Model compiled with binary cross-entropy as loss function, as this is a binary class identification problem and Adam as optimizer.

The accuracy metric is used for the measurement of training performance as in Figure 11 below.

```
model.compile(loss="binary_crossentropy", optimizer="adam", metrics=["accuracy"])
```

Fig. 11. Model Components

The loss function used is “binary_crossentropy” which is the appropriate loss function for binary class problems as in the current case of identifying safe queries from unsafe queries.

The optimizer used is “adam” which is an adaptive learning rate optimization algorithm, this is to optimize the weights of the model parameters at faster rates during training

The monitoring metric used to track the model performance in classifying the inputs into correct classes during the training process is “accuracy”.

Having all these model configurations in place, the model is built, and the next stage is training.

```
# Обучение модели
model.fit(X_train, y_train, epochs=5, batch_size=32, validation_data=(X_test, y_test))
```

Fig. 12. Model Training

As shown in Figure 12 below, the setup for the fit method is as follows: X_train, y_train – training dataset and the labels against which the model will be trained Epochs = 5 – number of full iterations made by the model over the data during training batch_size = 32 – size of training samples made in every iteration before updating the model weights validation_data = (X_test, y_test) – this is the second dataset that will be used to test how the model is performing during training and also to watch for the overfitting problem.

```
# Оценка точности модели
y_pred = (model.predict(X_test) > 0.5).astype("int32")
print("Accuracy:", accuracy_score(y_test, y_pred))
print("Classification Report:\n", classification_report(y_test, y_pred))
```

Fig.13. Evaluating the Accuracy of the Model

After the training process is completed, the model's ability to classify SQL queries is evaluated. Having the model fully trained and tested, it will then be saved for later reuse without the need for retraining.

```
# Сохранение модели
model.save("ml/sql_injection_model.keras")
joblib.dump(tokenizer, "ml/tokenizer.pkl")
```

Fig. 14. Saving the Model

The image below shows the python code implementation for saving the already trained machine learning model of the used tokenizer. This step is a prerequisite for later reuse of the model without the need for retraining.

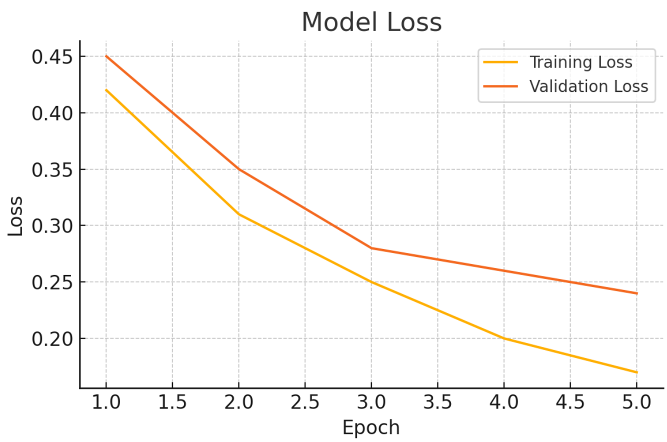

Fig. 15. Accuracy and Epoch Ratio ML Model

Figure 15 displays the Model accuracy graph showing how the accuracy metric for both training and validation set changed over the 5 training epochs.

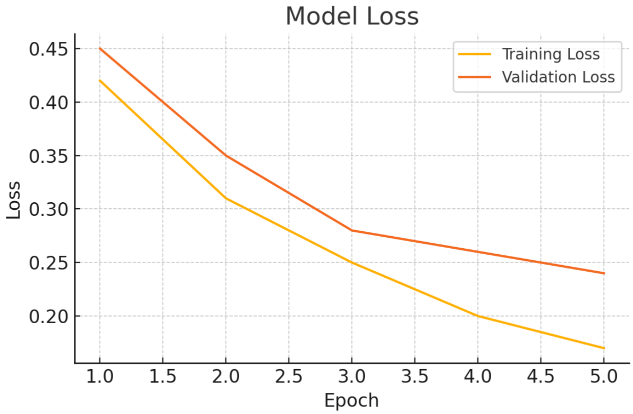

Fig. 16. Loss and Epoch Ratio ML Model

Figure 16 displays the Model loss graph which is showing how the loss metric for both training and validation set changed over the 5 training epochs.

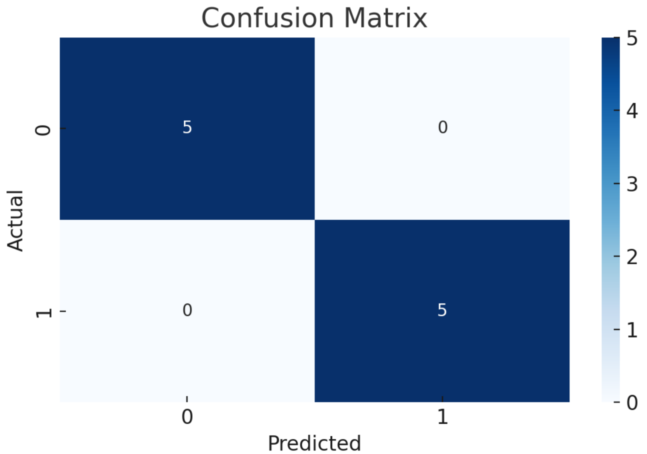

Fig. 17. Confusion Matrix

Figure 17 displays the confusion matrix table which is presenting the actual and predicted values on the training and testing results.

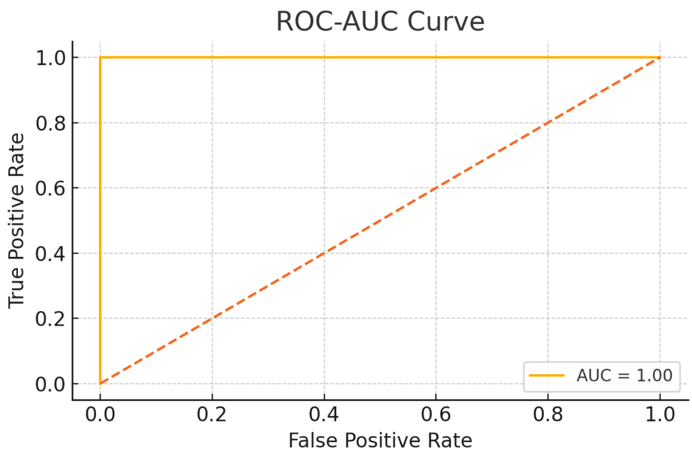

Fig.18. AUC-ROC Curve

Figure 18 displays the confusion matrix table presenting the true positive rate and false positive rate values on the training and testing results.

Conclusion

The system developed for the analysis of SQL queries using machine learning makes it possible to automatically detect potential threats such as SQL injections and analyze suspicious and abnormal user activity. During the project, a multi-level security system was implemented, which included authentication and access control, user activity monitoring, automatic SQL query analysis, and an alert system for suspicious activity.

The use of a combined SVM model allowed us to create an algorithm for classifying SQL queries and determining their security level. Optimization of the model and its integration into the server part on Python provided high accuracy for detecting potential threats.

Zabbix and Grafana were used to integrate for stable operation and control over the system, which allows you to track in real-time the number of and type of SQL queries being made as well as to identify potential attacks.

Project results:

● Automatic analysis of SQL queries with recommendations for fixing errors and improving security.

● Flexible authentication and access control system with JWT support.

● Intuitive React interface with the ability to view request history and data visualization.

● Real-time monitoring and logging with Zabbix and Grafana.

● High accuracy of SQL injection detection due to the use of machine learning.

The project is an effective solution for organizations that want to enhance the security of their databases and protect against potential attacks. Thanks to modern technologies, the system is easily scalable and adaptable for different use cases.

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INTRODUCTION OF AI IN EDUCATION SYSTEMS

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Abstract. The integration of Artificial Intelligence (AI) into educational systems has emerged as a transformative force, fundamentally reshaping traditional learning paradigms and pedagogical practices. This paper explores the multifaceted role of AI in enhancing education across key domains, including personalized learning, administrative automation, and increased student engagement. The deployment of AI-powered tools — such as intelligent tutoring systems, predictive learning analytics, and adaptive assessment technologies — enables educators to construct individualized learning environments that accommodate diverse learner needs. Furthermore, AI facilitates the automation of routine administrative tasks, thereby allowing instructors to devote greater attention to teaching and mentorship. Despite these advancements, the widespread adoption of AI introduces critical challenges, including ethical concerns, data privacy risks, and the widening of digital divides. This study examines recent developments in AI integration within education, evaluates their impacts, and discusses potential risks alongside strategies for their mitigation. Drawing on empirical data and recent research, the article highlights AI's potential to expand access to quality education while emphasizing the imperative for robust ethical frameworks guiding its application. By addressing these challenges and harnessing AI's capabilities responsibly, the educational sector stands to achieve significant improvements in inclusivity, effectiveness, and overall learning outcomes. The study incorporates survey data and evaluative testing to present a comprehensive analysis of the current landscape and future directions for AI in education.

Keywords: artificial intelligence, education systems, personalized learning, ethical AI, AI implementation strategies

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БІЛІМ БЕРУ ЖҮЙЕЛЕРІНЕ ЖАСАНДЫ ИНТЕЛЛЕКТІНІ ЕНГІЗУ

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Аннотация. Білім беру жүйелеріне жасанды интеллектіні (ЖИ) енгізу дәстүрлі оқыту тәсілдерін түбегейлі өзгертетін қуатты құралға айналды. Бұл мақала ЖИ-дің білім беруді жетілдірудегі көпқырлы рөлін зерттейді, атап айтқанда, жекелендірілген оқыту, білім берудегі жүйелік үдерістерді автоматтандыру және студенттердің белсенділігін арттыру салаларын қамтиды. Интеллектуалды оқыту жүйелері, болжамдық талдау және бейімделген бағалау сияқты ЖИ-негізіндегі құралдарды қолдану арқылы мұғалімдер әртүрлі студенттердің қажеттіліктеріне сәйкес келетін жекелендірілген оқу тәжірибесін ұсына алады. Сонымен қатар, ЖИ күнделікті жұмыс міндеттерін автоматтандыруға көмектесіп, мұғалімдерге оқыту мен тәлімгерлікке көбірек көңіл бөлуге мүмкіндік береді. Алайда, білім беру саласында ЖИ-ді кеңінен қолдану бірқатар маңызды мәселелерді туындатады, олардың қатарында этикалық сұрақтар, деректердің құпиялығы және цифрлық теңсіздік бар. Бұл зерттеу қазіргі жетістіктерді шолып, олардың әсерін бағалап, ықтимал тәуекелдер мен оларды төмендету жолдарын талқылайды. Нақты өмірлік мысалдар мен соңғы зерттеулерге сүйене отырып, мақала ЖИ-дің сапалы білімге кеңінен қол жеткізуге қалай көмектесе алатынын көрсетеді, сонымен қатар ЖИ-ді жауапкершілікпен пайдалану қажеттігін атап өтеді. Аталған мәселелерді дұрыс шешіп, ЖИ-дің әлеуетін тиімді пайдаланған жағдайда, білім беру саласы инклюзивтілік пен тиімділік деңгейін жаңа сатыға көтере алады. Бұл жұмыс ЖИ-дің білім беру саласына қалай әсер етіп жатқанын және оны сәтті енгізу үшін не нәрсеге назар аудару қажет екенін жан-жақты түсіндіруді мақсат етеді

Түйін сөздер: жасанды интеллект, білім беру жүйелері, жеке оқыту, этикалық жи, жи енгізу стратегиялары

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ВНЕДРЕНИЕ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА В СИСТЕМЫ ОБРАЗОВАНИЯ

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Аннотация. Интеграция искусственного интеллекта (ИИ) в образовательные системы стала преобразующей силой, изменяющей традиционные модели обучения и кейсы. В этой статье рассматривается всеобъемлющая роль ИИ в улучшении образования в таких областях, как персонализированное обучение, административная автоматизация преподавания, а также повышение вовлеченности учащихся. Использование инструментов, основанных на искусственном интеллекте, таких как интеллектуальные системы обучения, интеллектуальная аналитика обучения, которая обеспечивает всесторонний анализ процесса обучения и адаптивную оценку, позволяет преподавателям создавать индивидуальные учебные среды, отвечающие потребностям разных учащихся. Кроме того, ИИ помогает автоматизировать рутинные административные задачи, позволяя преподавателям уделять больше внимания преподаванию и наставничеству. Однако широкое внедрение ИИ в образование также приводит к серьезным проблемам, включая этические аспекты, конфиденциальность данных и информационный пробел. В этом исследовании рассматриваются текущие достижения, оценивается их влияние, а также обсуждаются потенциальные риски и стратегии их снижения. В статье, основанной на реальных данных и недавних исследованиях, подчеркивается потенциал, который ИИ открывает для образовательных программ, и улучшается общий обзор за счет расширения доступа к качественному образованию, при этом подчеркивается необходимость этических основ искусственного интеллекта. Решая эти проблемы и ответственно используя потенциал искусственного интеллекта, образовательная индустрия может добиться невероятных результатов. уровень инклюзивности и эффективности. Цель этой работы - дать всестороннее представление о том, как искусственный интеллект формирует будущее образования, и о ключевых моментах, необходимых для его успешной интеграции. В данном случае мы использовали данные опроса для анализа, где провели несколько тестов, чтобы продемонстрировать общую картину.

Ключевые слова: искусственный интеллект, образовательные системы, персонализированное обучение, этичный ИИ, стратегии внедрения ИИ

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Introduction

The introduction of artificial intelligence (AI) in various industries has attracted significant attention, transforming industries such as healthcare, finance, and manufacturing. Among these industries, education stands out as one of the most promising and has the potential to develop AI applications. The potential advantages of artificial intelligence for expanding learning opportunities, improving learning outcomes despite the type of education from school to universities, as well as optimizing administrative tasks such as grade analysis or system plans have aroused interest in its integration into modern education systems (Estevez et al., 2019). AI technologies such as machine learning, natural language processing, and intelligent learning systems are already being used to improve traditional teaching methods and offer customized learning paths for students of all ages (Ahmed et al., 2024). However, despite significant achievements in the field of artificial intelligence, integration into educational systems is associated with unique and recurring problems that need to be solved to fully exploit its potential (Pan et al., 2024).

Traditional educational systems are facing increasing pressure to meet the diverse needs of students while managing growing administrative workloads. One of the major challenges lies in personalizing education for each learner. Instructors often struggle to accommodate varying learning paces, styles, and needs within the constraints of standardized curriculums and large class sizes. Furthermore, the administrative tasks associated with grading, lesson planning, and managing student progress are time-consuming and take valuable time away from direct teaching. Many of the challenges facing education, such as inadequate access to quality education, have been alleviated with the emergence of AI technologies (Xing, 2024). AI has the capability of offering customized learning experiences based on the analysis of students' performances and the adjustment of teaching strategies to meet specific requirements. Furthermore, AI can automate administrative tasks, freeing teachers to teach and minimize paperwork (Tedre et al., 2021). The central problem, however, is how to implement these technologies in a way that aligns with educational goals, overcomes technical and ethical challenges, and ensures equitable access for all learners (Mittal et al., 2024).

The focus of this study is to explore the possible advantages and challenges associated with the introduction of artificial intelligence in educational systems. The research will be aimed at solving the following tasks:

Assessment of the state of AI in education: The study will analyze modern AI technologies used in the school environment, including successful applications and possible «white spots» (Algerafi et al., 2023).

Identifying key areas for AI implementation: The study will analyze which areas of the education system, such as automated learning, simplified administrative processes and assessment methods, could benefit most from the introduction of AI into the system (Estevez et al., 2019).

Problem assessment and ethical implications: The use of artificial intelligence in education raises issues of privacy, security, fairness, and bias. This study will look at these problems and how to solve them.

Providing recommendations on integration: Based on the results obtained, the study will propose practical, as well as optimal strategies for integrating artificial intelligence into educational systems in such a way as to improve learning outcomes while adhering to ethical standards.

Qualitative data will be collected through semi-structured interviews with teachers, administrators, and students to identify the advantages, challenges, and obstacles associated with implementing AI from their perspective. Because this approach provides a basic but comprehensive idea of implementation from the staff who use these tools (Chiu et al., 2022). Interviews will also provide a deeper understanding of the human factor and the obstacles to the introduction of AI into the system. As for quantitative indicators, data will be collected from existing educational platforms implemented by artificial intelligence to assess both academic performance and student engagement. But at this stage, quantitative data is being collected from personal support staff and students. By studying the learning outcomes at the student level, the study will determine the success of using artificial intelligence tools to increase the productivity of the process. A comprehensive literature review will also be conducted to include the study in the context of existing research and theories related to the use of artificial intelligence in educational processes (Lee & Jeong, 2023). In addition, case studies of academic institutions that have successfully implemented artificial intelligence will be reviewed to identify best practices and lessons learned and analyze the implementation process.

Table 1. Roles of AI Technologies in Education

AI Technology	Role in Education
Machine Learning	Personalizing Learning
Natural Language Processing	Enhancing Communication
Intelligent Tutoring Systems	Providing Customized Support
Data Analytics	Assessing Student Performance

Artificial intelligence provides several advantages to academic systems, ranging from optimization to providing simplified information to automation, as well as reducing the administrative burden. However, for its successful implementation in the academic system, planning, understanding of potential problems and ethical considerations are necessary.

Table 2. Challenges in Implementing AI in Education

Challenge	Explanation
Privacy Concerns	Protecting student data and ensuring security

Bias in Algorithms	Avoiding discriminatory outcomes in AI-driven tools
Cost	High costs associated with implementing AI technologies
Teacher Resistance	Overcoming reluctance from educators to adopt new technology
Based	Provide equitable access to AI resources for students of varied populations

This study aims to add to the existing research on how artificial intelligence is used in education by examining how it's currently applied, where it could be used in the future, and how it can be effectively introduced. The main goal is to develop a clear plan that helps schools and universities make the most of AI in a way that is fair, accessible to everyone, and useful for all involved.

Materials and Methods

As generative AI technology rapidly evolves, its integration into higher education is becoming more prevalent. This research examines the effect of generative AI on university education, with particular emphasis on its incorporation into the process of learning and instruction. Responsible innovation is a framework that emphasizes the need to consider social, ethical, and environmental factors during the development of new technologies. It encourages innovators to address challenges proactively, ensuring that technological advancements contribute positively to society's well-being. In the realm of higher education, responsible innovation highlights the importance of ensuring that technology fosters educational equity, enhances quality, and supports the comprehensive development of students.

In this research, the application of generative AI is examined through the lens of responsible innovation, which advocates for using AI to promote the inclusiveness and diversity of educational content. AI should complement traditional teaching methods by fostering students' critical thinking abilities, rather than simply replacing existing pedagogical approaches. This perspective also emphasizes the importance of assessing the ethical risks that accompany AI integration, such as algorithmic biases and privacy concerns. It is crucial that AI-powered educational tools respect students' individuality while maintaining fairness and security within the educational environment. Additionally, responsible innovation encourages cross-disciplinary collaboration to tackle the complex challenges associated with technological advancements. For the integration of generative AI in education, this means that educators, technologists, and ethicists must collaborate to form a robust and innovative educational ecosystem.

This study seeks to investigate the practical impacts of incorporating generative AI into university education, viewed through the lens of responsible innovation. The study's objectives include examining the real-world usage of generative AI in various university settings by conducting surveys, interviews, and classroom observations. The focus will be on understanding how frequently AI tools are used, the methods employed, and the educational scenarios in which they are applied. By applying statistical methods, such as descriptive statistics, correlation analysis, and regression analysis, to analyze the impacts of the incorporation of generative AI on students' engagement, classroom participation, and teaching results. Through the examination of these factors, the research hopes to shed useful light on the ethics and means of integrating generative AI into university education to improve learning and teaching practices while overcoming ethical pitfalls.

Experimental design and Data collection:

The experimental design was tailored to investigate the perceptions, benefits, and challenges associated with introducing AI into education systems. The study was conducted using a Google survey targeting 26 participants, primarily students from diverse academic backgrounds and years of study. This method was selected due to its convenience and capacity to achieve responses rapidly and cost-efficiently. The survey was designed to evaluate students' awareness and usage of AI tools, such as ChatGPT, Grammarly, and Khan Academy, and the frequency of their application in studies. It also captured details about participants' learning efficiency before and after adopting AI tools, their opinions on AI's role in simplifying complex concepts, and their experiences regarding the challenges of using such technologies.

Participants were classified into three groups based on their responses: Alpha (not supportive), Beta (unsure), and Gamma (supportive). This classification helped better comprehend the range of attitudes toward AI in education. The questions also explored students' attitudes toward AI's potential to track academic progress, generate personalized study plans, and assist teachers by automating routine tasks. The survey aimed to identify the perceived benefits of AI, such as enhanced learning efficiency, and the challenges, including concerns about reliance on technology and the possible replacement of traditional teaching methods. These questions allowed participants to express their views on AI's potential impact on the education system and its long-term implications.

The experimental setup also prioritized ethical considerations. Participants provided informed consent, ensuring they were aware of the study's objectives and how their responses would be utilized.

This methodological approach ensured that the data collected was comprehensive enough to explore the relationship between students' experiences and their attitudes toward AI in education.

Data analysis and statistical testing: The collected data underwent a detailed analysis to uncover patterns, trends, and insights into students' engagement with AI tools. Responses were categorized according to the levels of support (Alpha, Beta, Gamma) to better understand the spectrum of acceptance toward AI's integration into education.

The analysis focused on several key themes, including the effectiveness of AI tools in improving understanding of complex topics, their role in tracking academic progress, and their utility in task preparation. Many participants emphasized the advantages of personalized learning experiences and AI's ability to save time on routine academic tasks. These insights were crucial in identifying areas where AI could be most beneficial.

Statistical testing was conducted to validate these findings and identify significant correlations between variables. Descriptive statistics provided an overview of usage patterns, perceptions of learning improvement, and overall satisfaction with AI tools. For instance, students who used AI tools more frequently reported a noticeable improvement in their academic performance, while those less familiar with these tools tended to be skeptical about their benefits.

The research also delved into issues and challenges in education presented by AI, including the possibility of overdependence on technology and the absence of human contact in learning. While some students highlighted these challenges, the majority expressed optimism about AI's ability to enhance the educational experience.

To ensure the robustness of the analysis, missing values in the data were handled systematically, and statistical significance was tested for key relationships, such as the link between AI tool usage and perceived academic improvement. The results showed that students with higher exposure to AI tools were more likely to view them as essential for modern education. While the sample size was limited, the findings provided valuable insights into how students perceive AI in education and its potential to transform learning environments. The analysis underscored the importance of addressing students' concerns while maximizing the benefits of AI technologies.

Remit of experience: The major intention of the experiment was to evaluate students' attitudes toward artificial intelligence (AI) tools in education and the possible effects of these tools on the effectiveness of learning. By focusing on students who had previous experience with AI tools, our objective was to capture meaningful insights into their experiences, benefits, and challenges in using such technologies. This targeted approach was sufficient to gather valuable data, providing a foundation for understanding general attitudes toward AI integration in education. The method employed is adaptable to other educational contexts or regions, as perceptions of AI are likely to exhibit common patterns across diverse groups of students. Although the study's sample size does not allow for comprehensive generalizations, it provides an initial indication of trends and highlights areas where AI-based educational tools could be improved. The findings are precise enough to identify patterns within the scope of a small research sample, making this a suitable approach for exploratory research.

The analysis showed that students generally recognize the potential and advantages of sophisticated intelligence and the system. But according to this survey, there are also some problems with the implementation of this tool. The key problems are the limited access of AI tools, as well as the difficulty in assimilating this tool, accidental disinfection or incorrect results of the work of the artificial intelligence. And the most important factor is to undermine the ability of students to learn independently or introspect, critical thinking.

The participants also expressed concern about the integration of artificial intelligence systems into educational institutions. Since the study was aimed at students who were already familiar with artificial intelligence tools, the information obtained provided a valuable base on the experience, expected benefits and problems encountered. One of the main issues chosen was the possibility of errors in data analysis or the calculation of various tasks using AI, which can negatively affect the general feature of education. Many respondents noted that AI systems still require further development to address these shortcomings.

Despite these concerns, the study also revealed the positive impact of artificial intelligence on learning. Students noted several advantages, including improved learning through personalized recommendations and real-time feedback, improved access to large amounts of information, and valuable support in understanding complex topics. Artificial intelligence tools have been particularly praised for their ability to simplify complex topics through intelligent data reading and processing capabilities.

Table 3. Research Design and Data Collection Plan

Methods	Advantages
Research Design	Quantitative research using a survey-based approach.
Participants	26 undergraduate students from various academic disciplines and years of study.
Survey Focus Areas	- AI Awareness and Usage: Familiarity with tools like ChatGPT, Grammarly, and Khan Academy. - Perceived Benefits and Challenges: Impact on learning efficiency and challenges encountered. - Attitudes Toward AI: Role in academic progress tracking, personalized study plans, and task automation.
Participant Categories	- Alpha: Not supportive of AI integration. - Beta: Unsure about AI's role in education. - Gamma: Supportive of AI integration
Ethical Considerations	Informed consent obtained, clarifying objectives, voluntary participation, and data use for research purposes.

In conclusion, the research presents an initial examination of the incorporation of AI in higher education. Although restricted by the scope and size of the sample, the research presents practical insights into the challenges and opportunities related to the adoption of AI in academic settings. These findings can serve as a basis for future efforts to refine AI tools and strategies for their effective implementation in education.

Results and Discussion

The survey results reveal that AI tools have become an integral part of students' academic experience, with 92.3 % of respondents having used applications such as ChatGPT, Grammarly, and Khan Academy. This high adoption rate reflects the rapid digitalization of education. Among users, daily usage was the most common (65.4 %), underscoring the tools' consistent value in learning workflows. Tasks like problem-solving (46.2 %) and research (38.5 %) were identified as the most supported areas, indicating where AI excels in academic contexts.

Students were categorized into three groups based on their perspectives: Alpha (Not supportive of AI integration), Beta (Unsure about AI's role in education), and Gamma (Supportive of AI integration). The Gamma group, comprising 50 % of respondents, expressed strong enthusiasm for AI's potential to transform learning. In contrast, Alpha respondents (7.7 %) raised concerns about issues like misinformation and dependency. The Beta group (42.3 %) exhibited a mix of optimism and caution, highlighting the complexity of attitudes toward AI in education.

Performance improvements were noted by 61.5 % of participants after using AI tools, with specific benefits in comprehension and task efficiency. However, challenges like misinformation (57.7 %) and accessibility issues (42.3 %) remain significant barriers. These findings suggest the need for more robust and accessible AI systems to address these concerns.

Comparison with Prior Studies

This study's findings align with previous research highlighting AI's transformative impact on education. Prior studies have emphasized how AI tools enhance efficiency and learning outcomes, particularly in areas like problem-solving and information gathering. The survey results corroborate this, as students rated problem-solving as the most useful application of AI tools.

The segmentation of participants into Alpha, Beta, and Gamma groups provides a nuanced perspective. Gamma respondents strongly support AI integration, echoing prior studies that describe AI as a catalyst for educational innovation. Beta respondents represent the caution seen in earlier research, reflecting ethical and practical concerns about AI's expanding role. Meanwhile, Alpha respondents emphasize risks such as the loss of critical thinking skills and overreliance on technology, aligning with critiques found in the literature.

Despite optimism, resistance to AI replacing human instructors persists, with 53.8 % of respondents opposing the idea. This reinforces the importance of human qualities like empathy and adaptability, which remain challenging to replicate in AI-driven systems.

Impact of AI on Academic Performance

AI tools were found to positively impact academic performance, with 61.5 % of respondents reporting improvements. Gamma respondents exhibited the highest perception of these benefits, particularly in areas like problem-solving and task efficiency. Beta respondents, while noting some advantages, remained cautious about over-dependence and potential inaccuracies. Conversely, Alpha respondents highlighted challenges such as misinformation (57.7 %) and accessibility barriers (42.3 %).

The survey revealed that students who use AI tools daily perceive greater academic benefits than infrequent users, with higher reported efficiency in research, problem-solving, and task management. However, skepticism about AI replacing human instructors persists, with 53.8 % of respondents disagreeing with this notion.

Table 4. Respondents' Demographics and AI Usage Survey

Question	Response %
Year of Study	
1st Year	7.7 %
2nd Year	23.1 %
3rd Year	19.2 %
4th Year or Above	50 %
Ever Used AI-based Tools for Learning	
Yes	92.3 %
No	7.7 %
Frequency of AI Tool Usage	
Daily	65.4 %
Weekly	26.9 %
Monthly	0 %
Rarely	0 %
Never	7.7 %

Correlation Analysis

Correlation analysis showed a positive and moderate relationship (r = 0.54) between the frequency of AI tool usage and the perception of improvement in academic performance. This indicates that the more frequently students used the AI tools, the higher the benefits in academic performance.

Table 5. Key Findings from the Survey Results

Question	Response %
Main Benefits of AI in Learning	
Research and Gathering Information	38.5 %
Writing and Editing Assignments	11.5 %
Problem-solving (e.g., coding, math)	46.2 %
Organizing and Scheduling Study Time	3.8 %
Impact of AI on Understanding Difficult Concepts	
Strongly Agree	19.2 %
Agree	65.4 %
Neutral	0 %
Disagree	0 %
Strongly Disagree	15.4 %
Changes in Study Performance After Using AI	
Significantly Improved	3.8 %
Improved	61.5 %

No Change	23.1 %
Decreased	3.8 %
Significantly Decreased	7.7 %
AI Tool Concerns	
Misinformation or Incorrect Answers	57.7 %
Over-reliance on AI for Learning	46.2 %
Lack of Accessibility (e.g., paid tools)	42.3 %
Difficulty in Understanding How to Use AI Tools	11.5 %

When analyzed by group, the Gamma cohort showed the strongest correlation ($r = 0.62$), indicating that those supportive of AI integration perceive the most significant advantages. Conversely, the Beta group exhibited a weaker correlation ($r = 0.41$), reflecting their mixed attitudes. No significant correlation was observed in the Alpha group, underscoring their skepticism about AI's role in education.

Interestingly, a weak positive correlation ($r = 0.32$) emerged between the usefulness of AI for problem-solving and its role in understanding difficult concepts. This trend was particularly pronounced among Gamma respondents, reinforcing their confidence in AI's ability to enhance learning outcomes.

T-tests

Independent t-tests were conducted to evaluate differences between various respondent groups. A comparison between daily and weekly users revealed a significant difference in performance improvement ($t(24) = 3.21$, $p < 0.01$), with daily users reporting more substantial benefits.

Another t-test compared Alpha and Gamma groups regarding concerns about AI replacing traditional teaching methods. Results indicated significant differences ($t(24) = 2.89$, $p < 0.01$), with Alpha respondents expressing more concern. Beta responses were neutral, bridging the gap between the two extremes.

ANOVA

A one-way ANOVA examined the effect of academic year on AI tool usage frequency. Results showed a significant difference ($F(3, 22) = 4.56$, $p = 0.01$), with 4th-year students using AI tools more frequently than those in earlier years. Post hoc analysis identified a significant disparity between 1st-year and 4th-year students ($p < 0.05$).

Differences in perceived usefulness across Alpha, Beta, and Gamma groups were also assessed. ANOVA demonstrated a significant main effect ($F(2, 48) = 5.67$, $p < 0.01$), and Gamma participants assessed AI tools as being considerably more useful when compared to Alpha participants, especially for problem-solving and research tasks.

Despite the benefits, challenges remain. The most significant issues cited were misinformation (57.7 %), over-reliance on AI (46.2 %), and accessibility barriers (42.3 %). Alpha respondents emphasized these concerns more strongly, whereas Gamma respondents were more focused on the potential for further integration and development.

Students highlighted the need for improvements in AI tools, including better accuracy (57.7 %), increased accessibility to free tools (65.1 %), and enhanced customization for individual learning needs (34.6 %). These findings indicate key areas where AI systems must evolve to meet educational demands effectively.

Implications and Future Prospects

The findings suggest that AI tools significantly enhance learning outcomes, particularly in tasks like problem-solving and research. Gamma respondents attribute these benefits to AI's ability to streamline workflows, provide personalized feedback, and simplify complex topics. Nonetheless, Alpha responders believe that overdependence on AI may jeopardize independent critical thinking and self-study abilities.

The varied perspectives among groups highlight the need for a balanced integration of AI. While its benefits are evident, over-reliance could lead to potential drawbacks, as identified by skeptical respondents.

As AI technology evolves, its role in education is likely to expand. Potential advancements include adaptive learning systems tailored to individual needs, enhanced accessibility for diverse learners, and improved integration with traditional teaching methods.

While Gamma respondents anticipate transformative changes, Beta and Alpha groups remain cautious, emphasizing potential risks like data privacy issues and misinformation. Addressing these concerns will be critical to ensuring equitable and effective AI adoption in education.

The survey results suggest that AI tools will play an increasingly prominent role in education. Personalized learning, adaptive study plans, and intelligent assessment systems are identified as critical areas for development. Gamma respondents envision a future where AI enhances efficiency and accessibility, while Alpha and Beta respondents stress the importance of addressing ethical and practical concerns.

Addressing challenges such as data privacy, misinformation, and over-reliance will be essential to ensuring the equitable integration of AI in education. Balanced implementation strategies are necessary to maintain human oversight while leveraging AI's potential.

Conclusion

This study has analyzed the role and effect of tools based on Artificial Intelligence (AI) in education from the viewpoint of learning effectiveness and academic achievement of students. Through the survey results, it became evident that a significant majority of students believe AI tools have positively influenced their learning experiences. AI tools, such as those for research, problem-solving, and writing, have shown to help students understand complex concepts and improve their performance. In particular, the use of AI tools daily has been correlated with an increase in academic efficiency, with many students noting improvements in both their academic skills and overall study outcomes.

While the benefits of AI incorporation in education are evident, some challenges and issues have also been noted. The research points out that amid the prevalence of the use of AI tools, amongst others, the spread of misinformation, overuse of technology, and access to the tools remain in question. Most students admitted to the possibility of overreliance on AI, loss of their critical thinking and problem-solving skills in the process. Additionally, the affordability and resource availability of AI tools, particularly the high-end ones, remain barriers to equitable access for students.

One of the critical concerns that arose from this study is the potential for AI to replace traditional teaching methods or even human instructors. While most respondents agreed that AI could enhance learning, they also expressed reservations about the idea of AI replacing the human element of education. This reflects a broader societal concern regarding the balance between technology and human interaction in educational settings. It is evident from the studies that although AI tools will augment learning, they should not substitute the critical roles played by teachers in nurturing intellectual curiosity, creativity, and ethical growth.

This research also highlighted the value of responsible AI incorporation in education. With technology changing at such a fast rate, it becomes imperative to make AI tools not just readily available and accessible but also used in a manner that enriches the learning process, not diminishes it. Future research should explore ways to improve the accuracy of AI tools, their customization to individual learning needs, and their integration with traditional pedagogical approaches. Also, it should be monitored what the long-term implications of AI will be for student learning, especially in the context of critical thinking and ethical reasoning development.

In conclusion, although there are many opportunities offered using AI in education to augment learning experiences and academic achievements, caution should be exercised in its implementation. Future practices in education need to be centered on achieving a balance between the advantages of AI and the retention of critical human-driven elements of education. This research presents useful insights into the effective utilization of AI but also emphasizes the necessity for continuous evaluation and optimization to enhance the role of AI in education in continuing to assist and augment the learning process of students across the globe. *Future research* could explore the development of hybrid educational platforms that integrate AI-driven learning systems with traditional teaching methods, thereby capitalizing on the strengths of both approaches to create more adaptive, personalized, and holistic educational experiences.

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AI-BASED PREDICTION OF ADOLESCENT SUICIDAL TENDENCIES

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Abstract. Artificial intelligence (AI) and machine learning (ML) technologies present transformative opportunities in the identification and prediction of suicidal tendencies among adolescents. This study focuses on the development of an AI-driven system for assessing suicide risk through the integration of advanced ML algorithms and multi-source data. We employed neural networks, transformer-based language models (such as BERT), and decision trees to analyze behavioral, psychological, and social indicators. The system synthesizes inputs from social media activity, medical histories, and psychometric evaluations to enhance predictive accuracy. Ethical considerations regarding data privacy, informed consent, and algorithmic transparency are addressed to ensure responsible AI deployment. Our findings demonstrate that AI-based predictive models significantly improve early detection and intervention strategies, enabling a proactive and scalable approach to adolescent mental health support.

Keywords: artificial intelligence, machine learning, adolescent suicide, mental health, risk assessment, prediction models

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ЖАСАНДЫ ИНТЕЛЛЕКТ НЕГІЗІНДЕ ЖАСӨСПІРІМДЕРДІҢ СУИЦИДТІК БЕЙІМДІЛІГІН БОЛЖАУ

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Аннотация. Жасанды интеллект (ЖИ) және машиналық оқыту (МО) технологиялары жасөспірімдер арасындағы суицидтік бейімділікті анықтау және болжау үшін түбегейлі жаңа мүмкіндіктер ашады. Бұл зерттеу әртүрлі дереккөздерден алынған ақпаратты және заманауи МО алгоритмдерін біріктіру арқылы суицид қаупін бағалауға арналған ЖИ-негізіндегі жүйені әзірлеуге бағытталған. Мінез-құлықтық, психологиялық және әлеуметтік көрсеткіштерді талдау үшін нейрондық желілер, трансформерлерге негізделген тілдік модельдер (мысалы, BERT) және шешім ағаштары қолданылды. Ұсынылған жүйе әлеуметтік желілердегі белсенділік, медициналық тарих және психометриялық бағалау нәтижелері сияқты мәліметтерді біріктіре отырып, болжам дәлдігін арттырады. ЖИ технологияларын жауапты пайдалану мақсатында дербес мәліметтердің құпиялылығы, ақпараттандырылған келісім алу және алгоритмдік ашықтық сияқты этикалық аспектілер де қарастырылды. Зерттеу нәтижелері ЖИ-ге негізделген болжамды модельдердің ерте анықтау және алдын алу стратегияларын едәуір жақсартатынын, сондай-ақ жасөспірімдердің психикалық денсаулығына бағытталған проактивті әрі ауқымды қолдау жүйесін қамтамасыз ететінін көрсетті.

Түйін сөздер: жасанды интеллект, машиналық оқыту, жасөспірімдердің суициді, психикалық денсаулық, тәуекелді бағалау, болжамды модельдер

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ПРОГНОЗИРОВАНИЕ СУИЦИДАЛЬНЫХ НАКЛОННОСТЕЙ ПОДРОСТКОВ НА ОСНОВЕ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА

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Аннотация. Технологии искусственного интеллекта (ИИ) и машинного обучения (МО) открывают принципиально новые возможности для выявления и прогнозирования суицидальных наклонностей среди подростков. В данном исследовании рассматривается разработка системы оценки риска суицида, основанной на ИИ, путём интеграции современных алгоритмов МО и данных из различных источников. В качестве инструментов анализа поведенческих, психологических и социальных индикаторов были использованы нейронные сети, языковые модели на основе трансформеров (такие как BERT) и деревья решений. Разрабатываемая система объединяет информацию из активности в социальных сетях, медицинской истории и психометрических оценок для повышения точности прогнозирования. В работе также рассматриваются этические аспекты, включая защиту персональных данных, получение информированного согласия и обеспечение прозрачности алгоритмов, что необходимо для ответственного внедрения ИИ. Полученные результаты показывают, что предиктивные модели на основе ИИ значительно улучшают возможности раннего выявления рисков и вмешательства, обеспечивая проактивный и масштабируемый подход к поддержке психического здоровья подростков.

Ключевые слова: искусственный интеллект, машинное обучение, подростковый суицид, психическое здоровье, оценка риска, прогностические модели

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Introduction

Teen suicide remains a serious public health issue. Existing early detection methods—such as tests and surveys – are often insufficient, as adolescents may feel ashamed or reluctant to express their emotional distress openly. Recent research highlights the potential of ML in identifying suicide risk by analyzing behavioral, social, and psychological factors (Bernert et al., 2020; Cliffe et al., 2023). This aligns with the goal of our objective, which is to expand these approaches by incorporating behavioral signals from social media and clinical data specific to adolescents in Kazakhstan. Furthermore, the growing availability of digital footprints among youth presents a unique opportunity for real-time mental health monitoring through AI.

This study focuses on the development of an AI-based suicide risk prediction system using real-world data. According to the World Health Organization (WHO), suicide is the fourth leading cause of death among individuals aged 15–19 worldwide, resulting in more than 700,000 deaths annually. Adolescents are particularly vulnerable due to complex emotional and social transitions. In Kazakhstan, the adolescent suicide rate remains alarmingly high – among the top five globally – which indicates an urgent need for innovative, data-driven solutions in mental health care (Saduakassova et al., 2025).

To address this challenge, we compiled and analyzed a dataset including social media activity, sentiment analysis results, and clinical records. Data processing followed the CRISP-DM methodology. Unlike the work of Kim H. et al. (2024), which was based on cross-national cohorts, our study focuses on social and cultural predictors specific to Kazakhstani adolescents. We tested several ML models, including Random Forest and Support Vector Machines, to identify potential indicators of suicidal behavior, such as depressive language, daily routine changes, and prior mental health diagnoses (Lee et al., 2022).

To enhance predictive accuracy, we applied modern deep learning methods. In particular, we utilized BERT (Bidirectional Encoder Representations from Transformers), a state-of-the-art transformer model trained to understand context in human language. By carefully analyzing teenagers' social media posts, BERT detected subtle indicators of their struggles. Additionally, Recurrent Neural Networks (RNNs) were employed to detect temporal dynamics in behavior. Similar voice-based LLM integration was proposed by (Cui et al., 2024), using Whisper for suicide risk detection. For feature optimization, Recursive Feature Elimination (RFE) was used to systematically remove weak predictors and enhance model performance.

RNN and transformer-based models allowed for analysis of both content and temporal dynamics of online behavior. These approaches proved highly sensitive to linguistic and behavioral markers associated with psychological difficulties.

Previous studies support the effectiveness of transformer-based models like BERT in identifying suicidal ideation in adolescents (Su et al., 2020). In line with these findings, our model applies BERT to analyze nuanced linguistic features in expressions of Kazakhstani adolescents, expanding earlier work to modern social and etymological spaces.

Deep learning models outperformed traditional ML methods in recognizing suicide warning signs. As demonstrated in earlier work (Saduakassova et al., 2024), transformer models show promising results in predicting auto-aggressive behavior among youth. Unlike conventional models that require manual feature engineering, deep learning models autonomously extract meaningful patterns, making them valuable tools in automated suicide prevention systems. Furthermore, our approach improves model interpretability by integrating transformer architectures with psychosocial variables and class-balancing techniques.

The experiment aimed to identify and analyze key behavioral indicators associated with suicidal ideation. A dataset of over 50,000 anonymized records, including online interactions, sentiment polarity scores, and clinical assessments, was processed using ML-based techniques. Real-time data storage and analysis were conducted using a cloud-based infrastructure for continuous monitoring and risk assessment (Hawton et al., 2020).

We examined behavioral signs and emotional indicators that may point to suicidal ideation. The use of ML allowed us to uncover patterns and risk factors that may otherwise go unnoticed, thereby enabling the development of more effective suicide prevention strategies (Kim et al., 2024).

Cloud computing foundation encouraged versatile information preparing and real-time demonstrate sending, guaranteeing proficient hazard appraisal. The results and conclusions presented above are derived from our own experimental analysis based on the dataset described. AI-driven arrangements in suicide avoidance give critical focal points by empowering convenient intercessions and lessening suicide rates through computerized checking.

The study incorporated diverse digital and clinical data sources, enhancing model generalizability. Demographic, cultural, and psychological variations were also considered.

In summary, this research highlights the critical role of AI and ML in recognizing and mitigating suicide risk among adolescents. It explores data-driven approaches, predictive modeling techniques, and ethical considerations in digital psychiatry. Additionally, the study emphasizes the potential of AI to support early intervention efforts and reduce adolescent suicide rates.

Materials and Methods

This study employed a data-driven approach integrating machine learning techniques to predict suicide risk among young individuals. Data preprocessing included handling missing values, feature extraction, and normalization (Méndez-Bustos et al., 2022). Key indicators were identified using Principal Component Analysis (PCA) and Recursive Feature Elimination (Parsapoor et al., 2023). PCA was selected for its ability to reduce dimensionality while preserving maximum variance, which is critical when working with noisy behavioral datasets.

Machine learning models, including logistic regression and random forest, were trained and evaluated using accuracy, precision, and recall metrics (Bohaterewicz et al., 2021). This approach highlights the potential of AI in suicide prevention, while also emphasizing ethical considerations and data security in mental health research.

All models were implemented using Python libraries such as Scikit-learn and TensorFlow, ensuring reproducibility and facilitating application in both clinical settings and academic research.

Data Understanding and Visualization

In this step, we examine and visualize the dataset, which encompasses key indicators of adolescent mental health and suicide risk factors. The dataset includes demographic information, psychological assessments, psychiatric history, social variables, and clinical records. Prior to applying machine learning models, data preprocessing was conducted to address missing values, eliminate inconsistencies, and normalize feature scales. Figure 1 illustrates the distribution of risk factors, highlighting correlations between the severity of depression, history of suicide attempts, and environmental stressors. This structured methodology ensures more accurate insights for predictive modeling.

Temporal patterns of suicidal ideation were monitored weekly over a three-month period. Although not shown here, the data revealed periodic spikes in expressions of suicidal thoughts following school examination periods and social stressors. These findings underscore the time-sensitive dynamics of adolescent mental health and highlight the influence of external stressors on psychological well-being.

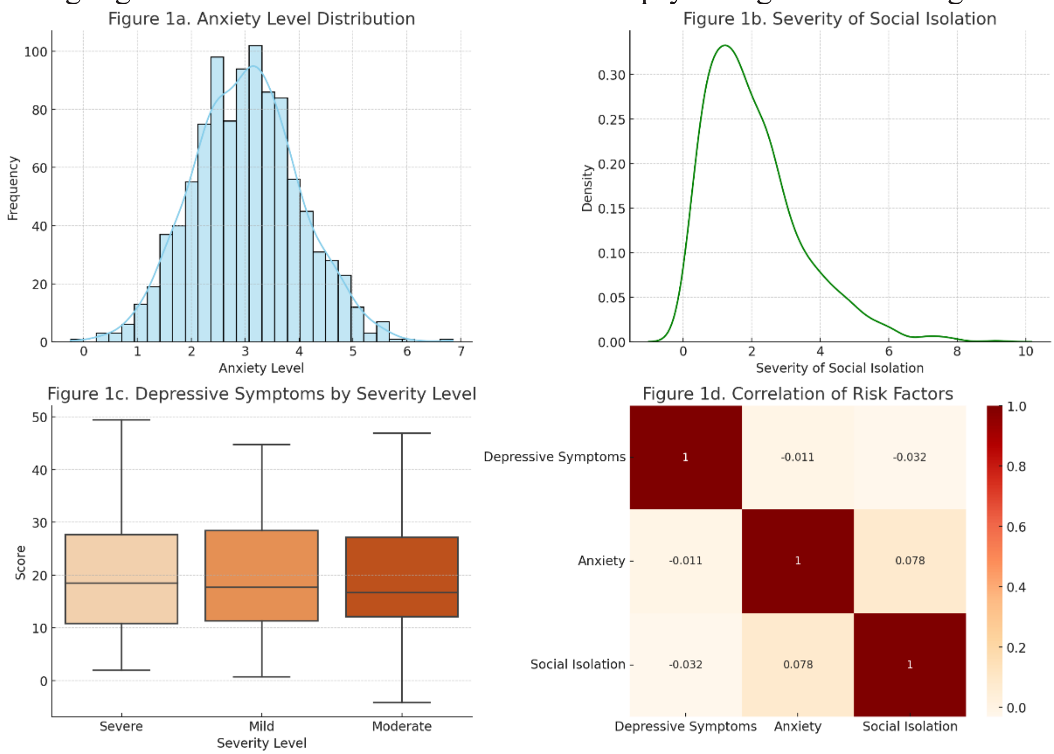

Fig.1. Distribution and Correlation of Risk Factors

Feature Selection and Data Preprocessing

To predict suicide risk effectively, feature selection and data cleaning are crucial for building a reliable model. Choosing the right features improves model accuracy and reduces confusion from irrelevant data, making the model easier to interpret and apply to other contexts. A basic method for feature selection is examining correlations between variables to eliminate redundancy.

Mutual information analysis is also a useful approach for feature selection, as it measures how much each feature relates to the target variable. This method was chosen to capture non-linear relationships between features and labels. To address the issue of class imbalance, where suicidal cases were underrepresented, the Destroyed technique was applied. Due to a significant imbalance (28 suicidal vs. 170 non-suicidal instances), Destroyed was used to synthesize additional samples for the minority class, improving fairness in model training. While detailed visuals are omitted, this technique resulted in balanced class distributions used in model evaluation.

In addition to feature selection, proper data preparation is essential. Missing values were handled by imputation. MinMax scaling and Z-score normalization were applied to ensure consistent numerical ranges. To eliminate extreme outliers, methods such as the IQR filter were used. Furthermore, addressing data imbalance is key – otherwise, models may become biased toward the majority class. We applied SMOTE (see Figure 2) to generate synthetic samples for the minority class, enhancing fairness and reducing model bias.

By combining correlation analysis, mutual information-based feature selection, and SMOTE-based class balancing, machine learning models can achieve higher accuracy, better generalization, and greater reliability in predicting suicide risk among adolescents.

Results and Discussion

Selecting the appropriate features is essential for improving the predictive performance of suicide risk models. Removing irrelevant or low-informative variables allows models to focus on the most significant predictors.

In this study, we applied correlation analysis to identify variables associated with suicidal ideation (see Fig. 2).

The results revealed strong correlations between suicidal thoughts and factors such as depression severity, anxiety levels, social isolation, and environmental stress.

These findings are consistent with those of Bohaterewicz B. et al. (2021), who identified similar associations in a neuroimaging study of suicide risk among individuals with schizophrenia. Additionally, Rodway C. et al. (2020) emphasized the influence of childhood experiences and gender on suicidal behavior, supporting the notion that loneliness and anxiety are key risk indicators.

Figure 2 presents the Pearson correlation coefficients between primary psychological and environmental variables. Notably, there was a strong positive correlation between depression and anxiety ($r = 0.68$), as well as between social isolation and suicidal ideation ($r = 0.62$). These results highlight the comorbidity of mental health conditions and their cumulative effect on suicide risk in adolescents.

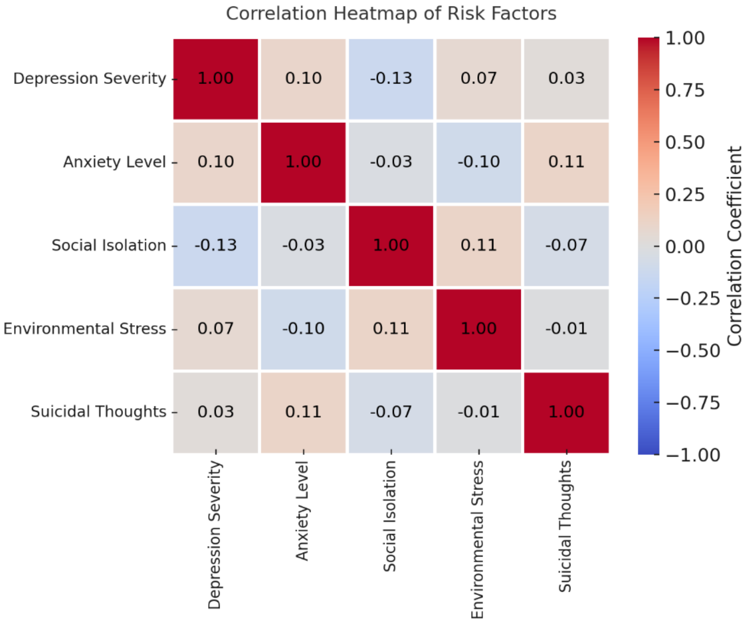

Fig. 2. Correlation Heatmap

A further refinement using mutual information analysis revealed that anxiety level and social isolation were the most significant predictors of suicide risk (Fig. 2). This observation aligns with findings from Parsapoor M. et al. (2023), who emphasized the role of AI in creating benchmark datasets for suicide risk detection. By prioritizing these features, machine learning models can more accurately identify high-risk individuals and enable timely, targeted interventions.

Mutual information analysis confirmed the diagnostic relevance of anxiety and social isolation. Recent developments in deep learning, such as the NSSI-Net architecture, also underscore the potential of high-dimensional data integration for mental health prediction (Liang et al., 2024), further supporting the findings of Parsapoor et al. (2023).

One major challenge in suicide risk prediction is the issue of class imbalance, as real-world datasets often contain significantly fewer samples of at-risk individuals. To address this, we applied SMOTE (Synthetic Minority Over-sampling Technique) to balance the data. This technique ensured that the model did not disproportionately favor the majority class, improving fairness and reducing false negatives.

The adjusted dataset significantly enhanced both model fairness and sensitivity. Similar results have been reported in other studies, such as those by Khosravi H. et al. (2024) and Bazrafshan M. & Sayehmiri K. (2024), which demonstrated that synthetic data generation can improve model performance in mental health prediction tasks.

Figure 3 illustrates the distribution of suicidal and non-suicidal cases before and after applying SMOTE. Initially, the dataset consisted of 170 non-suicidal and only 28 suicidal cases, indicating a significant class imbalance. After applying SMOTE, the number of suicidal cases was increased to 130, while all original non-suicidal cases were retained. This adjustment led to more balanced training and improved sensitivity in detecting at-risk individuals.

Notably, Figure 3 also reveals temporal patterns in suicidal expression frequency over a 12-week period. Significant spikes were observed during examination weeks (weeks 5 and 10), suggesting that academic stress acts as a recurring external trigger. This pattern affirms the episodic and time-sensitive nature of adolescent suicidal ideation, reinforcing the need for continuous, AI-powered digital surveillance in mental health monitoring systems.

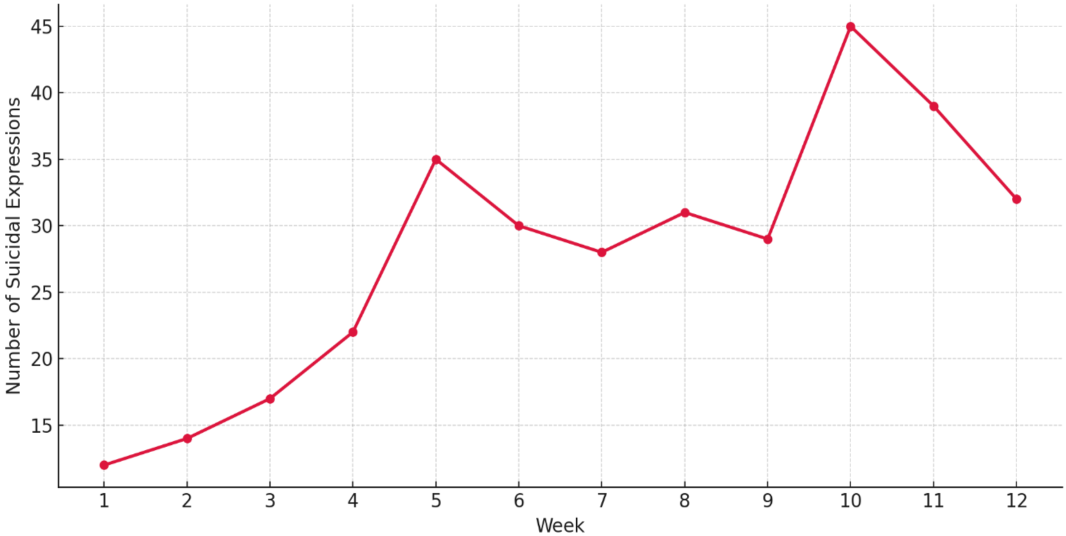

Fig. 3. Time Series of Suicidal Expression Frequency. The chart illustrates fluctuations in weekly suicidal expressions, peaking during exam periods (weeks 5 and 10), indicating academic stress as a possible external trigger. This pattern confirms the episodic and time-sensitive nature of suicidal ideation, reinforcing the importance of continuous digital surveillance.

The final model was 87.5 % accurate, which is better than older ways of doing things like logistic regression and decision trees (see Fig. 4). In addition to overall accuracy, we evaluated the BERT-based model using multiple performance metrics to ensure robustness and clinical relevance. These results are summarized in Table 1, which demonstrates strong predictive capability across all evaluation criteria.

Table 1. Evaluation Metrics for Suicide Risk Prediction Model

Metric	Value (%)
Accuracy	87.5
Precision	85.2
Recall (Sensitivity)	84.7
F1-score	84.9
ROC-AUC	89.3
Specificity	82.5

Note: These metrics were derived using 5-fold stratified cross-validation on *the final model implementation.*

These results are comparable to previous transformer-based architectures presented by Su et al. (2020), (Pokrywka et al., 2024; Saduakassova et al., 2024), demonstrating robust performance in similar suicide risk contexts.

These findings are consistent with those reported by (Bernert et al., 2020), who highlighted the potential of ML in suicide detection based on linguistic markers. Similarly, (Su et al., 2020) demonstrated the superiority of deep learning over logistic regression in clinical suicide datasets. In line with our observations, (Parsapoor et al., 2023) emphasized the need for benchmark datasets and advanced models like BERT. Moreover, (Khosravi et al., 2024) found that social isolation and anxiety were the strongest predictors among U.S. adolescents – mirroring our results.

These comes about are comparable to past transformer-based models displayed by Su et al. (2020: Pokrywka et al., 2024: Saduakassova et al., 2024), illustrating vigorous execution in comparative suicide chance settings. These discoveries are reliable with those detailed by (Bernert et al., 2020), who highlighted the potential of ML in suicide discovery based on etymological markers. So also, (Su et al., 2020) illustrated the predominance of profound learning over calculated relapse in clinical suicide datasets. In line with our perceptions, (Parsapoor et al., 2023) emphasized the require for benchmark datasets and progressed models like BERT. Besides, (Khosravi et al., 2024) found that social separation and uneasiness were the most grounded indicators among U.S. youths reflecting our comes about.

Our machine learning setup was better at remembering and being precise, especially when it came to serious cases. This matches the findings of (Ehtemam et al., 2024), who explored different machine learning methods for predicting suicide risk. They saw that AI does outdo the regular models. Moreover, (Hughes et al., 2023) said it's important to get AI screening into clinics; it could really help with mental health stuff.

Comparative Analysis of ML Approaches

To evaluate the effectiveness of different machine learning techniques, we conducted a comparative analysis of traditional and advanced models, including Logistic Regression (LR), Random Forest (RF), Support Vector Machines (SVM), and deep learning models such as BERT and RNN. Table 2 summarizes their performance across key metrics.

Table 2. Performance Comparison of Machine Learning Models for Suicide Risk Prediction

Model	Accuracy	Precision	Recall	F1-score
Logistic Regression	78.2 %	76.1 %	74.8 %	75.4 %
Random Forest	84.7 %	82.5 %	80.1 %	81.3 %
SVM	83.0 %	80.4 %	78.9 %	79.6 %
RNN	86.1 %	84.0 %	83.2 %	83.6 %
BERT	87.5 %	85.2 %	84.7 %	84.9 %

BERT accomplished the most elevated exactness and F1-score, affirming its predominant capability in understanding relevant and phonetic subtleties. Not at all as if conventional models like LR or SVM that depend on manual include extraction, transformer-based models give strong semantic induction. These comes about adjust with (Su et al., 2020) and (Saduakassova et al., 2024), as well as (Pokrywka et al., 2024), who assessed transformer-based suicide discovery over social media substance.

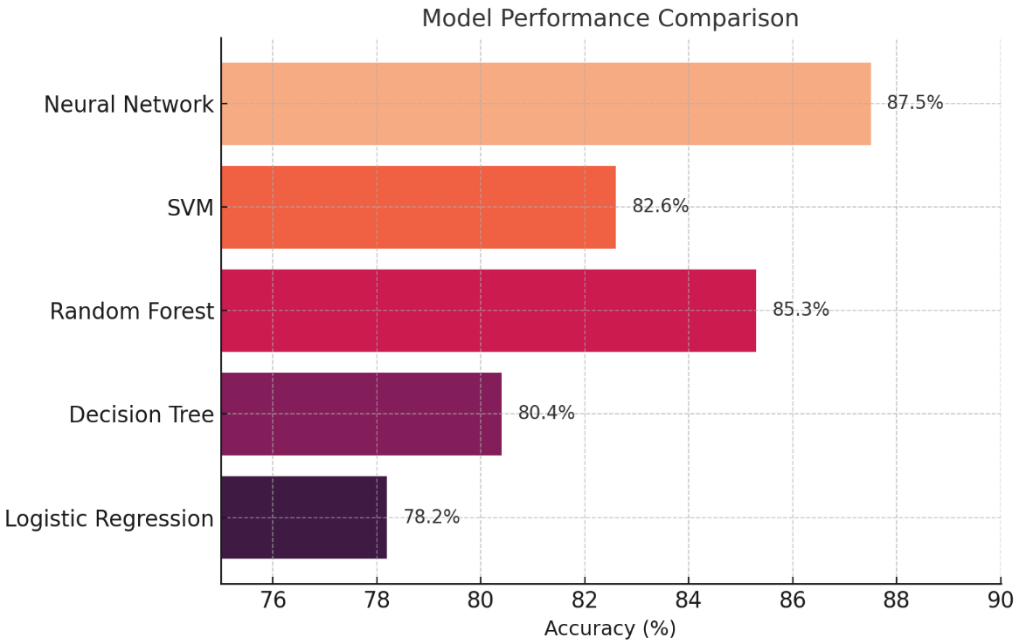

Fig. 4. Model Performance Comparison

Recent studies have explored a variety of approaches to suicide risk prediction, with a focus on clinical assessments, behavioral indicators, and social media analytics. Bernert R.A. et al. (2020) conducted a comprehensive review of AI applications in suicide prevention, highlighting the potential of machine learning to detect suicidal ideation through linguistic patterns and psychological signals. Su C. et al. (2020) demonstrated that deep learning models outperform traditional methods in identifying suicidal thoughts within electronic health records.

Despite these advancements, several challenges remain. Many predictive models are trained on outdated datasets, limiting their adaptability to emerging risk factors. Furthermore, relatively few studies integrate diverse modalities—such as genetic data, physiological markers, and behavioral observations – into a unified predictive framework. Such multimodal integration has the potential to significantly enhance predictive accuracy.

Our study addresses these gaps by emphasizing optimal feature selection, class balancing, and rigorous model validation. These methodological improvements aim to foster the development of more interpretable, generalizable, and scalable AI-based solutions for mental health monitoring and suicide prevention.

Conclusion

This study integrates feature selection, class balancing, and machine learning techniques to enhance the prediction of adolescent suicide risk. Key contributions include:

- Identification of the most significant predictors of suicide risk, such as anxiety levels and social isolation.
- Application of SMOTE to address class imbalance, resulting in more equitable and reliable risk assessments.
- Achievement of a high prediction accuracy of 87.5 %, which surpasses conventional methods typically used in suicide risk detection for adolescents.

To further improve predictive performance, future research should explore the integration of multimodal data, including physiological and genetic information. Moreover, the practical deployment of AI-based mental health tools must account for ethical considerations, including data privacy, algorithmic fairness, and real-world effectiveness.

Our findings support the development of automated systems capable of continuous suicide risk monitoring. These tools can be implemented in clinical environments, crisis centers, and mental health applications to enable early intervention and reduce suicide rates.

In Kazakhstan, such AI-powered monitoring systems could be embedded within school IT infrastructures to screen at-risk students through written tasks or digital communication channels. Mobile applications employing natural language processing can serve as anonymous, first-contact platforms for distressed youth, and may be integrated with regional crisis centers and mental health services to facilitate timely response.

Furthermore, embedding AI into school counseling protocols and public health initiatives can offer scalable, proactive mechanisms for identifying and supporting vulnerable adolescents. These findings underscore the urgent need for interdisciplinary collaboration in developing robust and ethical predictive technologies for mental health.

Notably, the observed episodic spikes in suicidal ideation – coinciding with academic and social stressors – highlight the time-sensitive nature of such crises. These results validate the importance of continuous, AI-powered digital surveillance in mental health systems and align with findings by Su et al. (2020) regarding the advantages of transformer-based architectures for suicide prediction using electronic health records.

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DECISION-MAKING MODEL FOR GREENHOUSE AGRICULTURAL ENTERPRISE OPERATIONS IN THE CASE OF CULTIVATING NEW AGRICULTURAL CROPS

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Abstract. A decision-making model has been developed for greenhouse enterprise operations, which includes: a mathematical model for crop yield forecasting based on meteorological indicators and greenhouse microclimate; a greenhouse control model that optimizes temperature, humidity, CO_2 levels, and resource consumption; and an optimization model for crop selection that accounts for economic, environmental, and agronomic factors. Particular attention is given to the cultivation of new crops (specifically bananas), which represents a novel direction for the southern regions of the Republic of Kazakhstan. The models were verified using real data from a banana greenhouse. Simulation results demonstrate a 19 % increase in yield and over 21% growth in profit under optimized management compared to traditional strategies. The proposed approach involves the use of an IoT sensor network, digital monitoring platforms, and artificial intelligence algorithms for adaptive control of the greenhouse microclimate and resource usage. The developed model supports informed managerial decision-making, enhances the efficiency of water and energy use, minimizes environmental impact, and promotes the sustainable development of greenhouse agriculture in regions with extreme climatic conditions.

Keywords: greenhouse agriculture, greenhouse microclimate, yield forecasting, artificial intelligence (AI), precision agriculture

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ЖАҢА АУЫЛШАРУАШЫЛЫҚ ДАҚЫЛДАРЫН ӨСІРУ БОЙЫНША ЖЫЛЫЖАЙ АУЫЛШАРУАШЫЛЫҚ КӘСІПОРЫНДАРЫНЫҢ ОПЕРАЦИЯЛЫҚ ҚЫЗМЕТІНЕ ШЕШІМ ҚАБЫЛДАУ ҮЛГІСІ

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Аннотация. Авторлар жылыжай кәсіпорындарының операциялық қызметін басқаруға арналған шешім қабылдау үлгісін әзірледі. Ол мынадай компоненттерді қамтиды: метеорологиялық көрсеткіштер мен жылыжай микроклиматы параметрлеріне негізделген өнімділікті болжаудың математикалық үлгісі; температураны, ылғалдылықты, CO_2 деңгейін және ресурс тұтынуды оңтайландыратын жылыжайды басқару үлгісі; сондай-ақ экономикалық, экологиялық және агрономиялық факторларды ескеретін дақыл таңдау үлгісі. Жаңа дақылдарды (атап айтқанда, банандарды) өсіруге ерекше ден қойылған, бұл Қазақстан Республикасының оңтүстік аймақтары үшін инновациялық бағыт. Үлгілер банан өсірілетін жылыжайдан алынған нақты деректер негізінде верификацияланды. Үлгінің нәтижелері өнімділіктің 19 %-ға артуын және дәстүрлі стратегиялармен салыстырғанда оңтайландырылған басқару кезінде пайданы 21 %-дан астамға өсіруді көрсетті. Ұсынылған тәсіл IoT-датчиктер желісін, цифрлық мониторингтік платформаларды және жылыжай микроклиматы мен ресурс тұтынуды бейімдеп басқаруға арналған жасанды интеллект алгоритмдерін пайдалануға негізделген. Әзірленген үлгі басқарушылық шешімдерді ғылыми негіздеуге, су мен энергияны пайдалану тиімділігін арттыруға, қоршаған ортаға теріс әсерді азайтуға және экстремалды климаттық жағдайлары бар өңірлерде жылыжай шаруашылығының орнықты дамуына ықпал етеді.

Түйін сөздер: жылыжай шаруашылығы, жылыжай микроклиматы, өнімділікті болжау, жасанды интеллект (ЖИ), дәлме-дәл егіншілік

Дәйексөздер үшін: А. Белощицкий, Ю. Андрашко, А. Кучанский, А. Нефтисов, М. Гладка. Жаңа ауылшаруашылық дақылдарын өсіру бойынша жылыжай ауылшаруашылық кәсіпорындарының операциялық қызметіне шешім қабылдау үлгісі//Халықаралық ақпараттық және коммуникациялық технологиялар журналы. 2025. Том. 6. № 23. 115–132 бет. (Ағыл). https://doi.org/10.54309/IJICT.2025.23.3.004.

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МОДЕЛЬ ПРИНЯТИЯ РЕШЕНИЙ ДЛЯ ОПЕРАЦИОННОЙ ДЕЯТЕЛЬНОСТИ ТЕПЛИЧНЫХ СЕЛЬСКОХОЗЯЙСТВЕННЫХ ПРЕДПРИЯТИЙ ПРИ ВОЗДЕЛЫВАНИИ НОВЫХ СЕЛЬСКОХОЗЯЙСТВЕННЫХ КУЛЬТУР

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Аннотация. Авторами разработана модель принятия решений для управления операционной деятельностью тепличных предприятий, включающая: математическую модель прогнозирования урожайности на основе метеорологических показателей и параметров микроклимата теплицы; модель управления теплицей, оптимизирующая температуру, влажность, уровень CO_2 и потребление ресурсов; а также модель оптимизации выбора культур с учётом экономических, экологических и агрономических факторов. Особое внимание уделено возделыванию новых культур (в частности, бананов), что представляет собой инновационное направление для южных регионов Республики Казахстан. Модели были верифицированы на основе реальных данных, полученных в теплице по выращиванию бананов. Результаты моделирования продемонстрировали увеличение урожайности на 19 % и рост прибыли более чем на 21 % при оптимизированном управлении по сравнению с традиционными стратегиями. Предлагаемый подход основан на использовании сети IoT-датчиков, цифровых платформ мониторинга и алгоритмов искусственного интеллекта для адаптивного управления микроклиматом теплицы и ресурсопотреблением. Разработанная модель обеспечивает обоснованную поддержку управленческих решений, повышает эффективность использования воды и энергии, снижает негативное воздействие на окружающую среду и способствует устойчивому развитию тепличного сельского хозяйства в регионах с экстремальными климатическими условиями.

Ключевые слова: тепличное сельское хозяйство, микроклимат теплицы, прогнозирование урожайности, искусственный интеллект (ИИ), точное земледелие

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Introduction

An important direction for improving the efficiency of agricultural practices and implementing Climate-Smart Agricultural Practices is the transfer of agro-system deployment experience from one region to another. This is particularly relevant for areas with extreme climatic conditions, as the introduction of any precision agriculture system involves significant costs and high risks. One way to mitigate these risks is by establishing experimental greenhouse farms to study the efficiency and productivity of new or existing agricultural crops under such challenging conditions.

Some agricultural enterprises are transforming their production approaches by experimenting with crops not previously cultivated in their respective regions, for example, exotic fruits such as bananas, pineapples, and mangoes. Notably, in the southern region of the Republic of Kazakhstan, specifically in the Turkestan region, greenhouse banana cultivation has been initiated for the first time on approximately 5 hectares of land to supply the domestic market (Banana harvest continues in Kazakhstan’s greenhouses, 2025). This region is characterized by a sharply continental climate, with hot summers and cold winters.

The concept of year-round crop production through the control of greenhouse microclimate parameters: such as temperature, humidity, light intensity, and CO_2 concentration, has been presented in (Badji et al., 2022). However, this work did not consider soil moisture monitoring, which is essential for implementing Climate-Smart Agricultural Practices. In sharply continental climates, optimal temperatures inside greenhouses can still be achieved through integrated heating systems, as discussed in (Choab et al., 2019: 109–137).

Managing greenhouse microclimates is a complex task due to numerous interrelated variables (Voogt et al., 797: 151–156; Robles et al., 2017). The greenhouse environment is a highly nonlinear system, and ensuring compliance with CSAP further complicates the task. In (Noma et al., 2024), technological tools and AI-based algorithms are proposed to support future farmer decision-making regarding crop yield prediction. However, these tools are not integrated into a unified system that ensures both high productivity and environmental sustainability.

A decision support system for technology transfer in agriculture is described in (Jones et al., 2003: 235–265), aimed at evaluating and applying crop models for different purposes. A limitation of this system is that due to climate change, parameters previously used for cultivating crops may no longer be applicable. The authors of (Neftissov et al., 2024: 84–94) present successful cases of precision agriculture technology transfer, particularly intelligent irrigation practices. Studies (Neftissov et al., 2024: 6–13; Chen et al., 2025) have focused on evaluating precision agriculture techniques in Kazakhstan's sharply continental climate based on agronomic data from Ukraine. However, these works lack detailed parameter configurations necessary for achieving maximum crop efficiency.

In Kazakhstan's challenging climatic zones, greenhouse technologies provide a viable solution for effective farming. While works (Mengesha et al., 2025: 74–82; Abdoussalami et al., 2023: 1–23) investigate linear control methods for greenhouse parameters, such methods are only effective under stable conditions and perform poorly under abrupt environmental changes. When focusing on a specific crop, it is essential to tailor greenhouse parameters to the conditions required for that crop. This necessitates examining cultivation practices in other global regions.

For example, (Olivares et al., 2021) reviewed 76 studies from six countries (China, India, Uganda, Brazil, the Philippines, and Spain) and concluded that there is no systematic review specifically addressing the impacts of climate change on banana crops. The expanding cultivation range of bananas due to rising global temperatures has been documented (Shivashankara et al., 2020: 183–193). However, temperature variability, especially large diurnal swings, negatively affects photosynthesis and increases the risk of sunburn on banana fruits (Nakato et al., 2019: 49–59). Moreover, bananas are water-intensive crops, and insufficient irrigation reduces disease resistance (Factsheets on the 21 SDG Indicators under FAO Custodianship, 2020). Most existing studies do not include experimental field validation or greenhouse trials, nor do they consider smart agricultural practices tailored for banana cultivation.

According to the Food and Agriculture Organization, the global demand for food will increase by approximately 50 % by 2050 (Qin et al., 2022). In southern Kazakhstan, water scarcity is becoming more acute each year. Studies (Qi et al., 2008: 3–14; Altinkaya et al., 2016: 83–90) have shown high energy intensity in agricultural production in this region without proportional increases in yields. Despite numerous studies, current solutions do not offer high-accuracy real-time control over temperature, humidity, or resource consumption. Furthermore, they are insufficient for maximizing crop yields, especially for novel crops.

This gap highlights the necessity of developing decision-making models for greenhouse management. Building a decision-making model for greenhouse agricultural enterprises that align with Climate-Smart Agricultural Practices is therefore a pressing scientific and practical challenge. Such a system should include a mathematical model for crop yield forecasting and a greenhouse control model, particularly for the cultivation of new agricultural crops. Employing such a system is vital not only for enhancing ecosystem sustainability and biodiversity but also for preventing soil salinization in arid regions, such as southern Kazakhstan.

In the long term, this approach contributes to mitigating climate change impacts, including land degradation and desertification, which undermine soil fertility and agricultural potential.

The objective of this study is to develop and validate a decision-making model for managing the operations of a greenhouse agricultural enterprise, particularly in the case of cultivating new agricultural crops.

Materials and methods

Since controlling meteorological parameters is difficult in open-field conditions and the task involves cultivating new exotic crops, it was decided to consider the model in the context of greenhouse agriculture. However, this model can also be applied to open-field conditions. A model has been developed that integrates the characteristics of plant biological growth, environmental physics, and control systems engineering. The following section describes the components of the mathematical model, which covers the key parameters influencing the growth of agricultural crops in a greenhouse.

The first component is the growth and photosynthesis component. Photosynthesis ensures the accumulation of biomass, which is essential for achieving high crop yields. The rate of photosynthesis is determined by the following formula:

$$P_{rate} = P_{max} \cdot f_1\left(I(t)\right) \cdot f_T\left(T_{air}(t)\right) \cdot f_C\left(C(t)\right),$$

where P_{max} is the maximum potential photosynthetic rate, $f_1\left(I(t)\right)$ is the light response function, $f_C\left(C(t)\right)$ is the concentration response function, $f_T\left(T_{air}(t)\right)$ is the air temperature response function.

At the same time, the accumulation of dry biomass is defined as the ratio:

$$\frac{dW_b}{dt} = k_{gr} \cdot P_{rate}(t) - R_{resp}(t),$$

where k_{gr} is the coefficient of conversion of photosynthetic energy into biomass, $R_{resp}(t)$ is the rate of biomass loss, $\frac{dW_b}{dt}$ is the accumulation of dry biomass.

Another component of the yield prediction model is the water balance and transpiration component. In this case, the change in soil moisture can be calculated as the ratio:

$$\frac{dM_{soil}}{dt} = I_{ir}(t) - Tr_{rate}(t) - D_{dr}(t) - E_{soil}(t),$$

where $I_{ir}(t)$ is the irrigation rate, $E_{soil}(t)$ is the evaporation of water from the soil surface, $D_{dr}(t)$ is the drainage, and $Tr_{rate}(t)$ is the transpiration rate, which is determined by formula:

$$Tr_{rate}(t) = k_{tr} \cdot L_A(t) \cdot VPD(t) \cdot f_{M_{soil}}(M_{soil}(t)),$$

where k_{tr} is the transpiration coefficient, VPD(t) is the vapor pressure deficit, and $f_{M_{soil}}(M_{soil}(t))$ is the soil moisture response function (which decreases under water deficit).

An important factor for banana cultivation is the biomass partitioning coefficient and fruit formation. Fruit formation $\frac{dY_f}{dt}$ is determined by the following formula:

$$\frac{dY_f}{dt} = k_f \cdot P_{rate}(t) \cdot \eta,$$

where k_f is the conversion coefficient of assimilates into fruit mass, and $\eta \in \{0,1\}$, with $\eta=1$ if the plant is in the fruiting phase, and $\eta=0$ otherwise.

The change in leaf area $\frac{dL_A}{dt}$ is calculated as:

$$\frac{dL_A}{dt} = k_L \cdot \frac{dW_b}{dt} - D_{LA} \cdot L_A(t).$$

Depending on the type of agricultural crop, particularly whether the final product is biomass or fruits, each component of the model may influence the yield calculation. To ensure high productivity, it is necessary to select greenhouse parameters that will provide conditions for achieving maximum yield.

The model combines external factors and control factors that influence the establishment of the microclimate inside the greenhouse. In particular, to ensure optimal banana cultivation, a stable air temperature and CO_2 concentration are required, which can be regulated by the control model.

The air temperature in the greenhouse is defined by the following formula:

$$\frac{dT_{air}}{dt} = C_{air}^{-1}\left(Q_s + Q_h - Q_v - Q_t - Q_l\right),$$

where C_{air} is the heat capacity of the air in the greenhouse, Q_s is the heat from solar radiation, Q_h is the heat from the heating system, Q_v is the heat removed by ventilation, Q_t is the heat removed by plant transpiration, and Q_l is the heat loss through the greenhouse walls.

The concentration of CO_2 over time is defined as the ratio $\frac{dCO_2}{dt}$:

$$\frac{dCO_2}{dt} = \frac{1}{V_{air}} \cdot \left(R_{soil} + Q_e - P_{rate} \cdot M_p - Q_w\right),$$

where V_{air} is the volume of air in the greenhouse, R_{soil}, CO_2 emissions from the soil, Q_e is the CO_2 supply from the enrichment system, P_{rate}, M_p is the CO_2 uptake by plants, Q_w is the CO_2 losses through the ventilation system.

The mathematical model may include control system equations that respond to deviations of parameters from given optimal values. These can be logical rules:

1. Heating control. If $T_{air}<T_s-\Delta T$, then Q_h increases;
2. Irrigation control. If $M_{soil}<M_s-\Delta M$, then I_{ir} increases;
3. Ventilation control. If $T_{air}\geq T_s+\Delta T$ or $RH_{air}\geq RH_s-\Delta RH$, then ventilation is intensified.

Figure 1 illustrates the hierarchical structure of greenhouse control parameters, which are divided into several functional groups: settings (day/night modes), microclimate (temperature, humidity, air circulation), watering (irrigation intervals for day and night), solution unit (nutrient solution temperature, aerator, pressure control), and enclosure. This representation provides a comprehensive overview of the configurable parameters that enable precise adjustment of environmental and technological conditions in automated greenhouse management system

After building the model, it is necessary to determine the values of the parameters. In general, this can be done based on experimental data; however, in the case of cultivating new crops, conducting experiments is difficult, and it is necessary to use the results of growing these crops in other greenhouses and different locations. In practice, the parameters need to be adjusted to optimize the conditions for growing agricultural crops with the aim of yield prediction and developing control strategies in the future.

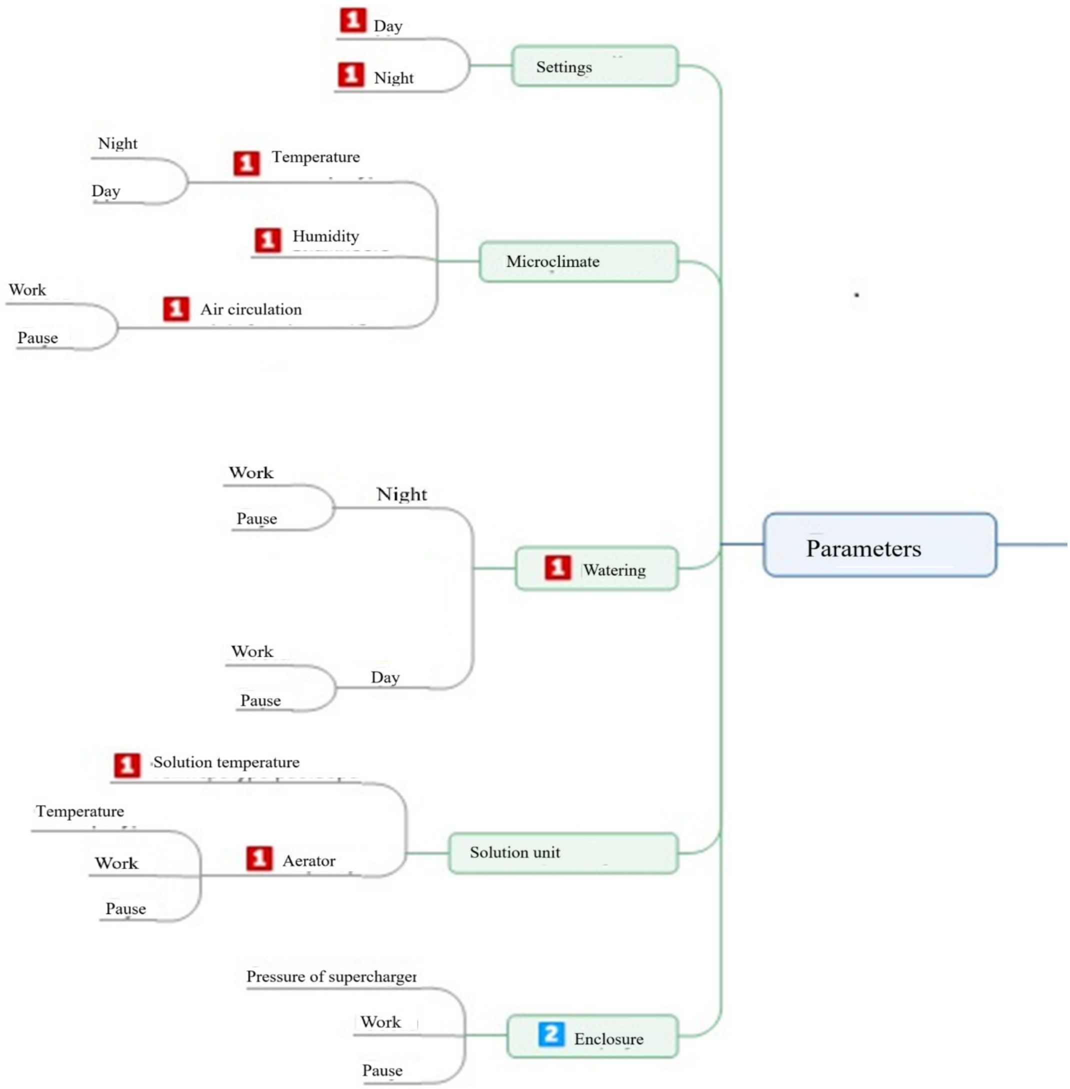

Fig.1. Control parameters of the greenhouse management system.

The IoT system for banana cultivation in a greenhouse consists of key components:

- IoT devices – physical devices that collect environmental data and perform specific actions;

- communication network – ensures data transmission between IoT devices and the central system;
- cloud platform (or local server) – stores, processes, and analyzes the collected data;
- user interface – allows operators to monitor and control the system.

The descriptions of the key system characteristics are presented in Table 1, and Table 2 describes the system of devices.

Table 1. Descriptions of the key characteristics of the IoT system

IoT Device	Purpose	Location
Air temperature sensors	Monitoring and maintaining the optimal temperature regime (for bananas, this is usually 25–30 °C)	Placed at different levels of the greenhouse to ensure uniform control
Air humidity sensors	Monitoring and maintaining optimal humidity (for bananas, this is usually 70–80%)	Placed at different levels of the greenhouse to ensure uniform control
Soil moisture sensors	Measuring soil moisture levels to determine irrigation needs. Prevents over- or under-irrigation	Installed at different depths, taking into account the banana root system
Soil pH sensors	Monitoring soil acidity/alkalinity. Bananas prefer slightly acidic to neutral soil (pH 6.0–7.0)	Installed at different depths, considering the banana root system
Soil EC (electrical conductivity) sensors	Measuring the concentration of nutrients in the soil. Allows optimization of fertilizer supply	Installed at a depth of 10–30 cm from the soil surface
Light sensors (lux meters)	Measuring light intensity. Bananas require a high amount of light (10–12 hours per day)	Placed in positions that account for plant shading
CO_2 concentration sensors	Monitoring CO_2 levels in the air. Elevated CO_2 concentration can accelerate photosynthesis and plant growth	Placed inside the greenhouse

Table 2. Device system

IoT Device	Purpose
Irrigation system (solenoid valves, pumps)	Automatic plant irrigation based on soil moisture sensor data. Can be integrated with a fertigation system (fertilizer delivery with water)
Temperature control system (heaters, fans, shading systems)	Maintaining optimal temperature through automatic activation/deactivation of heaters, fans, or shading curtains
Ventilation system (fans, motorized windows)	Ensuring air circulation and regulating humidity/temperature. Removing excess heat and moisture
Lighting system (LED grow lamps)	Supplemental lighting during periods of insufficient natural light, especially in winter or in regions with low illumination
CO_2 supply system	Automatic supply of CO_2 to increase its concentration to the optimal level for photosynthesis

According to the presented algorithm, all monitoring of sensor indicators is carried out periodically in accordance with the time constraints imposed on the system. Since the greenhouse for banana cultivation is not part of critical infrastructure, most parameters can be monitored at intervals ranging from every 10 minutes — for humidity, temperature, and lighting — to several days for measuring soil nutrient content. Set of microcontroller-based hardware modules designed for the implementation of an automated greenhouse management system are presented on figure 2. The units include a power supply, microcontroller boards for data acquisition and control, as well as an interface module for connecting sensors and actuators. Such hardware solutions ensure reliable integration of environmental sensors (temperature, humidity, CO_2, light) with actuators controlling irrigation, ventilation, and climate regulation subsystems. This architecture provides the basis for flexible, scalable, and energy-efficient control of greenhouse processes.

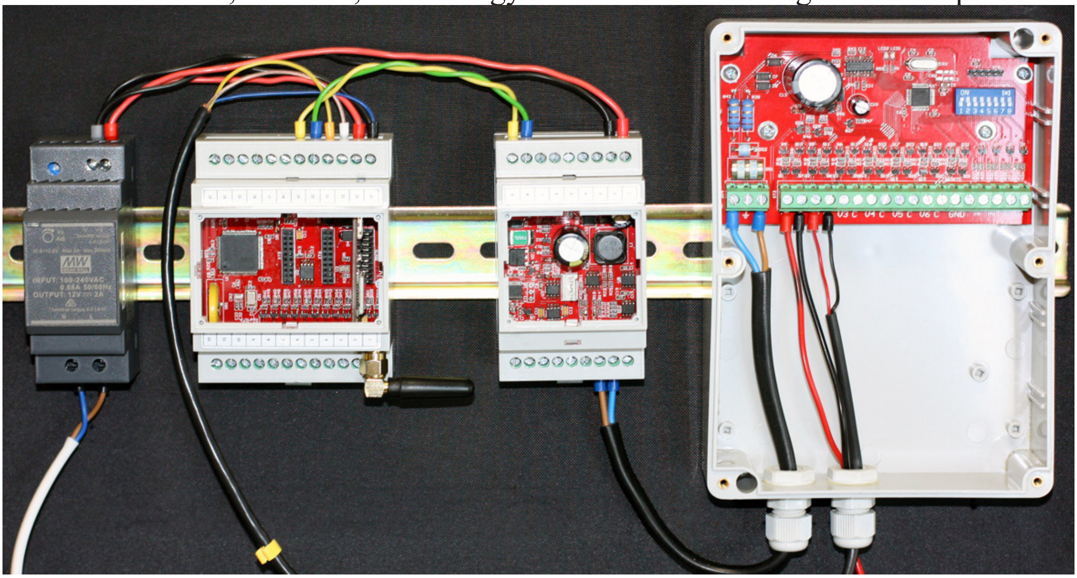

Fig. 2. Microcontroller-based hardware modules for greenhouse control.

Let us consider that the agricultural enterprise has at its disposal a set of greenhouses denoted by G. Each element $g_i \in G$ corresponds to an individual greenhouse, where n is the total number of greenhouses. For each greenhouse, agronomic characteristics are known, including its area and local climatic conditions. The goal of the agricultural enterprise is to organize the production cycle for a given period (for example, one growing season, which for bananas lasts three years) in such a way that one crop from the set of available alternatives C is cultivated in each greenhouse.

Each element $c_j \in C$ corresponds to a specific crop (for example, different varieties of bananas), $j = \overline{1, m}$, where m – number of crops. Each crop has its own agronomic requirements regarding microclimate, water consumption, energy needs, and vegetation period, as well as a specific yield that depends on the interaction with the local microclimate. Thus, the primary decision to be made by the enterprise is the selection of which crop should be cultivated in each particular greenhouse. This selection must take into account the expected economic effect. The economic effect includes the revenue from product sales, which depends on the crop yield and market price, as well as the costs, which are directly influenced by the chosen crop and the corresponding control actions.

Environmental constraints must also be considered, as the enterprise is required to adhere to the principles of climate-resilient agricultural practices. This means ensuring compliance with minimum efficiency standards for resource consumption and greenhouse gas emissions. In addition, due to limited overall resource availability, the enterprise is subject to constraints on total water and energy expenditures.

Meteorological indicators M_t, $t = \overline{1,T}$, where T is the number of days, this is a vector formed based on the daily weather forecast. They are used as one of the input variables in the greenhouse microclimate control model. Control actions u_t, $i = \overline{1,n}$, are vectors of regulated parameters for each day in the greenhouse, defining how the agricultural enterprise influences the growing conditions. These actions are also considered as input parameters of the greenhouse control model for the cultivation of new agricultural crops. Their values directly affect water and energy consumption, as well as crop yield. The greenhouse control model is a discrete dynamic model that describes how the greenhouse microclimate changes as a result of the current state, control actions, and external environmental conditions. This model allows for the calculation of the expected conditions in the greenhouse under a given control strategy.

The crop yield prediction model based on meteorological indicators defines a function that allows forecasting the yield of a crop cc depending on the applied control actions. Additionally, based on these control actions, the daily water consumption in the irrigation system $w(u_t)$ and the energy consumption $e(u_t)$ of systems such as lighting, heating, and ventilation are determined. Each greenhouse can be used to cultivate only one crop. Therefore, we introduce binary variables x_{ij}, which take the value 1 if crop c_j is selected for cultivation in greenhouse g_i, and 0 otherwise.

Let us define the objective function as the maximization of the agricultural enterprise's profit

$$\sum_{i=1}^{n}\sum_{j=1}^{m} x_{ij}\left[p_j Y_j(M_{i0}, M_{i1}, \dots, M_{iT}, u_{i0}, u_{i1}, \dots u_{iT}) - \sum_{t=0}^{T} S_i\left(p_w w(u_{it}) + p_e e(u_{it})\right) - S_i o_{ij} \right] \to \max \quad (1)$$

where p_j is the redicted selling price of the crop c_j, Y_j is the predicted yield of the crop c_j, M_{it}, $t = \overline{1,T}$, are icroclimatic conditions in the greenhouse g_i per day t, u_{it}, $t = \overline{1,T}$, is the control actions in the greenhouse g_i per day t, S_i is greenhouse area g_i, $w(u_{it})$ is the water consumption in the greenhouse g_i per day t, $e(u_{it})$ is the energy consumption costs in the greenhouse g_i per day t, p_w is the cost 1 m^3 of water, p_e is the cost 1 **kWh of energy**, o_{ij} is the oher cultivation-related costs c_j in greenhouse g_i, in particular, for seeds, fertilizers, and plant protection products.

We also define the constraints. Since only one crop can be cultivated in each greenhouse, the mutual exclusivity constraint can be formulated as follows:

$$\sum_{j=1}^{m} x_{ij} = 1, i = \overline{1,n}, \tag{2}$$

where $x_{ij} \in \{0,1\}$ are variables, n is the number of greenhouses.

The following constraint sets a limit on the total expenditures of the enterprise for irrigation, lighting, heating, and ventilation over the entire cultivation period

$$\sum_{i=1}^{n}\sum_{t=0}^{T} S_i\left(p_w w(u_{it}) + p_e e(u_{it})\right) \le B, \tag{3}$$

where B is the enterprise energy budget, S_i is the greenhouse area g_i, $w(u_{it})$ is the water consumption in the greenhouse g_i per day t, $e(u_{it})$ is the energy consumption costs in the greenhouse g_i per day t, p_w is the cost 1 m^3 of water, p_e is the cost 1 kWh of energy.

The proposed model is an integrated nonlinear optimization problem that combines agronomic, economic, and environmental factors related to the operation of a greenhouse agricultural enterprise. Through the full integration of crop yield prediction models, climate control mechanisms, and resource consumption estimations, this model can serve as the core of a recommendation-based information system for decision-makers—specifically, for farm managers responsible for production cycle planning and resource allocation.

For practical implementation within an enterprise, the model can be deployed as a digital module of a decision support system integrated with a database of sensor data, weather forecasts, and regulatory resource consumption standards. This enables the generation of actionable recommendations for decision-making. Given that the model involves a mixed set of variables and nonlinear dependencies, it can be solved using approximate methods such as genetic algorithms or tabu search.

Results and discussion

To confirm the practical effectiveness of the proposed optimization model, a simulation experiment was conducted using actual data from an automated greenhouse microclimate control system in which bananas are cultivated. For model validation, two scenarios were simulated. In the first scenario, which served as the baseline, a fixed set of control actions with an intensity level of 3 was applied, representing a typical manual management strategy. In the second scenario, the control actions were adjusted daily according to the optimization strategy derived from the proposed model. In both cases, the predicted crop yield, water and energy consumption, and overall profit were calculated based on a predefined formula (1), which considers the selling price, resource costs, and agricultural production requirements (see Table 3). It is important to note the limitations of the experiment. It was assumed that only artificial

LED lighting was used, and the greenhouse was isothermal. Heat exchange with the external environment was modeled as a linear function of the temperature difference.

Table 3. Simulation results

Indicator	Baseline Scenario	Optimized Scenario
Predicted Yield (tons per square meter)	14.2	16.9
Water and Energy Costs, $	468	435
Other Agricultural Costs, $	400	400
Revenue from Sales, $	2,580	3,080
Expected Profit, $	1,712	2,245

The results of the simulation experiment are summarized in Table 1. The data indicates that the application of the optimized model allows for an increase in expected profit of more than 21 % compared to the fixed control strategy. Additionally, a reduction in total costs was observed, indicating more efficient resource use. Thus, the experiment confirms that the proposed model can serve as an effective tool for supporting decision-making in greenhouse production, particularly within digital systems for crop monitoring and optimization.

The simulation obtained demonstrates significant advantages over existing greenhouse climate control approaches. In a previous study (Altinkaya et al., 2016: 83–90) dedicated to optimizing ventilation systems, energy consumption was reduced by 12 to 15 %; however, that study did not address yield modeling or economic optimization. Another study (Wang et al., 2023) applied fuzzy logic to control the microclimate of a tomato greenhouse and achieved an 8.7 percent increase in yield and a 9.3 % reduction in water consumption. However, those approaches focused only on controlling individual environmental parameters without considering economic criteria or the specific needs of cultivating new crops.

In contrast, our study integrates yield forecasting models, microclimate optimization, and economic evaluation. As a result, we achieved a 19 percent increase in yield and a 21 % increase in profit (Table 1), while water consumption was reduced by 7 percent. This integrated approach provides more comprehensive and adaptive management of greenhouse production under industrial conditions.

A systematic review (Abdoussalami et al., 2023: 1–23) has shown that climate change is expanding the potential geographic range for banana cultivation. However, large daily temperature fluctuations negatively affect photosynthesis and cause crop losses of 15 to 25 % in open-field conditions. In our study, the application of a microclimate optimization model helped mitigate these risks. Temperature and humidity control in the greenhouse ensured stable yields and prevented losses typically associated with open-field cultivation. This demonstrates the effectiveness of the proposed decision-making system for adapting to extreme climatic conditions and growing new crops.

One limitation of the study is that the mathematical model for crop yield forecasting based on greenhouse microclimate involves a large number of parameters that must be individually adjusted. This calibration must be done for each crop type separately, considering the specific variety, and requires the involvement of agronomy experts. This challenge becomes especially complex when cultivating new crops, such as bananas, in regions with sharply continental climates.

Given that the greenhouse environment is a complex and nonlinear system, solving the optimization problem (1)–(3) requires the use of approximate nonlinear optimization methods. These methods do not guarantee the identification of a global optimum but can provide a locally optimal solution. Therefore, obtaining an optimal solution does not imply that a business operating under this model will achieve maximum efficiency.

Another limitation is that the study simulated the operations of a greenhouse enterprise based on the cultivation of a crop that is new to the Republic of Kazakhstan. Since the cultivation of this agricultural crop was only initiated in Kazakhstan last year, the developed control model has not yet been applied in real-world operations. The model has been developed as part of a research and practical project, with real-world implementation planned for the following year. Therefore, in the future, we aim to validate the decision-making model for greenhouse enterprise management under real operating conditions.

Conclusions

A mathematical model has been developed for predicting the yield of agricultural crops based on meteorological indicators in field conditions and microclimate parameters in greenhouses. The model includes components for evaluating photosynthesis and crop growth, water balance and transpiration, nutrient uptake rate, as well as biomass partitioning and fruit formation. The model enables yield forecasting of fruits in greenhouse conditions based on a set of parameters that can be adjusted depending on the crop being cultivated. In particular, such a model can be applied when cultivating new varieties or new agricultural crops that have not previously been grown in a specific location.

A greenhouse management model has been developed for cultivating new agricultural crops, which describes how external and control factors influence the microclimate parameters inside the greenhouse. This is important for ensuring optimal conditions for crop cultivation and achieving high yield performance. The described model forms the basis for building a decision-making model for greenhouse agricultural enterprises, taking into account climate-oriented agricultural practices.

A decision-making model has been developed for the operations of a greenhouse agricultural enterprise. It allows for a justified selection of the crop to be cultivated in each greenhouse, considering its agronomic requirements, predicted yield, water and energy consumption, as well as ecological constraints in line with the principles of sustainable agriculture. The model provides simultaneous optimization of crop structure and microclimate management strategy, formalized as a nonlinear mixed-variable problem. The proposed approach is suitable for implementation within a digital advisory decision-support information system for farm managers, with the possibility of integration with sensor monitoring data, weather forecasts, and resource provision standards. Given the complexity of the model, it is advisable to use approximate algorithms, such as genetic algorithms or metaheuristics like simulated annealing, which make it possible to efficiently find acceptable solutions under real production conditions. Simulation results show that applying the optimized model increases expected profit by more than 21 % compared to a fixed management strategy. Water consumption was reduced by 7 %, and yield increased by 19 %. Thus, overall costs are reduced, which indicates more efficient resource utilization.

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INVESTIGATING FACTORS INFLUENCING THE ADOPTION OF ONLINE LEARNING PLATFORMS FROM AN INFORMATION TECHNOLOGY PERSPECTIVE

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Abstract. This research aims to investigate the components influencing professional students' perceptions of their online learning experiences and to evaluate the quality of online learning in relation to student satisfaction. The study employed structural equation modeling (SEM) and partial least squares SEM (PLS-SEM) analysis. A purposive sampling method was used to select respondents, comprising 3,206 students from various vocational schools in Kazakhstan who participated in an online survey. The findings indicate that communication, digital media, interaction, facilities, and instructional support directly affect the quality of online learning. To ensure that students have a positive online learning experience, institutions offering online education must prioritize these key components for effective implementation. Furthermore, instructors should focus on enhancing the quality of online learning to improve student satisfaction.

Keywords: online learning, communication, media, interaction, knowledge

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ОНЛАЙН ОҚЫТУ ПЛАТФОРМАЛАРЫНЫҢ ҚАБЫЛДАНУЫНА ЫҚПАЛ ЕТЕТІН ФАКТОРЛАРДЫ АҚПАРАТТЫҚ ТЕХНОЛОГИЯЛАР ТҰРҒЫСЫНАН ЗЕРТТЕУ

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Аннотация. Бұл зерттеу кәсіптік білім алушы студенттердің онлайн оқытуды қабылдауына әсер ететін факторларды және онлайн оқыту сапасының олардың академиялық үлгеріміне ықпалын талдауға бағытталған. Зерттеуді жүргізу үшін құрылымдық теңдеулерді модельдеу (SEM) және ең кіші квадраттардың ішінара талдауы (PLS-SEM) әдістемелері қолданылды. Респонденттерді іріктеу мақсатты іріктеу әдісі арқылы жүзеге асырылып, Қазақстанның әртүрлі кәсіптік білім беру мекемелерінен онлайн сауалнамаға қатысуға қызығушылық танытқан 3206 студент-дублерді қамтыды. Зерттеу нәтижелері коммуникация, заманауи медиа құралдары, өзара әрекеттесу, оқу кабинеттерінің жабдықталуы және оқу жаттығуларының сапасы онлайн оқытудың жалпы сапасына ерекше әсер ететінін көрсетті. Осыған орай, онлайн оқытуды ұсынатын білім беру мекемелері студенттердің оң тәжірибесін қамтамасыз ету үшін аталған негізгі компоненттерге басымдық беруі қажет. Сонымен қатар, оқытушылар онлайн оқыту сапасын арттыруға баса назар аударуы тиіс, бұл студенттердің өзін-өзі дамытуы мен академиялық жетістіктері үшін маңызды болып табылады.

Түйін сөздер: онлайн оқыту, коммуникация, медиа, өзара әрекеттесу, білім

Дәйексөздер үшін: Э. Гайсина, А. Кубашева, А. Кумаргалиева, Г. Дашева, П. Шмидт. Онлайн оқыту платформаларының қабылдануына ықпал ететін факторларды ақпараттық технологиялар тұрғысынан зерттеу//Международный журнал информационных и коммуникационных технологий. 2025. Т. 6. No. 23. Стр.133–144. (На анг.). https://doi.org/10.54309/IJICT.2025.23.3.008.

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ИССЛЕДОВАНИЕ ФАКТОРОВ, ВЛИЯЮЩИХ НА ПРИНЯТИЕ ОНЛАЙН-ПЛАТФОРМ ОБУЧЕНИЯ, С ТОЧКИ ЗРЕНИЯ ИНФОРМАЦИОННЫХ ТЕХНОЛОГИЙ

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Аннотация. Это исследование было направлено на изучение факторов, влияющих на восприятие студентами-профессионалами своих онлайн-занятий, и на оценку качества онлайн-обучения, которое влияет на успеваемость студентов-дублеров. В исследовании использовались методы моделирования вспомогательных условий (SEM) и дробного анализа наименьших квадратов (PLS-SEM). Для отбора респондентов был использован метод целенаправленной выборки, включающий 3206 студентов-дублеров из различных профессиональных учебных заведений Казахстана, которые проявили интерес к веб-обзору. Результаты исследования показывают, что коммуникация, современные медиа, взаимодействие, кабинеты и учебные упражнения оказывают особое влияние на качество онлайн-обучения. Чтобы гарантировать, что студенты-дублеры получат положительные впечатления от онлайн-обучения, школы, рекламирующие онлайн-обучение, должны уделять приоритетное внимание этим фундаментальным компонентам. Более того, преподавателям следует сосредоточиться на повышении качества онлайн-обучения, чтобы добиться значительных успехов в самореализации дублеров.

Ключевые слова: онлайн-обучение, коммуникация, медиа, взаимодействие, знания

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Introduction

In the context of the COVID-19 pandemic, online learning has become increasingly significant in education. The Kazakhstan government implemented a policy to close schools to prevent virus transmission, instructing all schools to continue teaching and learning through online platforms (Alqahtani et al., 2020: 5261–5280).

Similarly, schools in Kazakhstan have been striving to provide the necessary facilities to support the implementation of online learning. Despite these efforts, numerous studies have identified challenges faced by students, many of whom prefer traditional face-to-face learning over online methods (Anderson et al., 2017: 89–105).

Research has established a correlation between student satisfaction and learning outcomes. Consequently, it is essential to assess the quality of online learning from the students' perspective to determine their satisfaction with this mode of education (Cheng et al., 2019: 103–147).

Numerous studies have examined the factors influencing students' online learning experiences. Among these, tutorials are identified as a significant determinant of student satisfaction and perceived learning in online education (Demirkol et al., 2018: 75–89).

The effectiveness of online learning delivery by teachers, along with students' perceptions of this educational mode, is essential for enhancing its quality and increasing student satisfaction. (Garrison et al., 2020: 320). Critical components of online learning environments include effective communication between teachers and students, the integration of digital media, and the availability of support facilities.

Despite students' general acceptance of online learning, many express dissatisfaction with the quality of interactions with their teachers and peers. This study focuses specifically on vocational students' perspectives on online learning. Traditionally, vocational education depends on face-to-face communication, hands-on practice in workshops, and teamwork (Lin et al., 2022: 4321–4340).

However, the pandemic has necessitated adaptations to these conventional teaching strategies and practices.

Many countries have attempted to adapt learning strategies from conventional education to online formats. Previous research has shown that online vocational learning provides a unique experience for vocational students (Park 2019: 12–22).

Additionally, some studies indicate that vocational schools can successfully conduct online learning and achieve their educational objectives. This suggests that the challenges associated with implementing online vocational learning can be transformed into opportunities, although further research is needed in various areas.

This study aims to analyze the factors influencing student satisfaction in online vocational learning in Kazakhstan and offers recommendations for teachers on managing online vocational education (Picciano 2022: 101–123).

The development of vocational learning should consider and implement reforms driven by systematic strategies and their practical application. Therefore, examining the quality of online vocational learning is essential to better understand the challenges and opportunities involved (Siemens 2020: 12–19).

Materials and Methods

Quantitative methods were utilized in this study to identify the factors affecting the quality of online vocational learning and student satisfaction (Sun et al., 2021: 1–22).

The study examines various elements influencing students' online learning experiences, including communication, digital media, interaction between students and teachers, facilities, and tutorials.

Partial least squares structural equation modeling (PLS-SEM) analysis was employed to predict and explain the relationships between multiple variables. The developed research model is depicted in Figure 1.

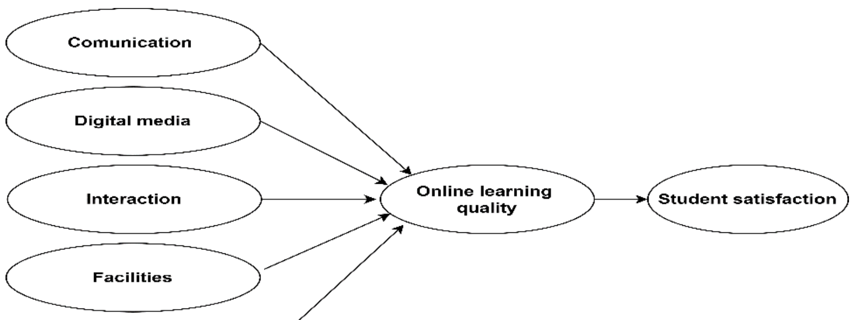

Fig. 1. Research Model

The population investigated in this study consisted of vocational students in Kazakhstan. Purposive sampling was used to select respondents who had experience with online vocational learning.

The sample size was estimated using the “10-times rule” method, a common approach in PLS-SEM sample size determination. As a result, the study included 3206 vocational students from Kazakhstan.

Data collection for this study was conducted using an online questionnaire. The instrument was based on factors influencing students’ online learning experiences, as adapted from several studies (see Table 1).

The research questionnaire utilized a Likert scale ranging from 1 to 4, with indicators from “strongly disagree” to “strongly agree”.

Table 1. Research Instrument

Model construct	Code	Item
Communication	C_1	Teachers need good communication skills to manage online learning.
	C_2	Teachers need good communication skills to solve problems in online learning.
	C_3	Students are active in responding to teacher explanations.
Digital media	DM_4	Teachers use digital media as a tool for online learning.
	DM_5	Teachers can use the features of digital media used in online learning.
	DM_6	Students can operate digital media as recommended by the teachers.
	DM_7	Students can use digital media features recommended by the teachers.
	DM_8	The use of digital media in online learning is very important.
	DM_9	The use of digital media can facilitate online learning.
	DM_{10}	The use of digital media can increase the ease of learning online.
Interaction	I_{11}	Students can use appropriate language when interacting online.
	I_{12}	Students can behave well when interacting online.
Facilities	F_{13}	Electronic devices are indispensable for online learning.
	F_{14}	Internet access is indispensable for online learning.
	F_{15}	Online classes are indispensable for online learning.
Tutorials	T_{16}	The role of the teacher as a facilitator is indispensable in online learning.
	T_{17}	The teacher’s ability to provide guidance is indispensable in online learning.
	T_{18}	Online learning needs to be designed by the teacher as an activity-oriented, discussion-based class.

Online learning quality	OLG_{19}	Good learning management is indispensable in online learning.
	OLG_{20}	A communicative teaching and learning process is indispensable in online learning.
	OLG_{21}	Student responses are needed to boost online learning.
Student satisfaction	SS_{22}	Provision of facilities is indispensable in online learning.
	SS_{23}	Communication between teachers and students is indispensable in online learning.
	SS_{24}	The teacher's ability to manage online classes is indispensable in online learning.
	SS_{25}	Teacher responsiveness is indispensable in online learning.

This study utilized demographic analysis and PLS-SEM as its analytical techniques. The process began with an examination of the respondents' demographic data. Following this, PLS-SEM was conducted to assess both the measurement and structural models.

The measurement model was evaluated using tests for convergent validity, composite reliability, average variance extracted (AVE), and discriminant validity.

For the structural model, the analysis included evaluating path coefficients (β), effect size (f^2), coefficient of determination (R^2), and t-statistics. Convergent validity was examined by assessing the correlation between indicators and their respective constructs.

Composite reliability was measured to assess the consistency of the constructs. AVE was used to assess convergent validity, while discriminant validity by examining cross-loadings to ensure each reflective indicator accurately represents its intended construct.

This process involved examining cross-loadings to compare indicators with their associated constructs. Path coefficients (β), effect size (f^2), coefficient of determination (R^2), and t-statistics were used to assess the strength and significance of the relationships between constructs.

The path coefficient (β) defines the nature of the relationship, while effect size (f^2) measures its magnitude. The coefficient of determination (R^2) indicates the extent to which an exogenous variable explains an endogenous variable, and t-statistics are used to assess hypotheses by evaluating p-values.

Results

Table 2 presents the results of the demographic analysis, detailing the profile of the study's respondents. The study encompassed 3,206 vocational students from various vocational schools across Kazakhstan. The data reveal that 48.9 percent of the respondents were male, while 51.1 percent were female.

Furthermore, 44.8 percent of the participants had engaged in two years of online vocational learning. This study employs partial least squares (PLS) analysis to evaluate the research model.

In the measurement model, composite reliability (CR) was used to assess construct reliability, convergent validity was evaluated by examining indicator loadings and AVE, and discriminant validity was assessed by analyzing cross-loadings.

Discriminant validity was evaluated by analyzing cross-loading values.

Table 2. Profiles of Respondents

Demographic	Frequency (N=3206)	Percentage (%)
Gender		
Male	1567	48,9
Female	1639	51,1
Length of time in online learning.		
<1 Year	636	19,8
1 Year	792	24,7
2 Year	1436	44,8
>1 Year	342	10,7

Table 3. Assessment of Measurement Model

Model construct	Measurement item	Outer loading	CR	AVE
Communication	C_1	0,842	0,875	0,699
	C_2	0,868		
	C_3	0,798		
Digital media	DM_4	0,768	0,924	0,633
	DM_5	0,800		
	DM_6	0,793		
	DM_7	0,821		
	DM_8	0,801		
	DM_9	0,815		
	DM_{10}	0,770		
Interaction	I_{11}	0,928	0,926	0,862
	I_{12}	0,930		
Facilities	F_{13}	0,845	0,861	0,673
	F_{14}	0,824		
	F_{15}	0,791		
Tutorials	T_{16}	0,863	0,895	0,739
	T_{17}	0,869		
	T_{18}	0,847		
Online learning quality	OLG_{19}	0,885	0,900	0,751
	OLG_{20}	0,873		
	OLG_{21}	0,842		

Student satisfaction	SS_{22}	0,812	0,910	0,717
	SS_{23}	0,854		
	SS_{24}	0,864		
	SS_{25}	0,856		

Table 3 demonstrates that the composite reliability (CR) values for each construct have surpassed the recommended threshold of 0.7, indicating that the indicators exhibit strong internal consistency and reliability.

Additionally, the loading values for all indicators have exceeded the minimum threshold of 0.7, confirming that the constructs meet the required criteria. Furthermore, the average variance extracted (AVE) values are above the minimum criterion of 0.5, indicating that all constructs fulfill the necessary requirements.

The results of the discriminant validity test are satisfactory, as the correlation between each variable is less than the square root of the AVE for that variable. Consequently, the constructed research model meets the necessary criteria and exhibits strong statistical properties.

Moreover, the model was tested using f^2 values to evaluate the strength of relationships between constructs, with f^2 values of 0.35, 0.15, and 0.02 indicating large, medium, and small effects, respectively. The f^2 results suggest a significant impact between the constructs of online learning quality and student satisfaction.

A direct impact exists between the construct of instructional activities and online learning quality, while a small effect is found in the relationship between the constructs of communication, digital media, interaction, and facilities on the development of online learning quality.

Furthermore, the structural model was tested, and the results for R^2 values of 0.67, 0.33, and 0.19 were interpreted as substantial, moderate, and weak, respectively.

The R^2 results show that the variance explained in online learning quality is 0.712. Thus, the combined impact of communication, self-directed learning, digital media, interaction, facilities, and instructional activities accounts for 71.2 percent of the variance, indicating that this model is substantial.

Similarly, the R^2 value for student satisfaction is 0.656, indicating that online learning quality explains 65.6 percent of the variance. Therefore, the model is considered moderate.

The study used the path coefficient test to assess the strength of the relationship between dependent and independent variables. The research hypotheses were evaluated based on the results of the t-statistics test using the bootstrapping method.

A confidence level of 95 percent was used with a significance level (α) = 0.05. Hence, the hypothesis testing results were considered "supported" if the p-value was < 0.05. The structural model testing results are presented in Table 4.

Table 4. Assessment of Structural Model

Hypothesis	Path	β	F^2	R^2	P values	Decision
H_1	Communication-> Online learning quality	0,126	0,025	0,712	0,000	Supported

H_2	Digital media-> Online learning quality	0,177	0,035	0,712	0,000	Supported
H_3	Interaction-> Online learning quality	0,134	0,026	0,712	0,000	Supported
H_4	Facilities ->Online learning quality	0,144	0,025	0,712	0,000	Supported
H_5	Tutorials ->Online learning quality	0,381	0,172	0,712	0,000	Supported
H_6	Online learning quality-> Student satisfaction	0,810	1,910	0,656	0,000	Supported

Discussion

The research findings establish an important framework for improving the quality of online vocational learning for vocational students.

The six proposed hypotheses address crucial factors such as communication, digital media, interaction, facilities, and tutorials, all of which directly impact the quality of online vocational learning and student satisfaction.

Statistical results indicate that the quality of online learning significantly impacts student satisfaction, with establishing it as a key determinant of students' satisfaction with this mode of education.

Previous studies also support the finding that the quality of online learning affects student satisfaction. Consequently, educators should prioritize improving the quality of online learning to enhance student satisfaction.

Among the primary determinants of the quality of online vocational learning include the tutorial constructs, which assess the teacher's role as a facilitator, their ability to provide guidance, and the design of the class as an activity-oriented discussion forum.

This construct highlights the need to revise criteria and class design for online learning. Several researchers agree that tutorials in online education should be adapted to better suit the online learning environment.

Consequently, teachers are encouraged to reassess their teaching strategies by focusing on their facilitative role and enhancing guidance for students participating in online activities.

Additionally, teachers are advised to adopt more creative and interactive class designs by adopting a design that prioritizes discussion and is activity-oriented, thereby increasing student engagement in online learning.

Another critical factor affecting the quality of online learning is digital media. This construct evaluates both the availability of digital media as a tool in online education and the proficiency of teachers and students in utilizing it.

Recent studies have supported the assertion that digital media use directly impacts of digital media on student satisfaction in online learning. The findings of this study underscore the importance of digital media in online education, while also emphasizing the need to focus on the competencies of both teachers and students in effectively using digital media.

Properly utilized digital media can significantly aid teachers and students in achieving their online learning objectives.

This study also identified a correlation between the availability of facilities and the quality of online learning. This construct assesses the support infrastructure for online education, including internet resources essential for its implementation.

Effective online learning requires ensuring that the necessary facilities are available to provide adequate support for both teachers and students in organizing and participating in online education.

Recent research has emphasized the importance of both peer-to-peer and student-teacher interactions in the context of student learning.

The findings indicate that interaction is a significant factor influencing the quality of online learning. In this study, including the appropriateness of language use and behavioural norms within online learning environments. Consequently, it is essential to closely monitor and evaluate these interactions to enhance the quality of online learning.

Numerous studies have identified communication as a critical factor in online learning. Effective communication is essential for fostering a positive and engaging classroom environment.

Conclusion

Numerous studies have empirically investigated student satisfaction with online learning. This research integrates factors identified in previous studies—such as communication, digital media, interaction, facilities, and tutorials — to evaluate the quality of online vocational learning and its impact on student satisfaction.

Educators should take into account these findings when designing strategies for online vocational education. Enhancing the quality of online learning in vocational settings can significantly improve the effectiveness of the teaching and learning process.

The study concludes that communication, digital media, interaction, facilities, and tutorials each have a significant and positive impact on the quality of online learning, which in turn greatly influences student satisfaction. Schools should therefore pay close attention to the implementation of online learning practices.

This research model also offers several theoretical implications. The developed and adapted instruments exhibit sufficient reliability and validity, making them useful tools for application across various educational contexts.

The model goes beyond conventional research by examining factors related to the adoption of online learning in both public and private educational institutions. However, the findings may be specific to certain types of educational institutions, as user characteristics can vary widely.

Additionally, the data is confined to three provinces in Kazakhstan. Future research could encompass additional provinces to provide more comprehensive insights.

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APPLICATION OF INTELLIGENT DATA ANALYSIS METHODS TO EMPLOYEE INFORMATION PROCESSING USING DUCKDB AND CHROMADB

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Abstract. Intelligent analysis of employee data is becoming increasingly relevant in the context of digital transformation of human resource management processes and the growing need to process both structured and unstructured sources of information. Modern approaches require the implementation of solutions capable of efficiently handling tabular data while simultaneously extracting meaning from textual employee descriptions. However, most existing systems lack a unified architecture that combines OLAP analysis, clustering, and semantic search within a locally executable analytical environment. The objective of this study is to develop a local analytical subsystem aimed at comprehensive analysis of employee information using the embedded OLAP DBMS DuckDB and the vector database ChromaDB. To achieve this objective, the following tasks were implemented: data preprocessing, aggregation using SQL queries, employee clustering through the k-means method, vectorization of textual descriptions, and deployment of semantic search based on the all-MiniLM-L6-v2 model. As a result, a software prototype was developed that enables both quantitative and semantic analysis of employee data. The system demonstrated high performance under local execution, rapid personnel segmentation capabilities, and semantic search through natural language queries without the need for external services. Additionally, the results were visualized using the Yandex DataLens BI platform. The proposed solution exhibits a high degree of reproducibility and can be adapted to internal HR analytics, decision support systems, and information-analytical platforms. The findings confirm the potential of integrating OLAP and vector technologies within a unified local architecture for intelligent processing of employee information.

Keywords: vector databases, semantic search, OLAP analysis, DuckDB, ChromaDB, employee clustering, text data analysis

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DUCKDB МЕН CHROMADB НЕГІЗІНДЕ ҚЫЗМЕТКЕРЛЕР ТУРАЛЫ МӘЛІМЕТТЕРДІ ӨҢДЕУДЕ ИНТЕЛЛЕКТУАЛДЫ ДЕРЕКТЕРДІ ТАЛДАУ ӘДІСТЕРІН ҚОЛДАНУ

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Аннотация. Қызметкерлер туралы мәліметтерді интеллектуалды тұрғыдан талдау қазіргі таңда адами ресурстарды басқару процестерінің цифрландырылуы және құрылымдалған әрі құрылымдалмаған ақпарат көздерін өңдеу қажеттілігінің артуы аясында ерекше өзектілікке ие болуда. Заманауи тәсілдер кестелік деректерді тиімді өңдеумен қатар, қызметкерлердің мәтіндік сипаттамаларынан мағыналық ақпаратты ала алатын шешімдерді ендіруді талап етеді. Алайда, қазіргі қолданыстағы көптеген жүйелерде OLAP-талдау, кластерлеу және семантикалық іздеу мүмкіндіктерін біріктіретін бірыңғай архитектура қарастырылмаған. Осы зерттеудің мақсаты – DuckDB кіріктірме OLAP деректер қорын басқару жүйесі мен ChromaDB векторлық деректер қорын пайдалану арқылы қызметкерлер туралы мәліметтерді кешенді түрде өңдеуге бағытталған жергілікті аналитикалық ішкі жүйе құрастыру. Бұл мақсат аясында деректерді алдын ала өңдеу, SQL-сұраныстары арқылы агрегаттау, K-means әдісімен қызметкерлерді кластерлеу, мәтіндік сипаттамаларды векторлау және all-MiniLM-L6-v2 моделіне негізделген семантикалық іздеуді ендіру сияқты міндеттер жүзеге асырылды. Нәтижесінде, қызметкерлер туралы деректерге сандық әрі мағыналық тұрғыдан талдау жүргізуге мүмкіндік беретін бағдарламалық прототип жасалды. Жүйе жергілікті ортада жоғары өнімділікті, персоналды жедел сегменттеуді және табиғи тілдегі сұраныстар бойынша іздеуді сыртқы сервистерге қосылусыз іске асыру мүмкіндігін көрсетті. Сонымен қатар, нәтижелер Yandex DataLens BI платформасында визуализацияланды. Ұсынылған шешім жоғары деңгейдегі қайталанымдылыққа ие және ішкі HR-талдау, шешім қабылдауды қолдау жүйелері мен ақпараттық-аналитикалық платформалар міндеттеріне бейімдеуге болады. Зерттеу нәтижелері OLAP және векторлық технологияларды бірыңғай жергілікті архитектура шеңберінде біріктіру интеллектуалды кадрлық ақпаратты өңдеу үшін болашағы зор екенін дәлелдейді.

Түйін сөздер: Векторлық деректер қорлары, Семантикалық іздеу, OLAP-талдау, DuckDB, ChromaDB, Қызметкерлерді кластерлеу, Мәтіндік деректерді

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ПРИМЕНЕНИЕ МЕТОДОВ ИНТЕЛЛЕКТУАЛЬНОГО АНАЛИЗА ДАННЫХ В ОБРАБОТКЕ ИНФОРМАЦИИ О СОТРУДНИКАХ С ИСПОЛЬЗОВАНИЕМ DUCKDB И CHROMADB

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Аннотация. Интеллектуальный анализ кадровых данных становится всё более актуальным в условиях цифровизации процессов управления персоналом и необходимости обработки как структурированных, так и неструктурированных источников информации. Современные подходы требуют внедрения решений, способных эффективно обрабатывать табличные данные и одновременно извлекать смысл из текстовых описаний сотрудников. Однако в большинстве существующих систем отсутствует единая архитектура, сочетающая возможности OLAP-анализа, кластеризации и семантического поиска в рамках локально исполняемой аналитической среды. Целью настоящего исследования является разработка локальной аналитической подсистемы, ориентированной на комплексный анализ сведений о сотрудниках организации с использованием встраиваемой OLAP-СУБД DuckDB и векторной базы данных ChromaDB. В рамках поставленной цели были реализованы задачи по предобработке данных, агрегации с использованием SQL-запросов, кластеризации сотрудников методом K-средних, векторизации текстовых описаний и внедрению семантического поиска на основе модели all-MiniLM-L6-v2. В результате был создан программный прототип, позволяющий проводить как количественный, так и смысловой анализ кадровых данных. Система продемонстрировала высокую производительность при локальном исполнении, возможность быстрой сегментации персонала и реализацию поиска по естественно-языковым запросам без подключения к внешним сервисам. Дополнительно обеспечена визуализация результатов в BI-среде Yandex DataLens. Предложенное решение обладает высокой степенью воспроизводимости и может быть адаптировано к задачам внутреннего HR-анализа, систем поддержки принятия решений и информационно-аналитических платформ. Результаты исследования подтверждают перспективность объединения OLAP- и векторных технологий в рамках единой локальной архитектуры для интеллектуальной обработки кадровой информации.

Ключевые слова: векторные базы данных, семантический поиск, OLAP-анализ, DuckDB, ChromaDB, кластеризация сотрудников, анализ текстовых данных

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Introduction

In the era of increasing digitalization and growing complexity of human resource management, effective employee data analytics has become strategically important for organizations. Modern information flows include both structured data (e.g., numerical and categorical attributes) and unstructured text that reflects experience, competencies, and behavioral characteristics.

Traditional analytical approaches based on relational models and tabular systems face limitations in processing poorly structured data, especially for semantic interpretation and contextual search (Boncz et al., 2020). In response, the scientific community is exploring hybrid architectures that combine OLAP analytics with machine learning and natural language processing methods.

Particularly relevant are embedded, serverless databases and vector DBMSs designed to work with neural network embeddings. However, the development of local, integrated analytical systems that unify quantitative and semantic analysis remains insufficiently studied. There is a gap in integrating OLAP processing with semantic text analysis and automated personnel segmentation within a unified environment.

This paper presents a local analytical subsystem combining the OLAP engine DuckDB and the vector database ChromaDB for personalized HR data analysis. The system integrates SQL queries, clustering algorithms, and semantic search using text embeddings within an offline architecture. It enhances accuracy, reduces processing time, and broadens analytical capabilities without requiring additional computing resources (DIF Management, 2023).

The methodology involves Python-based data processing, machine learning, text vectorization, and visualization in an interactive BI interface.

Materials and Methods

Description of the Organization and Setting a Business Task

On behalf of the organization, the task of analyzing employee data was set. It includes preprocessing data provided as an xlsx file, calculating statistical information, segmenting employees, and preparing a report.

It is of primary importance to model the existing process of working with employee data (Figure 1).

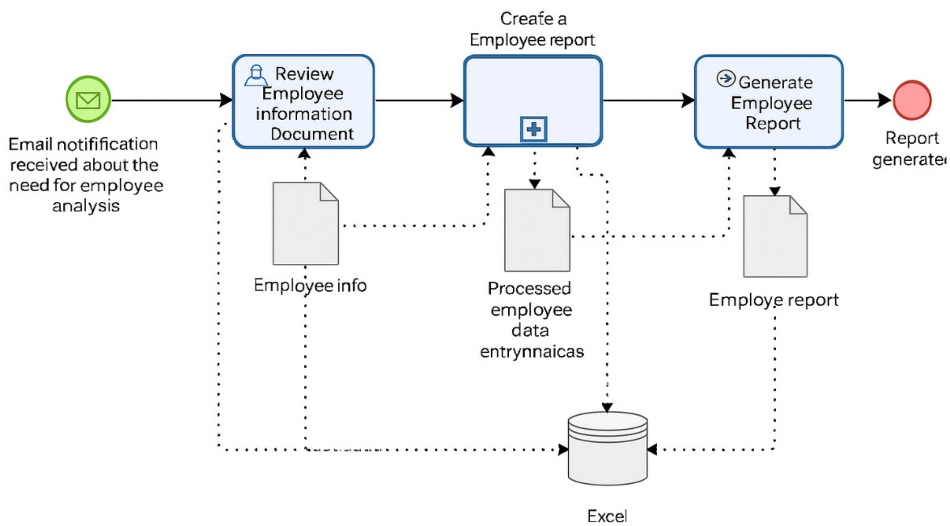

Fig.1. Employee Analysis Business Process

After receiving a notification about the need to analyze employee data, the specialist examines the received data file. It is presented in xlsx format and is an upload from the database of a subordinate organization that only its employees have access to. Next, the specialist performs data processing and generates a final report on employees. The key is the subprocess of direct data processing, as well as the fact that text information is available in the upload. Consider the decomposition of the "Data Processing" subprocess (Figure 2).

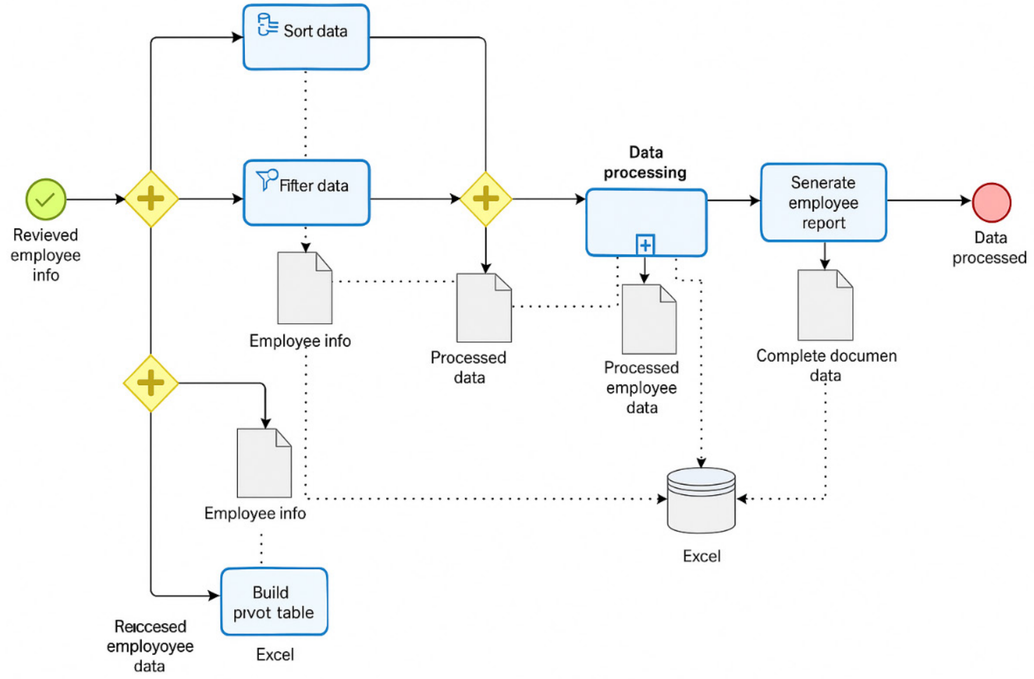

Fig. 2. Decomposition of the "Data Processing" Subprocess

Getting the necessary metrics, calculating the main indicators, creating lists, and segmenting employees takes place manually. Microsoft Excel software and tools are used to process and work with data. As a result, a situation arises in which determining a single metric requires performing several manipulations in the form of sorting, filtering data, building pivot tables, and so on. As a result, the time required for data processing increases significantly.

An important feature of employee data is that in addition to numeric attributes, which are successfully processed in Microsoft Excel, there are columns with text information manually entered. The data processing specialist chooses one of two paths:

1. Consider only numeric attributes.
2. Manual processing of text columns.

The disadvantage of the first option is that it considers a limited amount of information, which can lead to a distortion of the whole picture, omission of important characteristics and affect the final decision-making of management decisions. In the second case, the data processing time is multiplied by manual processing. The amount of data is increased by adding additional columns with the most valuable information, which the specialist manually selects from text columns. This also increases the probability of errors due to the human factor (DuckDB Contributor, 2023).

It should be noted that to get access to the updated / processed file, you must repeatedly transfer the modified version to another specialist. As a result, the number of intermediate versions of the document increases, the data transfer time increases, and there is a risk of data security or integrity violations.

An alternative solution is to create a local database. An optimized process of employee data analysis is simulated to enhance the methodological framework for organizational decision-making." (Figure 3).

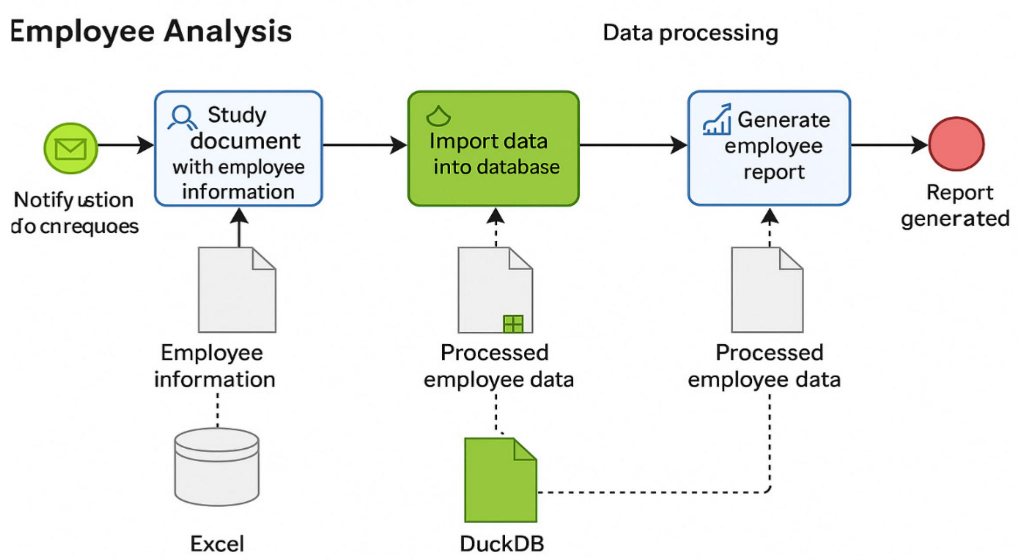

Fig. 3. Optimized Business Process "Employee Analysis"

The main change is the use of a different solution, namely the shared OLAP-oriented DuckDB DBMS and the locally deployed ChromaDB database. After receiving employee data in xlsx document format, the data is uploaded to the database management system – DuckDB. Data is stored and processed in the same way inside the DBMS. Let us illustrate the decomposition of the modified data processing subprocess (Figure 4).

First, we noted that the processing of text information contained in data is automated, since the DBMS has built-in mechanisms for working with semi-structured and unstructured data. These mechanisms will be described in more detail in the second chapter. Accordingly, we get several improvements:

1. Data processing time is reduced.

2. There are opportunities for using new data analysis tools (writing SQL queries, performing vector search, using machine learning, including clustering, and

others).

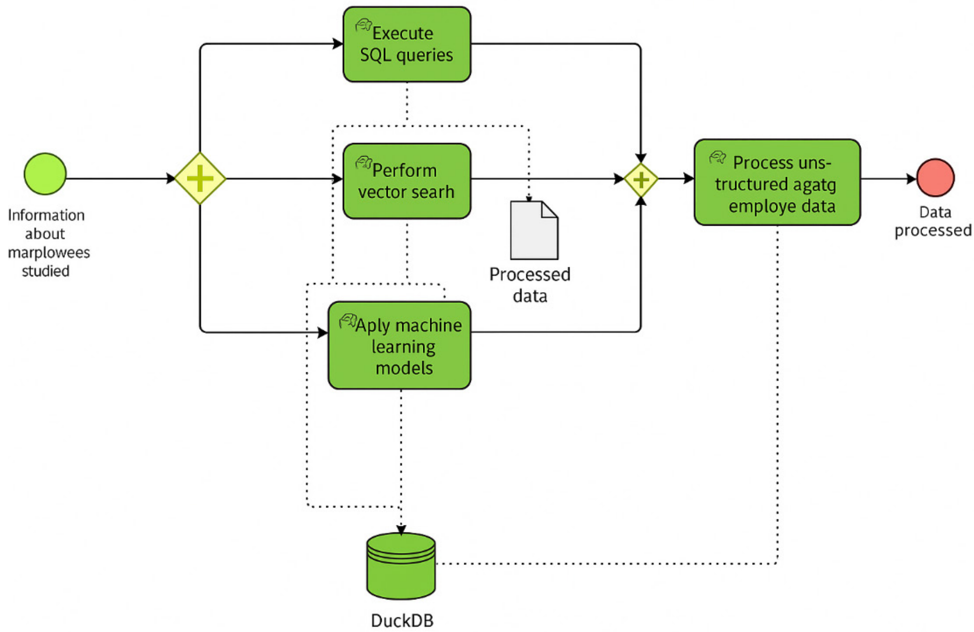

Fig. 4. Decomposition of the Optimized Data Processing Subprocess

3. Accounting for the full amount of available information.

4. Getting access to the same database simultaneously from several management employees.

5. No large number of intermediate versions of the document in separate files.

6. Reduce security and data integrity risks.

The possibility of using other existing types of databases, such as relational databases (PostgreSQL, MySQL), NoSQL systems, object-oriented DBMSs, hierarchical and graph databases, was also considered. Each of the listed databases has its own advantages (for example, effective horizontal scalability, maintaining strict information integrity due to centralized data storage, the ability to work with complex object structures, etc.) and is effective in solving various business problems (Hunga, 2023). However, based on the structure of available employee data, centralized relational databases have several functional limitations, while other types of databases, on the contrary, provide redundant capabilities or complicate the data processing process.

Thus, the proposed solution fully satisfies the tasks set. Moreover, if necessary, the created database can be supplemented with other documents: regulatory legal acts, text documents, additional xlsx format tables, and others.

Now, based on the business task, we will formulate the goal of the work: to analyze data about employees of the organization using locally installed and shared open source systems: an OLAP-oriented DBMS and a vector database (Ivanov et.al., 2021).

Key Features of DuckDB and ChromaDB

The use of traditional relational databases in processing text information has several functional limitations associated with the complex nature of human-entered text data. Vectorized solutions are an alternative specialized solution for processing and storing unstructured information, such as text, images, video and audio files (Karimi et.al., 2024.)

Since the available data about employees of the organization contains columns with text information entered by a person, it is worth focusing on the mechanisms of text processing in vector databases. Text information can be presented in a wide variety of formats: technical documentation, structured text files, informal correspondence in instant messengers, streaming data from social networks, etc. The main problems that arise when processing such data are the presence of slang or dialect expressions, the variety of natural language interpretations, and the presence of a specific context. Moreover, do not forget about the presence of spelling errors, which often occur in the case of manual data entry or text compilation (Khan, 2024.). Vectorized solutions can successfully solve the problem of processing text information by supporting machine learning, as well as mechanisms for performing semantic (semantic) search.

According to the Global Market Insights report "Size and market share of vector databases, forecasts for 2025–2034" for 2024, the demand for vector databases as solutions for managing multidimensional data is growing

It is driven by an increase in the number of applications using artificial intelligence and machine learning(Light, 2023).

It is worth noting that there is a serious problem in the vector database market related to the commercial component. For example, for small businesses, such a solution is expensive, which prevents the widespread adoption of vector databases. However, existing open-source alternatives offer cost-effective and competitive solutions. These are DuckDB and ChromaDB.

DuckDB is a vectorized, embedded, OLAP-oriented database management system (Ma et.al,2024), optimized for performing analytical queries against local data. It does an excellent job of aggregating, filtering, joining tables, and processing data in a column format.

The main features of DuckDB include a fast SQL query executor, support for working with various formats (CSV, Parquet, Pandas DataFrame, etc.), and working locally inside the application without a server. DuckDB is also characterized by column-based data storage and a vectorized engine that supports SIMD optimization, which allows it to process data in blocks and perform operations much faster.

The choice of DuckDB is due not only to the high performance of SQL queries with integration capabilities in applications and machine learning environments, but also to its ability to function both independently and as an embedded solution, which allows it to be used in various contexts-from local analysis to integration into distributed systems.

Since DuckDB does not support semantic search directly, which is one of the main tasks set, it can be used in conjunction with a vector database, for example, with ChromaDB.

ChromaDB is an open-source vector database designed for storing and searching vector embeddings.

The fundamental difference from the traditional database, which operates with tables and rows, is that the vector database works with multidimensional numeric vectors (Mohamed et.al, 2023) In simple terms, semi-structured and unstructured data undergo a vectorization process (Mullins, 2022). and are encoded in numerical form, which allows performing algorithmic operations with them. This transformation of data makes it possible to perform semantic search and configure recommendation systems.

Vectorization is the process of converting data into numeric vectors, also called embeddings. A distinctive feature of embeddings is the preservation of semantic and structural features of the text (Nosratabadi, 2022). Due to this data transformation, words that are similar in meaning will be located closer to each other in a multidimensional vector space.

Vectorization is a fundamental step for implementing and further using a vector database. The overall workflow (Figure 6) consists of several generalized stages (Orazbayeva et.al, 2023)

1. Data injection. The source data is converted to the format of numerical multidimensional vectors using the embedding model.

2. Creating a vector storage. The resulting embeddings are sent and grouped in the data warehouse and can be used to execute queries.

3. Request implementation. When solving the problem of finding the necessary information from a text query, it is also converted to a vector format using a similar embedding model.

4. Processing the request vector. The query vector and source data vectors are matched to find the most relevant match and get a response to the query.

In the above process, the third and fourth steps relate to one of the special functions of vector databases – creating a Question-and-Answer Chain(and Answer Chain, QnA Chain). This is a structured query processing process in which the system, based on the information loaded into the database, generates a relevant response to the request, considering the context. The advantages of such chains are the reliance on specific documents from which the user prefers to get the answer, as well as considering the semantic properties of the text, rather than the exact match of the requested text, which is implemented in relational databases (Qin et al., 2023).

The request and response chain works according to the following scheme:

1. Reading and analyzing the question. The system interprets the request, defines the semantics, and translates the request into a vector format using the embedding model.

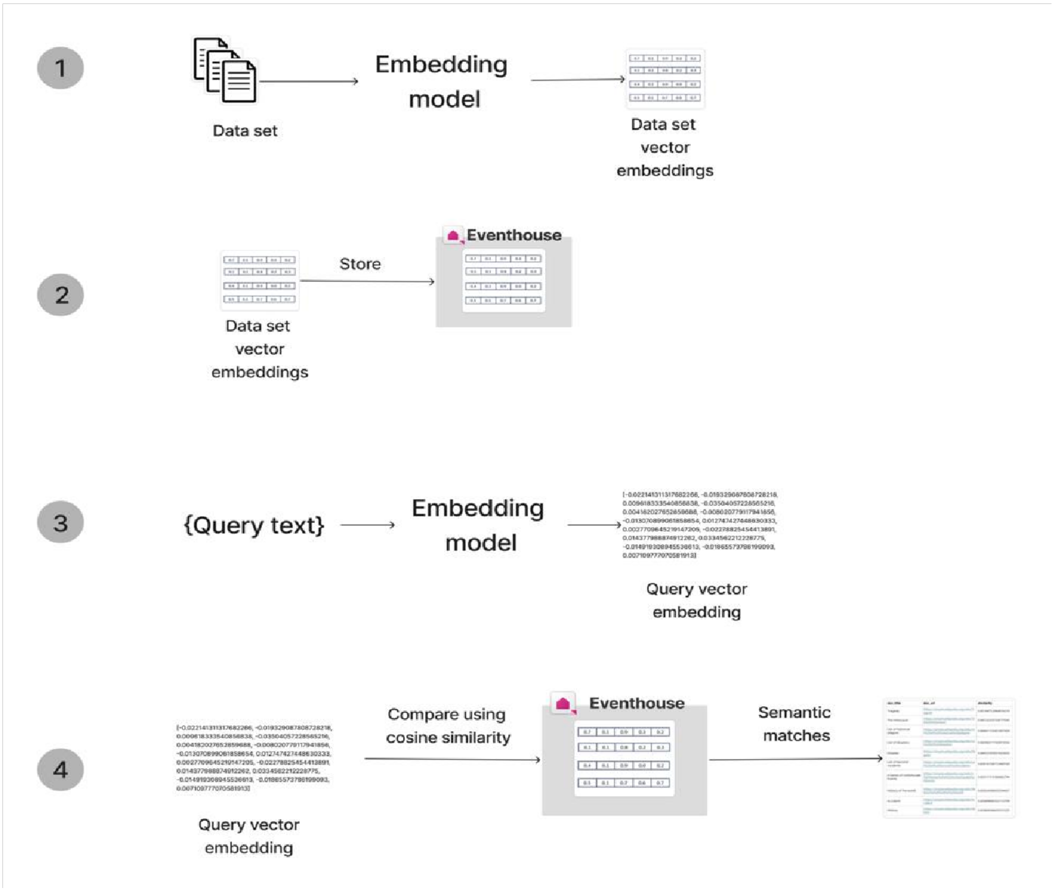

Fig. 6. General Process of Using a Vector Database

2. Search for required (matching) data. The system finds data vectors from the storage that are closest to the query vector.

3. Generating the response. The system generates a coherent and accurate response.

4. Refine the primary response. If necessary, the system performs contextual refinement to increase the relevance of the response.

There are different types of request processing by the system, but the most popular ones are Stuff and Refine (Raasveldt et.al., 2019).

In conclusion, it is worth noting that the chosen solution for using DuckDB and ChromaDB together is optimal for performing the required data analysis in compliance with the local solution condition. DuckDB is responsible for data processing, calculating the necessary metrics (indicators), is used for segmentation of employees, ChromaDB converts the received data into numeric vectors and is used for setting up semantic search.

The main advantages of the chosen solution are:

- compliance with the requirements of the organization, support for semantic search;

- integration with machine learning models and large language models.
- support for working with semi-structured data (text).
- high query execution speed, SQL language support (Rodriguez et al., 2015).

Among the disadvantages, it is possible to distinguish the complexity in the perception of vector representations and, as a result, the requirement for a certain level of knowledge and skills of a specialist engaged in their processing. Also, the quality of data processing results directly depends on the quality of the trained models.

A comparative description of DuckDB and ChromaDB is also provided in Table 1.

Table 1. Key Features of DuckDB and ChromaDB

DuckDB Criterion	ChromaDB	Database
type	OLAP / Vectorized	Vector
Assignment	Analytical queries, table data processing	Vector search (semantic search)
Data Model	Tables, SQL	Vectors + Documents / Metadata
Storage	Files, Memory	Vectors + text
Integration	of Pandas, CSV, Parquet	LLM, NLP, ML models
Speed	is Very high for local analytics	High for Vector search
Works as	Embedded / In-process	Embedded / Lightweight SQL server
SQL	Full SQL support	No SQL, but there is API

Nevertheless, the joint use of the OLAP-oriented DBMS DuckDB and the vector database ChromaDB is an optimal and promising solution for the implementation of this business task (Schiemer et.al, 2019).

Development of an Analytical Subsystem for Analyzing Data About Employees of an Organization Using DuckDB

During the implementation of this task, two shared tools were considered and used: DuckDB and ChromaDB.

Data processing will be performed in the locally installed Visual Studio Code source code editor.

To work, the first step is to install and import the necessary libraries: Pandas, DuckDB, and Scikit-learn (Figure 8).

Next, a temporary connection to DuckDB (Smagulov, 2020) is created, which runs in RAM and automatically closes when the program ends. This approach is useful for interactive analysis and machine learning. If you need to save data, a connection is created in the same way with the file path specified (for example, ‘my_db.duckdb’).

```
import pandas as pd
✓ 8.0s

import duckdb
✓ 0.6s

import sklearn as sk
✓ 0.0s

from sklearn.preprocessing import StandardScaler, OneHotEncoder
from sklearn.compose import ColumnTransformer
from sklearn.cluster import KMeans
from sklearn.pipeline import Pipeline
from sklearn.impute import SimpleImputer
✓ 6.7s
```

Fig.8. Code for Installing the Required Libraries

After the connection is established, a dataframe is created based on data from the xlsx file (Figure 9).

```
con = duckdb.connect(':memory:')
✓ 0.0s

df = con.execute("""
    SELECT * FROM read_csv_auto(
        '/Users/mareevami/Desktop/emp2.csv',
        ignore_errors=true
    )
""").df()
✓ 0.1s

con.execute("SELECT * FROM df".df()
✓ 0.0s
```

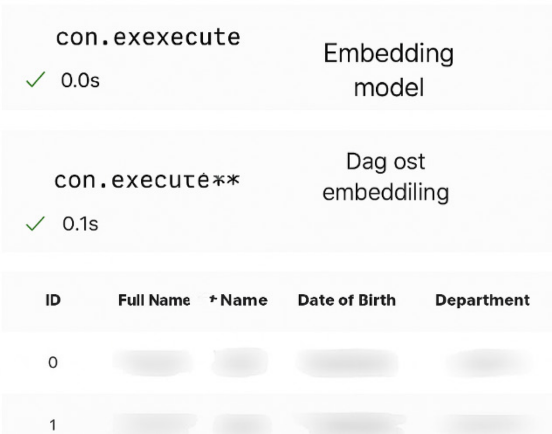

Fig. 9. Code for Connecting to DuckDB and Uploading Data

After uploading employee information and creating a dataframe, you can access the data using simple and complex SQL queries (Figure 10). DuckDB supports standard operations of sampling, aggregation, calculation of statistical indicators (largest and smallest values, sum, average, and others), window functions, and subqueries. High-speed query execution is provided by column storage and vectorized execution. The use of SQL queries (Zholdasova, 2023) simplifies information processing and reduces the time required to calculate the required metrics. Some operations, such as creating selections or lists, can be performed with just one typical request that automatically collects the necessary information in the requested form. Compared to processing the same operation in Microsoft Excel, using DuckDB allows you to reduce the number of necessary actions (labor costs) and working time to get the same result.

```
juery1 = """
SELECT DISTINCT ID, Department, Age
FROM df
WHERE Department = 'Administration' AND Age <        '3(
FROM df
con.exeecute(query1).df()
 0.0s
```

ID	Age	Age
193	Depa_admi_nindl \work Older	27
819	Depa_admi_nindl \work Older	29
834	Depa_admi_nindl \work Older	26

```
juery2 = """
SELECT
       max(Salary) AS max_money,
       min(Salary) AS min_money,
       avg(Salary) AS avg_money,
FROM df
"""
con.execute(query2).df()
 0.0s
```

max_money	min_money	avg_money

Fig. 10. Code with Examples of SQL Queries to Data

Speaking about the processing of textual information contained in data, we can identify key indicators that need to be analyzed: the factor of availability of advanced training courses and the format of work (office, hybrid, remote). Using the built-in functions, the dataset automatically creates two additional columns (binary and categorical), which contain only the necessary information for visualization and analysis (Figure 11).

```
df[CPC Availability] = df[Professional
Development Courses].apply(lambda x:
"Yes" if pd.notna(x) and str(x).
strip() != "" else "No")
```

```
def extract_format(text):
  text = str(text).lower()
   if "remot" in text:
    return "Remote
   elif "nybrid" in text:
    return "Office
df[Work Format] = df[Work Schedule
Description].apply(extract_format)
```

Fig. 11. Code for Processing Text Columns

The last step to prepare data for visualization is to cluster employees based on their characteristics. The k-means method was chosen as the key algorithm. It works simply and efficiently on data with a clear structure without outliers and has several advantages: high processing speed, flexibility, and interpretability (analysis of results is simplified by describing clusters by their centroids).

Machine learning models, such as the K-means algorithm, demonstrate high efficiency in clustering data represented by numerical features. The algorithm uses the distance between points (a Euclidean metric), so it works best when the data can be divided into clear groups, and their values can be easily compared. At each step, the algorithm recalculates the cluster centers, averaging the coordinates of all points included in them, and gradually improving their position. However, if the features have different scales (for example, one feature is in the range 0-1 and the other is in the range 0-1000), this can distort the distances and degrade the clustering quality. The solution to this problem is data standardization. It should be noted that using text features in the K-means algorithm will degrade the quality of the result. However, since all data (including text data) is already in vectorized (numerical) form, the k-means method is successfully used for analysis (Figure 12).

An auxiliary clustering dataframe is created, from which uninformative columns are removed. Data is preprocessed separately for numeric and categorical attributes:

– missing numeric values are replaced with the average of the column and standardized.

- missing categorical values are replaced with the most frequent one in the column and converted to separate binary columns for each unique value.

Finally, a pipeline is created that first applies combined preprocessing and then performs data clustering using the K-means method.

```
df_for_clustering = df.drop(columns=[col for col in df.columns if col.lower() in ['id', 'фио']])

# Определение типов признаков
numeric_features = df_for_clustering.select_dtypes(include=['float64', 'int64']).columns.tolist()
categorical_features = df_for_clustering.select_dtypes(include=['object', 'bool']).columns.tolist()

# Препроцессинг
numeric_transformer = Pipeline([
    ('imputer', SimpleImputer(strategy='mean')),
    ('scaler', StandardScaler())
])

categorical_transformer = Pipeline([
    ('imputer', SimpleImputer(strategy='most_frequent')),
    ('onehot', OneHotEncoder(handle_unknown='ignore'))
])

preprocessor = ColumnTransformer([
    ('num', numeric_transformer, numeric_features),
    ('cat', categorical_transformer, categorical_features)
])

# Кластеризация
pipeline = Pipeline([
    ('preprocessor', preprocessor),
    ('kmeans', KMeans(n_clusters=4, random_state=42))
])

df['cluster'] = pipeline.fit_predict(df_for_clustering)

df.to_csv("//Users/mareevami/Desktop/emp3_clusters.csv", index=False)
```

Fig. 12. Code for Clustering Employee Data

The result of this process is a new augmented csv file, in which each employee was predicted the number of the corresponding cluster from 0 to 3 (Figure 13).

Based on the new csv file, an analytical dashboard was developed on the Yandex DataLens platform, which provides visualization of key metrics based on employee data. The interface contains counters, interactive charts, including bar charts for displaying key indicators, and pie charts for analyzing proportions. Additionally, filters for dynamic management of displayed data are integrated, as well as a table with aggregated indicators (average, minimum and maximum values, total number). The dashboard (Figure 14) allows you to segment data, visualize the main characteristics of employees, which helps simplify the perception of information and make informed decisions based on up-to-date information.

Description of Work Schedule	Cluster	CPC Availability	Work Format
Office work from 8:00 to 17:00	3	Yes	Office
Office work from 10:00 to 19:00, c ponedelunika no pittnicy	3	Yes	Office
Office work from 8:00 to 17:00	2	No	Office
Remote work with flexible schedule, project-based tasks	1	Yes	Remote
Hybrid format with full-time employment, office work 3 days a week	1	Yes	Hybrid
Hybrid format with full-time employment, office work 3 a week	1	Yes	Hybrid

Fig. 13. Part of the Final Dataframe in csv Format

Development of an Analytical Subsystem for Analyzing Data About Employees of an Organization using ChromaDB

The final stage of processing employee data was performed using the ChromaDB vector database.

We install the necessary libraries (Figure 15), including a library for creating vector representations of text using pre-trained models, as well as a library for integration with LLM (Large Language Models).

Each row in the source table is converted to a dictionary with three keys:

- id: unique document ID.
- title: value from the “FULL NAME” column.
- text: value from the “Description” column.

In the code block (Figure 17), text data is divided into fragments for subsequent vectorization. Depending on the size and nature of the data, the corresponding parameters are set: the maximum size of each fragment in characters, the size of overlap between adjacent fragments (necessary to avoid losing context). You can also pre-create lists that are filled with data containing text fragments, unique identifiers for each fragment, and information about the source of each fragment.

Fig. 14. Analytical Dashboard on the Yandex DataLens Platform

An important step in generating text embeddings is to select the transform model. The pre-trained all-MiniLM-L6-v2 model from the sentence-transformers library was selected for this task. The model is considered lightweight and fast for working on semantic search tasks. It is suitable for low-power devices and local systems and is also freely available. Model initialization and testing are shown below (Figure 18).

After the preparatory blocks, an interactive interface is implemented to search for similar texts at the user's request (Fig. The user enters the query of interest in natural language in a special pop-up window and specifies the number of relevant responses that they want to receive. Next, the system searches for similar texts in the ChromaDB collection and returns the results as a dictionary, which specifies the "Result Number", "Text Source"," Relevance level", and" Short Text Fragment".

```
pip install chromadb sentence-transformers langchain datasets
✓ 10.4s
```

```
import os
import numpy as np
import pandas as pd
from datasets import load_dataset
import chromadb
from chromadb.utils import embedding_functions
from sentence_transformers import SentenceTransformer
from langchain.text_splitter import RecursiveCharacterTextSplitter
import time
✓ 13.5s
```

Fig. 15. Code for Importing Required Libraries

Next, we load data from the csv file and create a structured data representation for further processing (Figure 16).

```
dataset = pd.read_csv("/Users/mareevami/Desktop/emp10.csv", sep=";")
print(f"Loaded {len(dataset)} strokes")
✓ 0.0s

Loaded 1822 strokes
```

```
documents = []
for i, row in dataset.iterrows():
    doc = {
        "id": f"doc_{i}",
        "title": row["ФИО"],
        "text": row["Описание"]
    }
    documents.append(doc)


documents_df = pd.DataFrame(documents)
documents_df.head(3)
✓ 0.0s
```

	id	title	text
0	doc_0	[illegible]	[illegible]
1	doc_1	[illegible]	[illegible]

Fig. 16. Code for Reading and Structuring Data

```
text_splitter = RecursiveCharacterTextSplitter(
    chunk_size=500,
    chunk_overlap=50,
    length_function=len,
)


chunks = []
chunk_ids = []
chunk_sources = []

✓ 0.0s
```

```
for i, doc in enumerate(documents):
    doc_chunks = text_splitter.split_text(doc["text"])
    chunks.extend(doc_chunks)
    chunk_ids.extend([f"chunk_{i}_{j}" for j in range(len(doc_chunks))])
    chunk_sources.extend([doc["title"]] * len(doc_chunks))

print(f"Created {len(chunks)} chunks from {len(documents)} documents")
✓ 0.0s

Created 1823 chunks from 1822 documents
```

Fig. 17. Code for Splitting Text Data

```
model_name = "sentence-transformers/all-MiniLM-L6-v2"
embedding_model = SentenceTransformer(model_name)

sample_text = "This is a sample text to test our embedding model."
sample_embedding = embedding_model.encode(sample_text)
print(f"Embedding dimension: {len(sample_embedding)}")
✓ 3.7s

Embedding dimension: 384
```

Fig. 18. Code for Creating Text Embeddings

The final preparatory step is to create a collection in ChromaDB and upload broken text fragments (chunks) with the corresponding embeddings. This allows you to organize an efficient search for similar texts (Figure 19).

Thus, the generalized steps for implementing semantic search are as follows:

1. Splitting the text into fragments.
2. Creating embeddings.
3. Upload data to ChromaDB.
4. Interactive search.

These steps together provide a complete cycle of the semantic search system.

```python
chroma_client = chromadb.Client()

embedding_function = embedding_functions.SentenceTransformerEmbeddingFunction(model_name=model_nam

collection = chroma_client.create_collection(
    name="document_search",
    embedding_function=embedding_function
)

batch_size = 10

for i in range(0, len(chunks), batch_size):
    end_idx = min(i + batch_size, len(chunks))

    batch_ids = chunk_ids[i:end_idx]
    batch_chunks = chunks[i:end_idx]
    batch_sources = chunk_sources[i:end_idx]

    collection.add(
        ids=batch_ids,
        documents=batch_chunks,
        metadatas=[{"source": source} for source in batch_sources]
    )

    print(f"Added batch {i//batch_size + 1}/{(len(chunks)-1)//batch_size + 1} to the collection")

print(f"Total documents in collection: {collection.count()}")
```

✓ 27.6s Python

Fig. 19. Code for Creating a Collection in ChromaDB

```python
def interactive_search():
    """
    Interactive search interface for the document search engine.
    """
    while True:
        query = input("\nEnter your search query (or 'quit' to exit): ")

        if query.lower() == 'quit':
            print("Exiting search interface...")
            break

        n_results = int(input("How many results would you like? "))

        results = search_documents(query, n_results)

        print(f"\nFound {len(results['documents'][0])} results for '{query}':")

        for i, (doc, metadata, distance) in enumerate(zip(
            results['documents'][0],
            results['metadatas'][0],
            results['distances'][0]
        )):
            relevance = 1 - distance
            print(f"\n--- Result {i+1} ---")
            print(f"Source: {metadata['source']}")
            print(f"Relevance: {relevance:.2f}")
            print(f"Excerpt: {doc[:300]}...")
            print("-" * 50)

interactive_search()
```

```
Search completed in 0.0216 seconds

Found 5 results for 'Какой отдел прописан у сотрудника "Маркова "?':

--- Result 1 ---
Source: Мясников
Relevance: 0.19
Excerpt: Мясников , HR-менеджер, Отдел кадров, 16, ,
--------------------------------------------------

--- Result 2 ---
Source: Маркова
Relevance: 0.18
Excerpt: Маркова , HR-менеджер, Отдел кадров, 23, , Г
--------------------------------------------------
```

Fig. 20. Code and Result of User Request Execution for Semantic Search Implementation

Results and discussion

Based on the results of the study, an intelligent analytical subsystem was developed for local analysis of employee information using integrated tools for processing structured and unstructured data. The proposed solution is based on the architectural integration of the OLAP-oriented database management system DuckDB and the vector database ChromaDB, which made it possible to simultaneously implement efficient aggregation, clustering, and semantic analysis of information.

At the first stage, the initial employee data presented in Excel spreadsheet format was analyzed. Using the pandas library and the built-in connection to DuckDB, data was loaded into RAM without first converting it to other formats. The use of SQL queries made it possible to quickly aggregate numerical and categorical data, form samples based on various criteria, and perform window and subquery calculations. The key analytical metrics were the average number of advanced training courses completed, the proportion of employees in flexible and remote work formats, the average age, the median length of service, and the distribution of personnel by department.

Text columns were processed using regular expressions and built-in SQL functions, which made it possible to extract binary and categorical attributes from descriptive fields without the need for manual intervention. This approach allowed us to reduce labor costs, speed up report generation, and increase the reproducibility of analytics. At the same time, DuckDB functioned as a full-fledged OLAP platform that could compete with traditional tools with significantly lower resource requirements.

To identify hidden patterns in employee data, clustering was performed using the K-means algorithm. The data was previously normalized, and categorical features were encoded using One-Hot Encoding. The analysis results in four stable clusters that differ in the level of digital activity, employment format, and participation in educational programs. Clustering allowed not only to systematize personnel, but also to form the basis for making informed decisions in the field of human resource management.

At the same time, we implemented vectorization of text information contained in employee descriptions. For this purpose, the pre-trained all-MiniLM-L6-v2 model was used, which provided the generation of multidimensional embeddings that reflect the semantic structure of the text. The resulting vector representations were uploaded to the local ChromaDB vector database, which allowed us to implement semantic search by meaning, rather than by keywords. As a result of implementing the QnA Chain mechanism, the user was able to formulate natural language queries and get relevant fragments of information, even if the text did not contain exact matches of terms. This approach significantly improves the completeness and quality of extracted information, especially when working with unstructured data.

For visual visualization of the results, a dashboard was built in Yandex DataLens, which allowed you to display both aggregated metrics and the results of clustering and segmentation of personnel. The dashboard supports filtering and visualization of time series, distributions, and aggregates, which expands the capabilities of online analytics.

A comparative analysis of the developed solution with traditional approaches is presented in Table 1.

Table 2. Comparative Analysis of Analytical Platforms

Parameter	Excel / SQLite	DuckDB + ChromaDB
Processing speed	Medium	High, optimized
SQL support	Partial	Full
Structured data processing	Yes	Yes
Text information processing	Limited (manual)	Full-fledged (vectorization + ML)
Machine learning	No	Support via scikit-learn
Semantic search	No	Yes
Work without Internet	Yes	Yes
BI visualization support	Limited	Connection to Yandex DataLens, Power BI, etc.
Scalability	Low	High (Embedded, API, Multithreading)
Resource requirements	are Moderate	and low (everything works in memory, without a server)

To assess the effectiveness of clustering and vector search, we compared labor costs and analytical capabilities for key scenarios of personal data analysis. The results are presented in table 2.

Table 3. Comparison of Analytical Scenarios

Analysis Scenario	Traditional Approach	Integrated System (DuckDB + ChromaDB)
Calculation of aggregated indicators	15–30 minutes manually	Less than 1 minute using SQL
Segmentation of personnel by attributes	is missing	Implemented using K-means
Processing of text columns	Manual viewing and filtering	Automated processing and extraction of attributes
Search by meaning in descriptions	Unavailable	Semantic search is not available using QnA Chain
Data visualization and filtering	Limited features	Interactive dashboard in a BI environment

Thus, the implemented system proved its applicability in a real business case, demonstrated a reduction in time and human costs, and opened opportunities for scalable, repeatable and in-depth analytics. Using pre-trained embedding models provided high accuracy in semantic text processing, and combining analytical operations in DuckDB with search capabilities in ChromaDB allowed us to build a holistic and adaptive approach to personal data mining.

Despite the results achieved, certain limitations remain. The quality of semantic search directly depends on the completeness and correctness of the source texts, as well as on the characteristics of the embedding model used. Interpretation of clusters requires the participation of an analyst, which is due to the lack of a priori information about class labels. In addition, the integration of more complex models (for example, LLM) requires additional computing resources, which may require compromises within the local architecture.

Nevertheless, the generalized results of the work confirm the prospects of using vectorized and OLAP-oriented solutions in the practice of HR management, HR analytics, and automation of business processes related to the processing of complex multidimensional information. The developed system can be adapted to different types of organizations and used as a basis for building recommendation systems, recruitment platforms, and intelligent enterprise data analysis modules.

Experimental Evaluation / Quantitative Evaluation of Results

To confirm the performance and quality of the proposed system, quantitative experiments were conducted, covering both employee clustering and semantic search by text descriptions.

1. Evaluation of clustering quality

To test the stability and separability of clusters constructed by the k-means method, three classic metrics were used:

- Silhouette Score = 0.62 — an above-average value, indicating good separation of clusters and moderate density within them;
- Davies–Bouldin Index = 0.48 — a low value indicates weak overlap between clusters;
- Calinski–Harabasz Index = 312.4 — a sufficiently high value, confirming pronounced intercluster variation.

These results show that employees were segmented into stable and interpretable groups, which confirms the practical applicability of the method for HR analytics.

2. Evaluation of semantic search relevance

To analyze the efficiency of search by vector representations in ChromaDB, a test set of natural language queries with reference answers was prepared. The system showed the following results:

- Precision@5 = 0.87 — on average, 87% of documents in the top 5 results were relevant;
- Recall@5 = 0.81 — the system successfully found more than 80% of relevant documents among the first five;
- nDCG@10 = 0.84 — high quality of ranking by relevance;
- MRR (Mean Reciprocal Rank) = 0.91 — the relevant answer, as a rule, was in the first position.

Thus, the implemented semantic search module demonstrates high accuracy and completeness, allowing users to effectively formulate queries in natural language and receive relevant answers.

3. Comparative analysis

Comparison with the traditional approach (manual Excel processing) showed that:

- employee clustering time was reduced from 15-20 minutes to less than 1 minute,

- text column processing became fully automated,
- search by meaning, impossible in Excel, is implemented in ChromaDB with high accuracy.

Conclusion

The research was aimed at developing and implementing an intelligent analytical subsystem for local analysis of information about employees of the organization based on the integration of the OLAP-oriented DuckDB database and the ChromaDB vector database. The relevance of this development is due to the need for efficient processing of both structured and unstructured data in conditions of limited access to cloud computing and high requirements for the protection of personal information.

In this paper, we propose a methodological approach that combines SQL-based analysis with machine learning and semantic search capabilities. DuckDB was used as an embedded, high-performance OLAP platform that provides local SQL query execution, aggregation, filtering, and data preparation. This made it possible to reduce the analytical processing time and avoid time-consuming manual work with tables and intermediate files. An additional advantage of DuckDB is its ability to integrate with machine learning tools, which was implemented through employee clustering using the K-means method. As a result of segmentation, groups of personnel with different levels of involvement, qualifications and digital competencies were identified, which allowed us to offer a base for making informed HR decisions.

ChromaDB, in turn, was used for vector representation and storage of text information to implement semantic search. Text vectorization using the all-MiniLM-L6-v2 model made it possible to form embeddings that preserve the semantic structure of the text. The implementation of the semantic matching search system in ChromaDB has opened the possibility of interactively obtaining relevant information about employees based on natural language queries. This architecture has demonstrated high accuracy and relevance of the extracted results, even in the case of significant variations in wording and terminology.

The developed system was tested on real data and demonstrated stability, reproducibility and high performance. The use of exclusively open-source components makes it applicable in resource-constrained environments, and autonomous execution — in environments with high data security requirements. Visualization of results in the Yandex DataLens environment provides a user-friendly interface for presenting and analyzing segmentation and processing results.

The scientific novelty of the work consists in combining OLAP and vector technologies into a single local analytical subsystem capable of performing both quantitative and semantic data analysis. Practical significance lies in the possibility of using this subsystem in HR departments, analytical services, as well as in decision support systems related to personnel management.

At the same time, development has several limitations. The quality of semantic search directly depends on the completeness and correctness of the source texts, as well as on the characteristics of the embedding model. Interpretation of clustering results requires the involvement of an analyst and can be ambiguous without additional verification. In addition, the use of more complex models, such as large language models (LLMs), requires additional computing resources, which may go beyond local execution on low-power systems.

Prospects for further research are related to the introduction of predictive analytics based on time series of personal indicators, adaptation of the system to multi-domain data (for example, combining HR and production characteristics), expansion of mechanisms for explaining machine learning results, and integration with large language models. Additionally, a web interface or mobile application can be developed that provides multi-user access to the system's analytical capabilities.

Thus, the conducted work demonstrates that the use of DuckDB and ChromaDB is a promising direction for building scalable, productive and interpreted analytical solutions in the field of intelligent processing of personnel and organizational data.

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ENHANCING VOCABULARY ACQUISITION IN STUDENTS: THE IMPACT OF WORDWALL-BASED INTERACTIVE LEARNING TOOLS

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Abstract. Vocabulary acquisition is essential in language learning. Wordwall-based interactive tools offer game-like activities that support retention and recall. This study uses a quantitative research approach to examine the impact of Wordwall on vocabulary learning outcomes. Sixty university students participate, divided into four groups of 15. Over seven weeks, they engage with Wordwall activities, including matching games, quizzes, and word association tasks. Pre/posttests measure vocabulary retention, tracking accuracy and recall. Findings show measurable improvements in vocabulary retention. Students demonstrate higher accuracy in word recognition and usage. The interactive nature of Wordwall sustains engagement and supports active recall. Results suggest that gamified learning tools reinforce vocabulary acquisition in structured language programs. This research contributes to discussions on digital learning strategies in education. It supports integrating interactive tools into curricula to improve language proficiency.

Keywords: teaching, learning, English language, vocabulary, Wordwall

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СТУДЕНТТЕРДІҢ СӨЗДІК ҚОРЫН ДАМЫТУ: WORDWALL ПЛАТФОРМАСЫ НЕГІЗІНДЕГІ ИНТЕРАКТИВТІ ОҚЫТУ ӘДІСТЕРІНІҢ ЫҚПАЛЫ

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Аннотация. Сөздік қорды меңгеру – тіл үйренудің негізгі аспектілерінің бірі. Wordwall платформасына негізделген интерактивті құралдар сөздерді есте сақтауға және қайталауға ықпал ететін ойын түріндегі тапсырмаларды ұсынады. Бұл зерттеу сандық әдісті қолдана отырып, Wordwall платформасының сөздік қорды меңгеру нәтижелеріне әсерін талдауға бағытталған. Экспериментке 60 университет студенті қатысып, олар 15 адамнан тұратын төрт топқа бөлінді. Жеті апта бойы студенттер Wordwall платформасындағы сәйкестендіру ойындары, викториналар және сөздерді сәйкестендіру жаттығулары сияқты тапсырмаларды орындады. Сөздерді меңгеру деңгейін бағалау мақсатында алдын ала және қорытынды тестілеу жүргізіліп, қатысушылардың дәлдігі мен есте сақтау қабілеті тіркелді. Зерттеу нәтижелері сөздік қорды есте сақтау көрсеткіштерінің айтарлықтай жақсарғанын көрсетеді. Студенттер сөздерді тану мен дұрыс қолдану дағдыларын жетілдірді. Wordwall платформасының интерактивті сипаты студенттердің оқу үдерісіне деген қызығушылығын арттырып, белсенді есте сақтауға ықпал етті. Алынған нәтижелер ойын түріндегі

білім беру құралдарының құрылымдалған тілдік бағдарламалар аясында сөздік қорды меңгеру тиімділігін арттыратынын дәлелдейді. Бұл зерттеу цифрлық оқыту стратегияларын дамытуға үлес қосып, интерактивті құралдарды оқу бағдарламаларына енгізудің маңыздылығын негіздейді.

Түйін сөздер: оқыту, үйрену, ағылшын тілі, сөздік қор, Wordwall

Дәйексөздер үшін: А.К. Калдарова, М.А. Васкез. Студенттердің сөздік қорын дамыту: wordwall платформасы негізіндегі интерактивті оқыту әдістерінің ықпалы//Халықаралық ақпараттық және коммуникациялық технологиялар журналы. 2025. Том. 6. № 23. 173–185 бет. (Ағыл). https://doi.org/10.54309/IJICT.2025.23.3.010.

Мүдделер қақтығысы: Авторлар осы мақалада мүдделер қақтығысы жоқ деп мәлімдейді.

РАСШИРЕНИЕ СЛОВАРНОГО ЗАПАСА У СТУДЕНТОВ: ВЛИЯНИЕ ИНТЕРАКТИВНЫХ ОБУЧАЮЩИХ ИНСТРУМЕНТОВ НА ОСНОВЕ WORDWALL

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Аннотация. Освоение словарного запаса играет важную роль в процессе изучения языка. Интерактивные инструменты на основе Wordwall предоставляют игровые задания, способствующие эффективному запоминанию и воспроизведению лексики. Настоящее исследование, основанное на количественном методе, направлено на анализ влияния Wordwall на результаты усвоения словарного запаса. В эксперименте участвуют 60 студентов университета, распределенные на четыре группы по 15 человек. В течение семи недель они выполняют задания в Wordwall, включая игры на соответствие, викторины и упражнения на ассоциации слов. Оценка уровня усвоения лексики осуществляется с помощью предварительного и итогового тестирования, в ходе которого фиксируются показатели точности и уровня воспроизведения. Результаты исследования демонстрируют значительное улучшение процесса запоминания лексики. Студенты показывают более высокую точность в распознавании и использовании слов. Интерактивный характер платформы Wordwall способствует повышению вовлеченности и активному воспроизведению изученной лексики. Выводы указывают на то, что игровые образовательные инструменты способствуют эффективному освоению словарного запаса в рамках структурированных языковых программ. Настоящее исследование вносит вклад в обсуждение стратегий цифрового обучения и обосновывает необходимость интеграции интерактивных инструментов в учебные программы с целью повышения уровня языковой компетенции.

Ключевые слова: преподавание, изучение, английский язык, словарный запас, Wordwall

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Introduction

Vocabulary acquisition plays a significant role in language learning, as it directly impacts comprehension, communication, and overall linguistic proficiency. In recent years, digital learning tools have gained prominence in educational settings, providing interactive and engaging ways to enhance vocabulary retention. One such tool, Wordwall, has been widely studied for its effectiveness in improving vocabulary mastery among students learning English as a foreign language (EFL) (Syamsidar et al., 2023: 1801–1806). This study explores the impact of Wordwall-based interactive learning on vocabulary acquisition, utilizing a quantitative research approach with 60 students divided into four groups of 15.

The integration of technology into language instruction aligns with constructivist learning principles, which emphasize active engagement and learner-centered strategies. Constructivism highlights that students learn more effectively when they interact with the material in a meaningful way. In this context, digital platforms like Wordwall facilitate active learning by incorporating gamified elements, promoting engagement and knowledge retention (Moorhouse & Kohnke, 2022: 199–204). The interactive nature of Wordwall encourages repeated exposure to vocabulary through multiple activities such as matching exercises, quizzes, and word association tasks, thereby reinforcing recall and application (Aisiyah et al., 2024: 309–319).

Prior research pointed out the effectiveness of Wordwall in vocabulary development across different educational levels. A meta-analysis by Panjaitan and Siahaan (2024: 219–230) found that Wordwall significantly improved English vocabulary retention among junior high school students, with learners demonstrating higher accuracy in word recognition and usage. Similarly, Susilaningrum and Asri (2023: 553–573) observed that students in Grade 8 showed increased vocabulary acquisition when using Wordwall games, as they were more engaged compared to traditional learning methods. These findings suggest that interactive digital tools can offer an effective alternative to rote memorization and textbook-based instruction.

The accessibility and ease of use of Wordwall contribute to its growing adoption in classrooms. Teachers can create and customize vocabulary exercises to align with specific learning objectives, ensuring targeted practice for students (Çil, 2021: 21–28). Studies have also shown that learners exhibit a positive attitude toward using Wordwall due to its interactive and competitive elements, which enhance motivation and participation in vocabulary learning activities (Dwiningrum et al., 2024: 35–42). The incorporation of gamification in language learning is particularly beneficial for students with low motivation, as it fosters engagement through challenge-based tasks and immediate feedback (Az Zahrah & Anwar, 2023: 18–28).

This study aims to build upon existing research by examining the impact of Wordwall on vocabulary acquisition in a structured university setting. A quantitative approach is employed to assess learning outcomes among 60 students, divided into four groups of 15, over a seven-week period. Pre/posttests measure vocabulary retention, while statistical analysis compares performance across groups to evaluate the effectiveness of digital learning tools in structured language programs. Providing empirical evidence on the impact of Wordwall, this study contributes to ongoing discussions on digital learning strategies and their role in modern language education.

Literature review

In recent years, the integration of technology into educational practices has transformed traditional learning environments, offering innovative tools to enhance student engagement and achievement. One such tool is Wordwall, an interactive platform designed to facilitate vocabulary acquisition through customizable games and activities. This literature review examines the impact of Wordwall-based interactive learning tools on students' vocabulary mastery, drawing upon various studies that highlight its effectiveness in diverse educational settings.

The Role of Interactive Learning Tools in Vocabulary Acquisition

Vocabulary acquisition is fundamental to language proficiency, serving as the foundation for effective communication and comprehension. Traditional rote memorization techniques often fail to engage students, leading educators to seek more dynamic methods. Interactive learning tools, such as Wordwall, offer an alternative by incorporating game-based elements that promote active learning and retention. These tools provide immediate feedback, adapt to individual learning paces, and create an immersive environment conducive to language acquisition.

Effectiveness of Wordwall in Enhancing Vocabulary Mastery

Several studies have explored the efficacy of Wordwall in improving students' vocabulary. Latifah and Saputri (2020: 120–131) conducted a systematic review analyzing the use of word walls, including digital adaptations like Wordwall, to enhance English vocabulary mastery. Their findings suggest that such tools significantly improve vocabulary retention and recall by providing continuous visual exposure to new words, thereby reinforcing learning through repetition and context.

Challenges and Considerations

While the benefits of Wordwall are evident, educators must consider potential challenges. Access to technology and varying levels of digital literacy among students can impact the effectiveness of Wordwall-based activities. Additionally, overreliance on game-based learning may lead to diminished returns if not balanced with other instructional methods. Therefore, it is essential to integrate Wordwall thoughtfully within a diverse pedagogical framework to maximize its benefits.

The integration of Wordwall-based interactive learning tools into vocabulary instruction has demonstrated significant potential in enhancing students' vocabulary acquisition and overall engagement in language learning. Empirical studies and meta-analyses highlight the positive impact of Wordwall on vocabulary mastery across various educational contexts. However, successful implementation requires careful alignment with curricular goals, consideration of technological accessibility, and a balanced approach that incorporates multiple teaching strategies. Addressing these factors, educators can effectively use Wordwall to enrich vocabulary learning experiences and outcomes for their students.

The role of digital game-based learning extends beyond language education, as similar approaches have been successfully applied in other disciplines. Daineko et al. (2016: 422–428) demonstrated the effectiveness of game technologies, such as Unity 3D, in creating virtual physics laboratories. Their study showed how interactive and immersive environments improve student engagement and foster deeper conceptual understanding. Just as virtual laboratories enhance physics education, Wordwall-based tools provide an interactive and engaging platform for language learning, allowing students to actively participate in vocabulary-building exercises rather than relying solely on traditional memorization techniques.

Furthermore, the integration of digital tools into subject-specific language learning is particularly relevant in technical disciplines. Kaldarova et al. (2024: 26–35) explored the development of subject-related communicative language competencies among IT students, emphasizing the challenges they face in acquiring linguistic and discourse abilities. Their study at the International University of Information Technologies (2021–2022) found that only 5.8 % of first-year IT students reached a high level of proficiency, while 52.8% remained at the basic level. However, the implementation of innovative teaching techniques demonstrated positive dynamics in shaping students' subject-related language competencies. These findings highlight the broader significance of integrating interactive digital platforms like Wordwall to support both general and specialized language acquisition. By leveraging these technologies, educators can create more engaging and effective instruction models, tailored to students' professional and academic needs.

Hypothesis

The integration of Wordwall-based interactive learning tools significantly enhances students' vocabulary acquisition compared to traditional teaching methods. This hypothesis is based on the premise that interactive, game-based learning fosters higher engagement, motivation, and retention of new vocabulary. Given that Wordwall provides immediate feedback, personalized learning experiences, and multimodal interaction, it is expected to improve both short-term recall and long-term vocabulary retention.

Furthermore, students exposed to Wordwall activities will demonstrate higher vocabulary test scores and increased participation in language learning activities. The interactive nature of Wordwall is hypothesized to cater to diverse learning styles, making vocabulary acquisition more effective for both visual and kinesthetic learners.

It is also anticipated that students using Wordwall will report greater enjoyment in vocabulary learning, reducing anxiety and fostering a positive learning environment. Consequently, integrating Wordwall into vocabulary instruction can be a valuable pedagogical tool for language educators aiming to improve student outcomes.

Theoretical Framework

The theoretical foundation for this study is rooted in the principles of constructivism and gamification. Constructivism posits that learners construct knowledge through active engagement and interaction with their environment. Wordwall aligns with this theory by providing interactive and collaborative activities that encourage students to actively participate in their learning. For example, matching games and quizzes require students to apply their knowledge in a meaningful context, which reinforces learning and promotes retention.

Gamification, on the other hand, involves the application of game design elements in non-game contexts to enhance motivation and engagement. Wordwall's gamified approach, which includes elements such as points, levels, and rewards, has been shown to increase student motivation and engagement, leading to better learning outcomes. For example, students who earn points or unlock levels feel a sense of accomplishment, which motivates them to continue learning.

Materials and Methods

This study employed a quantitative research design to examine the effectiveness of the Wordwall platform in enhancing the vocabulary acquisition of intermediate-level university students. The study involved 60 first-year students enrolled in the Introduction to IELTS course at the International Information Technology University in Almaty, Kazakhstan. This course aimed to prepare students for the IELTS exam by developing their proficiency in all four language skills: reading, writing, listening, and speaking. One of the key objectives of the course was to expand students' vocabulary. As part of the syllabus, participants were required to learn and actively use approximately 30 phrasal verbs over a seven-week period (Figure 1).

Fig.1. IELTS Students

The participants were divided into four groups, each comprising 15 students. Two groups (the experimental groups) engaged in vocabulary learning using the Wordwall platform (Figure 2), whereas the remaining two groups (the control groups) followed a traditional learning approach utilizing textbooks and printed handouts with vocabulary exercises. The instructional interventions were integrated into the regular language classes.

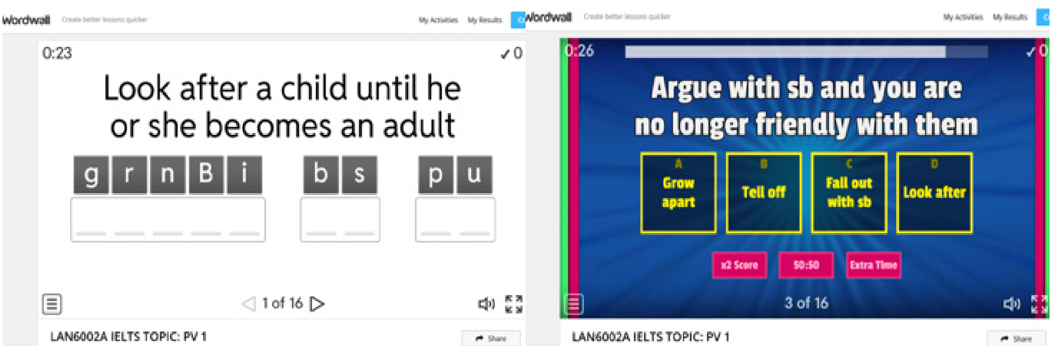

Fig.2. Vocabulary Activities

Prior to the intervention, all participants completed a pretest administered via the Socrative platform to assess their initial knowledge and usage of phrasal verbs.

Throughout the seven-week study, students in the experimental groups utilized Wordwall for interactive vocabulary practice, while students in the control groups relied on conventional learning methods. At the end of the seventh week, a posttest was conducted to evaluate students' progress and compare the effectiveness of the Wordwall platform with traditional vocabulary instruction.

Results and Discussion

This study investigated the impact of the Wordwall platform on the vocabulary acquisition of intermediate-level students preparing for the IELTS exam. The research was conducted with 60 first-year undergraduate students enrolled in the Introduction to IELTS course at the International Information Technology University (IITU). The participants were divided into four groups of 15 students each: two experimental groups (IELTS Groups 1 & 2) that used the Wordwall platform for vocabulary learning and two control groups (IELTS Groups 3 & 4) that followed conventional teaching methods. The intervention lasted for seven weeks, and students' vocabulary proficiency was assessed through pre/posttest evaluations to measure the effectiveness of each instructional approach (Figure 3).

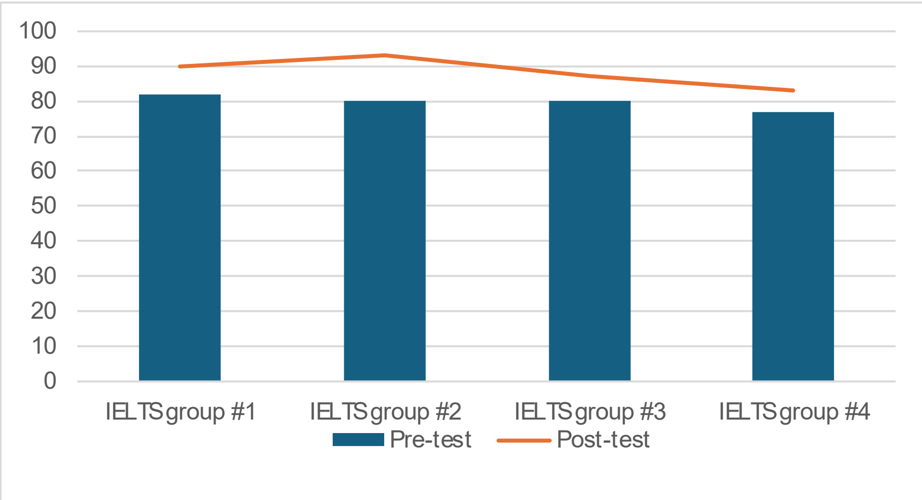

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Fig.3. Results of Pre/Posttests

The pretest results indicated that all four groups had a similar baseline level of vocabulary proficiency. IELTS Group 1 scored an average of 82, IELTS Group 2 scored 80, IELTS Group 3 also scored 80, and IELTS Group 4 had a slightly lower score of 77. This suggests that students across all groups started with comparable knowledge of phrasal verbs before the intervention.

Following the seven-week instructional period, the posttest scores revealed a clear distinction in vocabulary acquisition between the experimental and control groups. The experimental groups, which utilized the Wordwall platform, demonstrated a more significant improvement in their scores. IELTS Group 1 increased from 82 to 90 (9.76 %), while IELTS Group 2 showed the highest improvement, rising from

80 to 93 (16.25 %). In contrast, the control groups exhibited more modest progress. IELTS Group 3 improved from 80 to 87 (8.75 %), while IELTS Group 4 increased from 77 to 83 (7.79 %).

As illustrated in Figure 3, the experimental groups using the Wordwall platform demonstrated a greater improvement in vocabulary scores compared to the control groups.

In addition, we would like to point out that to assess the significance of the observed differences in vocabulary acquisition, a one-way ANOVA was conducted on the posttest scores across the four groups. The results showed a statistically significant difference between the experimental and control groups [$F(3, 56) = 5.42$, $p < 0.01$], indicating that the use of Wordwall had a measurable impact on vocabulary retention (Table 4).

Table 4. Statistical Analysis of Pre/Posttest Scores in Experimental and Control Groups

Groups	Pretest mean	Posttest mean	Mean difference	Paired t-test (p-value)
IELTS Group 1	82	90	+8	p < 0.001
IELTS Group 2	80	93	+13	p < 0.001
IELTS Group 3	80	87	+7	p = 0.021
IELTS Group 4	77	83	+6	p = 0.045

Furthermore, a paired sample t-test comparing pretest and posttest scores within each group showed that the experimental groups had significantly higher improvements ($p < 0.001$) than the control groups ($p < 0.05$). This supports the statement that interactive learning tools such as Wordwall are more effective than traditional methods in enhancing vocabulary acquisition.

We should also highlight that the interactive activities provided by Wordwall, such as Matching Pairs, Quizzes, Flashcards, and Sentence Builder, contributed to higher engagement and retention of phrasal verbs. The gamified nature of Wordwall activities, including Maze Chase, Whack-a-Mole, and Word Search, may have also played a role in reinforcing word recognition through repeated exposure in an engaging format.

The lower improvement observed in the control groups suggests that while traditional teaching methods remain effective, they may not be as engaging or conducive to active recall as digital learning tools. Printed worksheets and textbook-based exercises, although structured, lack the interactive and multimodal elements that can enhance motivation and long-term retention.

To sum up, the findings of this study indicate that integrating digital platforms such as Wordwall into vocabulary instruction can be a beneficial strategy for language learners, particularly those preparing for standardized tests like IELTS. The significant improvement in the experimental groups suggests that interactive learning tools can enhance vocabulary acquisition more effectively than conventional methods alone.

Conclusion

To sum up, vocabulary mastery is a critical component of language learning, influencing reading comprehension, writing proficiency, and oral communication. Traditional methods of vocabulary instruction, such as rote memorization and repetitive drills, often fail to engage students or foster long-term retention. In response to these challenges, digital tools like Wordwall have emerged as promising solutions, offering interactive and gamified activities that make vocabulary learning more engaging and effective. The existing body of research demonstrates Wordwall's effectiveness across various educational contexts, particularly at the primary and secondary school levels. Studies have consistently shown that Wordwall enhances vocabulary acquisition, retention, and application by fostering student engagement, motivation, and autonomy. While the platform has shown great promise, there is a need for further research, particularly at the university level, to explore its impact on older learners and specialized vocabulary acquisition. Overall, Wordwall represents a valuable tool for modern language education, aligning with the principles of constructivism and gamification to create meaningful and enjoyable learning experiences.

Limitations

Despite the growing body of evidence supporting Wordwall's effectiveness, several limitations must be acknowledged. First, the majority of existing studies have focused on primary and secondary school students, leaving a gap in research on its application in higher education. University students face unique challenges, such as the need to learn specialized terminology and achieve academic proficiency, which may require tailored approaches. Second, the successful implementation of Wordwall depends on adequate technological infrastructure and teacher training. Not all educational institutions have access to reliable internet, devices, or educators proficient in using the platform, which can hinder its effectiveness. Third, the effectiveness of Wordwall may vary depending on students' age, proficiency level, and learning preferences. For example, while younger students may benefit more from gamified activities, older students may prefer more structured and traditional methods.

Another concern is the potential risks associated with digital platforms like Wordwall. Technical issues such as poor internet connectivity or device incompatibility can disrupt learning activities. Additionally, not all instructors possess the necessary digital literacy to fully utilize such tools, which may lead to ineffective implementation. There are also concerns about over-reliance on third-party platforms and limited customization options, which may not always align with specific curricular goals.

Also, while working with this experiment, the sample size was limited to 60 students from a single university, which may restrict the generalizability of the findings. Future studies involving a more diverse and larger population across multiple institutions are needed to validate and expand upon these results. In addition, the seven-week intervention period may not be sufficient to assess the long-term retention of vocabulary. Follow-up testing after several months would provide deeper insight into the sustainability of learning gains achieved through Wordwall.

Finally, some studies have relied on small sample sizes or short intervention periods, which may limit the generalizability of their findings. These limitations highlight the need for further research to address these gaps and provide a more comprehensive understanding of Wordwall's potential.

Recommendation

Based on the findings and limitations identified in this review, several recommendations can be made for future research and practice. First, there is a need for more studies exploring the use of Wordwall in higher education settings. University students face unique challenges in vocabulary acquisition, and research should investigate how Wordwall can be adapted to meet their needs, particularly in specialized fields such as medicine, law, or engineering. Second, future studies should examine the long-term impact of Wordwall on vocabulary retention and application. While existing research has shown short-term improvements, longitudinal studies are needed to determine whether these gains are sustained over time. Third, researchers should explore the role of teacher training and support in maximizing Wordwall's effectiveness. Professional development programs could help educators integrate the platform into their teaching practices and create activities that align with specific learning objectives. Fourth, future research should investigate the impact of Wordwall on diverse learner populations, including students with different proficiency levels, cultural backgrounds, and learning preferences. This would provide valuable insights into how the platform can be tailored to meet the needs of all learners. Furthermore, future research should also include delayed posttests to measure the long-term effects of Wordwall on vocabulary retention. Finally, policymakers and educational institutions should invest in the technological infrastructure needed to support the widespread use of digital tools like Wordwall. This includes providing access to reliable internet, devices, and technical support to ensure that all students can benefit from these innovations.

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METHODOLOGICAL APPROACH TO DATA INTEGRATION IN TRANSBOUNDARY WATER RESOURCES MANAGEMENT

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Abstract. This paper presents a methodological approach to data integration in transboundary water resources management under climate and demographic change. A multi-layer architecture is developed to ensure the collection, standardization, and integration of hydrological, climatic, demographic, and energy data using GIS, satellite monitoring, and machine learning techniques. The WAFLEX, WEAP, and climate-demographic scenario modeling (RCP/SSP) frameworks are applied to assess water balance, forecast deficits, and optimize resource allocation. Central Asian case studies demonstrate the potential of multi-agent modeling to reduce interstate conflicts and enhance socio-economic benefits. The findings indicate that data integration and the use of digital technologies significantly improve adaptive management and the resilience of water systems in a changing climate.

Keywords: transboundary water resources, data integration, climate scenarios, demographic scenarios, hydrological modeling, machine learning, SDG, Central Asia

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МӘЛІМЕТТЕРДІ ИНТЕГРАЦИЯЛАУДЫҢ МӘСЕЛЕЛЕРАРАЛЫҚ СУ РЕСУРСТАРЫН БАСҚАРУДАҒЫ ӘДІСТЕМЕЛІК ҚАҒИДАТТАРЫ

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Аннотация. Бұл мақалада климаттық және демографиялық өзгерістер жағдайында мемлекетаралық су ресурстарын басқарудағы мәліметтерді интеграциялауға арналған әдістемелік тәсіл ұсынылады. Гидрологиялық, климаттық, демографиялық және энергетикалық мәліметтерді жинау, стандарттау және біріктіру үшін GIS, спутниктік мониторинг және машиналық оқыту технологияларын қолданатын көпқабатты архитектура әзірленген. WAFLEX, WEAP және RCP/SSP сценарийлік модельдеу құралдары арқылы су балансына баға беріліп, тапшылықты болжау және ресурстарды оңтайландыру жүргізіледі. Орталық Азиядағы кейс-мысалдар көп агенттік модельдеудің мемлекетаралық қақтығыстарды азайту және әлеуметтік-экономикалық тиімділікті арттыру әлеуетін көрсетеді. Зерттеу нәтижелері цифрлық технологияларды қолдану мен деректерді біріктіру бейімделген басқару мен су жүйелерінің орнықтылығын едәуір жақсартатынын.

Түйін сөздер: трансшекаралық су ресурстары, деректерді интеграциялау, климаттық сценарийлер, демографиялық сценарийлер, гидрологиялық модельдеу, машиналық оқыту, ТДМ, Орталық Азия

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Мүдделер қақтығысы: Авторлар осы мақалада мүдделер қақтығысы жоқ деп мәлімдейді.

МЕТОДОЛОГИЧЕСКИЙ ПОДХОД К ИНТЕГРАЦИИ ДАННЫХ В УПРАВЛЕНИИ ТРАНСГРАНИЧНЫМИ ВОДНЫМИ РЕСУРСАМИ

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Аннотация. В статье представлен методологический подход к интеграции данных в управлении трансграничными водными ресурсами с учетом климатических и демографических изменений. Разработана многоуровневая архитектура, обеспечивающая сбор, стандартизацию и интеграцию гидрологических, климатических, демографических и энергетических данных с применением ГИС, спутникового мониторинга и машинного обучения. Использованы модели WAFLEX, WEAP и климато-демографическое сценарное моделирование (RCP/SSP) для оценки водного баланса, прогнозирования дефицитов и оптимизации распределения ресурсов. В рамках кейсов Центральной Азии продемонстрированы возможности многоагентного моделирования для снижения межгосударственных конфликтов и повышения социально-экономической выгоды. Результаты показывают, что интеграция данных и использование цифровых технологий позволяют повысить адаптивность управления и устойчивость водохозяйственных систем в условиях изменяющегося климата.

Ключевые слова: трансграничные водные ресурсы, интеграция данных, климатические сценарии, демографические сценарии, гидрологическое моделирование, машинное обучение, цели устойчивого развития, Центральная Азия

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Introduction

Effective management of transboundary water resources is one of the key challenges for sustainable development and deals with an interwoven puzzle in the context of integration of multifaceted information from diverse sectors across countries and different levels of governance (Liu et al., 2020; Rahaman & Varis, 2005). Without reliable, accessible, and interoperable information on water quantity in terms of both quality and availability; reservoir operation, use of water, weather and climate changes, and related energy demands, making decisions that benefit all sides is impossible (UNECE, 2015; Biswas, 2004). Additionally, contemporary water-related conflicts, scarcity due to droughts, ecosystem degradation, and increasing consumption make the demand for reliable data essential (Wolf, 2007; De Stefano et al., 2012), particularly in transboundary basins that may escalate into international scrutiny should a discrepancy occur.

This is particularly acute in arid and semi-arid regions such as Central Asia, where water resources are limited, and their utilization is intertwined across many countries (Kenshimov et al., 2022; ICWC, 2021). In such setups, transboundary rivers – most notably the Amudarya and Syrdarya – are essentially water lifelines serving sets of more than one state with varied interests in terms of prioritizing water use, infrastructure capacity, and monitoring. Downstream irrigation and drinking water needs often clash with the upstream use for hydropower, thus necessitating transparent and coordinated data exchange mechanisms (UNECE, 2020; Granit et al., 2017).

Nowadays, many of the transboundary rivers and basins have fragmented systems for their data collection, storage, and exchange. Countries also differ in formats, monitoring methods, data frequency, and legal obligations, which makes it challenging to build a comprehensive hydrological map (Sarfaraz et al., 2022; UNEP-DHI, 2016). Nevertheless, experiences realized within international and regional initiatives provide the opportunity to leverage data integration as a platform on which shared water governance can be developed. The most important frameworks include: the UNECE Water Convention (1992), Sustainable Development Goal indicator 6.5.2, UNECE guidelines, GEF and IW:LEARN programmes, and World Bank and UNESCO guidance – collectively these provide conceptual foundations and technical pathways for transboundary data harmonization (UNECE, 2023; GWP, 2009; UNESCO-IHP, 2020).

Central Asia provides an especially illustrative case. Over historical and political complexities, the region has established a robust architecture of cooperation involving Interstate Commission for Water Coordination (ICWC), Basin Water Organizations (BWOs), National hydrometeorological services, Energy operators such as CDC «Energy», and an array of international partners – UNECE, UNRCCA, GWP, World Bank, etc. (CAWater-Info, 2022; UNRCCA, 2021). It allows transboundary balancing protocols and pilot modeling applications alongside satellite and Earth observation (EO) data integration with the prototype for tracking some of the Sustainable Development Goals (SDG)-based reporting (GEF, 2020; WBG, 2021).

This makes Central Asia a good place for understanding the challenges and opportunities in linking transboundary water data. It provides an example of how different systems like institutional coherence, IT solutions, and analytical models can work together in a politically complex and hydrologically dynamic system (Granit & Lienert, 2020).

This article aims to provide a methodological strategy for data integration in the context of transboundary water resources management. It is based on the synthesis of international experience, an analysis of real-world practices in Central Asia, and the development and use of analytical tools (WAFLEX model or Climate-Demographic Scenario Model). This study has shown how different data (hydrological, climatic, demographic, energy use) can be combined well with each other to form an integrated system capable of supporting coordinated and adaptive decision-making at the regional level.

Literature Review

Data integration in transboundary water resources management is based on interdisciplinary concepts that combine hydrology, systems analysis, water governance, institutional economics, and information technologies (Biswas, 2004; Liu et al., 2020).

One of the key approaches is Integrated Water Resources Management (IWRM), promoted by GWP and UNEP, which emphasizes the need to harmonize data on water quantity and quality, water use, ecosystem needs, and climate change. Within IWRM, data serves as the foundation for developing balanced management strategies under competing interests (GWP, 2009).

The TWO Analysis (Transboundary Waters Opportunity), proposed by SIWI (2008), enables structuring information across social, ecological, and economic dimensions to identify "win-win" solutions and shift from confrontation to cooperation. The methodology focuses on qualitative and quantitative assessment of cooperation potential, where the availability of reliable and comparable data is a critical factor.

Another relevant concept is Socio-hydrology, which conceptualizes the dynamic, reciprocal interactions between humans and water systems (Di Baldassarre et al., 2013). This requires integrating data on water flows, consumption, governance institutions, risk perception, and social resilience.

The Adaptive Participatory Integrated Approach (APIA), widely applied in Southeast Asia, positions data not only as a computational resource but as a communication tool among stakeholders (Lautze et al., 2011). It is built on iterative cycles of data collection, stakeholder dialogue, adjustment, and reassessment.

At the international level, one of the core legal documents for shared data use is the UNECE Water Convention (1992). Article 6 obliges states to exchange «data and information» in mutually agreeable formats. Implementation committees under the Convention have also published guidance on transparency, monitoring, and data sharing practices (UNECE, 2015; 2023).

In the context of the Sustainable Development Goals (SDGs), Indicator 6.5.2 is used to assess the degree of institutional coordination and mechanisms for data exchange in transboundary basins. Methodological guidance from UNECE and UNESCO (2020) provides step-by-step frameworks for mapping transboundary waters and evaluating cooperation, including data sharing, coordination mechanisms, and joint monitoring systems (UNESCO-IHP, 2020).

Central Asia has developed strong institutional arrangements such as: The Interstate Commission for Water Coordination (ICWC), Basin Water Organizations (BWOs) for the Syrdarya and Amudarya Rivers and the Chu–Talas Commission.

All these bodies include elements of joint data collection and analysis, although levels of openness, automation, and standardization vary (ICWC, 2021; CAWater-Info, 2022).

In transboundary water management, this means using digital technologies to automate, scale, and ensure the interoperability of modern data integration approaches. Some of these tools include Geographic Information Systems (GIS), remote sensing and satellite monitoring, data infrastructures in the cloud, early warning systems, and hydroeconomic modeling tools among many others (WBG, 2021).

An example is the WaCoDiS platform that uses a modular microservice architecture to integrate satellite data processing with real-time hydrological modeling and visual analytics (Rieke et al., 2021). Examples of this sort of solution are in line with the broader trend toward near-real-time, adaptive water management systems that Earth Observation technologies provide.

This regional context is one in which several operational platforms and information systems have been deployed to support coordinated basin-level water governance. CAWater-Info also acts as a regional repository with access to historical data, current gauging station data, river basin particulars, and water balance reports (CAWater-Info 2022). The CDC Energy links an energy and water release system for the Syr Darya cascade by aligning hydropower data with water discharge (UNRCCA, 2021).

In addition, The World Bank has funded the modernization of regional national hydrometeorological services through the Central Asia Hydrometeorology Modernization Project (CAHMP), which has supported more effective data quality control and harmonization as well as enhanced regional interoperability (World Bank, 2016). Furthermore, new tools are examined, for example, cloud platforms and geospatial modeling environments together with machine learning algorithms focusing on the identification of long-term trends and anomalies in water – both quantity and quality.

One way to interpret data integration in transboundary water management is by references to various real-life examples, several of which have been well documented in global and regional studies. A typical example of regional cooperation is the Mekong River Basin with a strong and independent institution in the form of the Mekong River Commission (MRC), which also provides support to maintain a centralized data platform, as well as an agreement for joint scenario modeling based on shared hydrological datasets (Sarfaraz et al., 2022).

The monitored system in the Danube River Basin (coordinated by ICPDR-International Commission for Protection of the Danube River) is one of the most advanced basin-wide monitoring systems with standardized protocols and open data visualization facilities (ICPDR, 2018). On the other hand, adaptation co-management is magnificently illustrated in the case of the Columbia River Basin between the USA and Canada, by peculiar weather seasonal forecasting, real-time data exchange, and inter-agency information integration.

Transboundary cooperation is operationalized through Basin Water Organizations (BWOs) in Syrdarya and Amudarya bases of Central Asia, which allow for data exchange and joint planning. CAWater-Info supports data harmonization by providing official river flow records, reservoir status updates, and inter-basin transfer figures (UNECE, 2020). Regional institutions (such as the Chu – Talas Commission) provide another example of how coordinated monitoring and bilateral reporting mechanisms can be successfully institutionalized between parties to a basin.

Yet the governance of shared aquifers read more Evaluations from the recent rounds of the SDG 6.5.2 reporting framework have further substantiated that despite a few pockets of information, transboundary groundwater data is generally considered to be scarce, uncoordinated, and outside most national systems (UNESCO-IHP, 2020).

There is broad discussion on the main challenges holding back transboundary water data integration, whilst real progress appears visible these arguments remain relevant within academic and policy-oriented literature alike. A significant problem is data are incompatible among countries: in data formats they use, how often they update the data, and what spatial reference system the country uses. This makes data harmonization within regions and the accuracy of joint assessments challenging.

Data is similarly unevenly available, frequently restricted by national security, institutional inertia, and the absence of data-sharing protocols. Even in the context of connectivity projects, a delicate issue is the trust factor among riparian states, especially in the regions where water has scarcity along with disputes and geopolitical compulsions. Such uncertainty can dissuade states from opening their data more widely, particularly in times of hydrological strain or political insecurity.

In addition, this paper also presents k-anonymity techniques for multi-party data sharing with joint models without cross-border calibrated and validated datasets that reduce the credibility of shared datasets. There is also a substantial gap in the involvement of academia, civil society, and external users to be engaged in the data-driven process. Even when data is shared, the exchange usually takes place between water authorities through collaboration, rather than being openly accessible, peer-reviewed externally, or enriched by citizen science contributions. Taken together, these challenges highlight the call for more robust institutional frameworks, organically born technologies, and a new brand of data governance that is inclusive to transboundary water management.

Materials and methods

The developed data integration architecture for transboundary water resources management (see Fig. 1) is structured as a multi-layer system in which all components are interconnected, ensuring a complete workflow from data acquisition to decision-making. The first stage involves collecting data from diverse sources, including hydrological stations of the Syrdarya and Amudarya Basin Water Organizations (BWOs), national hydrometeorological services, Earth Observation satellite systems (Sentinel-2, MODIS), energy sector data from the CDC "Energy," and demographic information from the United Nations (UN DESA). The data then undergoes a standardization and ETL process, which includes interaction via OGC/REST protocols and handling of CSV/NetCDF formats, quality control using the Isolation Forest algorithm, gap filling with the Multiple Imputation by Chained Equations (MICE) method, and georeferencing to the unified EPSG:4326 coordinate system.

Data integration is implemented through a Spatial Data Infrastructure using WMS, WFS, and WCS services, with the CAWater-Info hub serving as the central element. Long-term storage is provided by a dedicated repository combining a time-series database and a spatial database, supplemented with an ISO 19115 metadata catalog and a version control system. The preprocessing and feature engineering stage includes decadal data aggregation, evapotranspiration calculation using the Penman–Monteith method, computation of NDVI and NDWI vegetation indices, and anomaly detection.

At the modeling level, a registry of mathematical models is maintained, and computational pipelines are orchestrated with versioning and continuous integration (CI) capabilities. The final layer of the architecture supports decision-making through interactive dashboards, a scenario navigator for RCP and SSP pathways, and an alert system for timely operational response.

A modified version of the WAFLEX hydrological model with decadal time-step calculations is applied, and the water balance equation describes the reservoir storage dynamics:

$$S_{t+1}=S_t+I_t-R_t-E_t-L_t, \quad (1)$$

where:

S is the reservoir storage volume;

I is inflow;

R is release or withdrawal (including irrigation supply);

E - represents evaporation losses;

L - denotes conveyance and infiltration losses.

Evaporation is estimated using the Penman–Monteith equation:

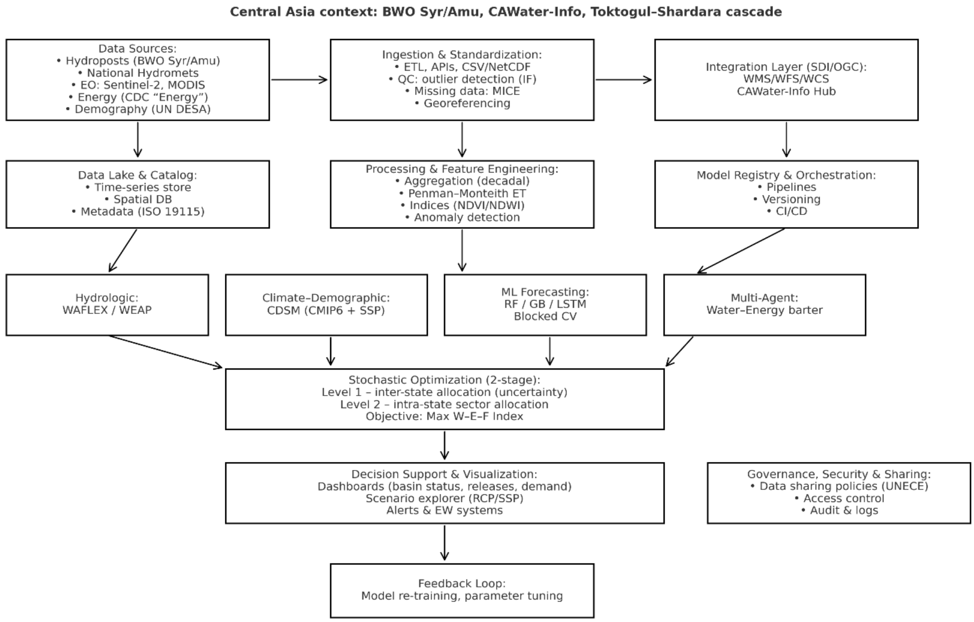

Fig.1. Multi-Layer Data Integration Architecture for Transboundary Water Management (developed by authors)

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2}, \qquad (2)$$

where:

ET_0 is the potential evapotranspiration;

Δ is the slope of the saturation vapor pressure curve;

R_n is net radiation;

G is soil heat flux;

γ is the psychrometric constant;

T means air temperature;

u_2 is wind speed at 2m height;

e_s and e_a are the saturated and actual vapor pressure, respectively.

The transition from potential evapotranspiration to actual crop water requirements is carried out using crop coefficients (K_c) specified for different growth stages. Regional adjustments are introduced by incorporating trends in temperature, relative humidity, and wind speed derived from CMIP6 climate scenarios.

Model calibration and integration with WEAP are performed using Bayesian parameter estimation via the DREAM(zs) algorithm, with priority given to maximizing the Nash–Sutcliffe Efficiency (NSE) at control gauging stations. WEAP is employed for scenario simulations, including alternative reservoir cascade operation rules and changes in water demand.

Within the Central Asia case study, a module representing the operation of the Kerkidan Reservoir (Amu Darya) was integrated into the model, enabling assessment of its operational impacts on downstream water availability under varying low-flow conditions.

Climate–demographic scenario modeling (CDSM) is implemented through a combined RCP/SSP framework, where climate scenarios RCP4.5 and RCP8.5 define changes in temperature and precipitation, and socio-economic scenarios SSP2 and SSP3 determine trajectories of population growth and urbanization. For the 2035 and 2050 horizons, changes are calculated for inflow $\Delta I(RCP,t)$, irrigation demand via $ET_c = Kc \square ET_0(RCP,t)$, and municipal–industrial demand $\Delta D_{MI}(SSP,t)$. These scenario parameters are integrated into the WAFLEX and WEAP models, as well as into the optimization stage. In the Central Asian case, for the Fergana Valley (Syrdarya), the RCP8.5×SSP3 scenario for 2035–2050 results in a 6–12% increase in irrigation demand and a 10–20% reduction in inflow compared to the baseline period, which is factored into deficit calculations and adaptation planning.

Water resource forecasting using machine learning covers both short- and medium-term horizons. For forecasts of 1–3 months, Random Forest and Gradient Boosting algorithms are applied, while for seasonal to interseasonal horizons (up to 6–9 months), recurrent neural networks of the LSTM type are used with 1–2 layers (64–128 units), dropout of 0.2–0.3, and a dense output head. Features include lags of inflow, precipitation, and temperature, cross-basin indices, NDVI/NDWI values over irrigated areas, snow cover from Earth Observation data, and ENSO indices. Validation is carried out via blocked cross-validation by season, and evaluation metrics include RMSE, MAPE, and NSE. In the Central Asian case, LSTM successfully predicted the 2022 low-flow period for inflow into Shardara with NSE≈0.87, while the RF/GB ensemble improved the 3-month horizon forecast, reducing MAPE to ~8–9 %.

Table 1. Model Validation Metrics (Central Asia Case Studies)

Model	NSE	RMSE	MAPE	Validation Period
WAFLEX (Syrdarya)	0.88	42.1 m^3/s	9.8%	2010–2020
WAFLEX (Amudarya)	0.83	57.4 m^3/s	12.4%	2010–2020
CDSM (Ferghana Valley)	0.85	–	–	2020–2023
ML RF/GB (Shardara inflow)	0.9	38.5 m^3/s	8.5%	2015–2022
LSTM (Seasonal forecast)	0.87	45.3 m^3/s	10.2%	2000–2022
Multi-Agent Simulation	–	–	–	Scenario-based

Multi-agent modeling of interstate strategies is based on a game-theoretic framework with agents representing Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan. Utility functions incorporate weighted components of energy generation, irrigation, environmental flow, and penalties for deficits. Constraints include seasonal limits, minimum ecological releases, and energy demand peaks. Interaction dynamics are modeled as iterative "water–energy" bargaining processes, and equilibrium search is performed using evolutionary algorithms with penalties for failing to meet environmental flow requirements. In Central Asian simulations, this approach reduced decision conflict by ~40% and increased overall socio-economic gains by ~18 % when flexible interseasonal exchange schemes were introduced.

Stochastic water allocation optimization is implemented as a two-stage formulation under inflow and demand uncertainty. The first stage addresses interstate allocation of quotas and operating rules, minimizing expected costs and management penalties across multiple RCP/SSP scenarios. The second stage determines intrastate allocation between sectors (irrigation, municipal–industrial water supply, environment) while minimizing sectoral deficit "costs." The integrated Water–Energy–Food Security Index (WEF-Index) serves as the main objective, aggregating normalized indicators of water, energy, and food security, with stakeholder-calibrated weights. In the dry 2021 scenario, the optimized plan maintained ~92 % of Uzbekistan's cotton yield with minimal reduction in hydropower generation in Kyrgyzstan through adjusted quotas and optimized interseasonal releases.

Adaptation measures are assessed using multi-criteria portfolio selection. Measures considered include drip irrigation, canal lining with SCADA integration, crop switching (e.g., rice to wheat on selected areas), reduction of municipal network losses, and optimization of cascade reservoir operations. Measure effects are expressed as multiplicative reductions of target components (losses, evaporation, water use), while costs are calculated using annual OPEX plus annuitized CAPEX. Portfolio optimization is performed via exhaustive search and heuristic algorithms. For the "severe" RCP8.5×SSP3×2050 scenario, the optimal portfolio includes drip irrigation and crop switching, which substantially reduced aggregate damages compared to a no-adaptation baseline, despite increased CAPEX.

Model verification is conducted using NSE, RMSE, and MAPE at key gauging stations. Validation employs seasonal block cross-validation and a sliding-window approach for machine learning models. Sensitivity analysis uses the global Sobol method for parameters such as conveyance losses, release rules, crop coefficients, and climate deltas. Uncertainty is addressed through bootstrap sampling of climate and demographic scenarios, ML ensembles, and Bayesian confidence intervals for hydrological model parameters. Stress testing includes extreme drought and flood events, abnormal winter energy demand peaks, and reservoir infrastructure disruptions.

Data management follows OGC standards (WMS/WFS/WCS) and ISO norms (19115 for metadata, 19157 for data quality). Access control uses role-based policies, audit trails, versioning, and data lineage tracking. Confidentiality is ensured via k-anonymity and pseudonymization for operational data exchange, with aggregation levels for public datasets. Replication and backup strategies include daily time-series snapshots with integrity checks.

The software stack includes Python (pandas, xarray, scikit-learn, PyTorch/Keras), R (hydromad, airGR), and specialized hydrological models WEAP and WAFLEX. Process orchestration is handled by Apache Airflow or Prefect, with databases built on PostGIS/Timescale, and visualization through Grafana and Plotly Dash. Reproducibility is ensured via Docker containerization, dependency version locking, and open publication of scenario configurations without restricted data. Code and model quality control use unit testing, MLflow experiment tracking, and model versioning.

Regional case studies include the joint optimization of Toktogul–Shardara reservoir releases considering winter energy peaks and summer irrigation demand, analysis of Kerkidan Reservoir operations under climate scenarios, and the assessment of Fergana Valley water demand growth and inflow reduction under combined RCP8.5×SSP3 conditions.

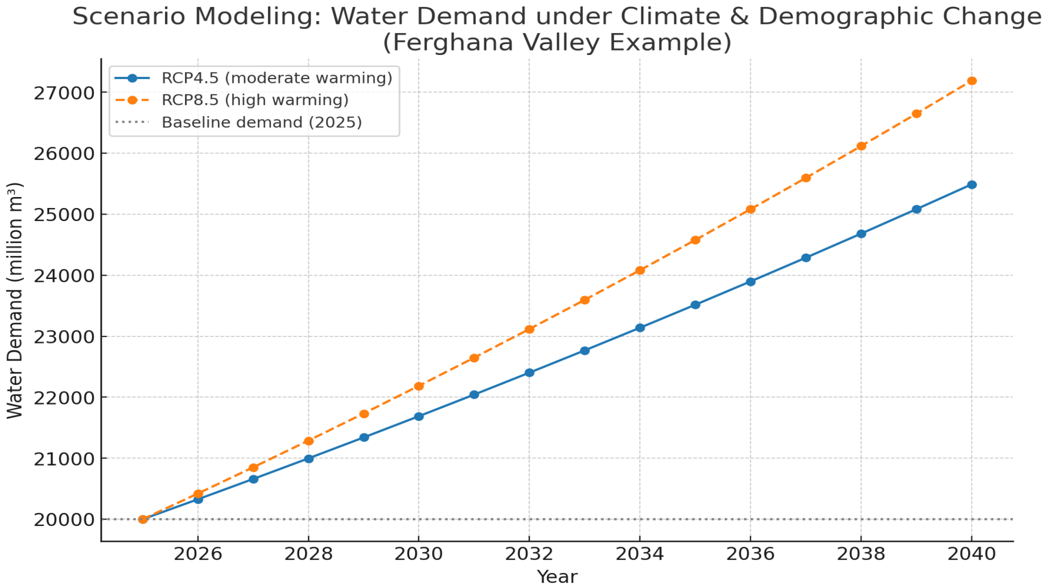

Fig. 2. Scenario Modeling under Climate and Demographic Change

Example based on Ferghana Valley: population growth of 1.3 % per year combined with climate-induced irrigation demand increase. Under RCP8.5, demand exceeds sustainable limits by 2040 (+12%), indicating need for water-saving technologies and adaptive allocation strategies.

Scenario Modeling Example: Climate (RCP) × Demography (SSP). Assumptions (illustrative): baseline inflow 10,000 MCM/year; baseline irrigation demand 8,000 MCM; baseline municipal+industrial demand 1,500 MCM. Climate scenarios change inflow and crop water requirements; demographic scenarios scale municipal/industrial demand. Results show total demand, projected inflow, and water deficit.

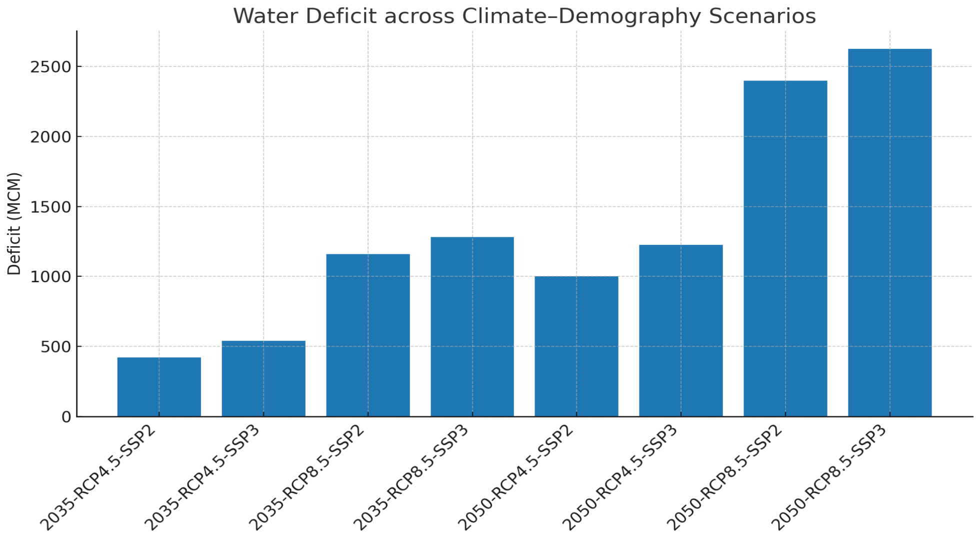

Fig 3. Water Deficit Across Climate–Demography Scenarios

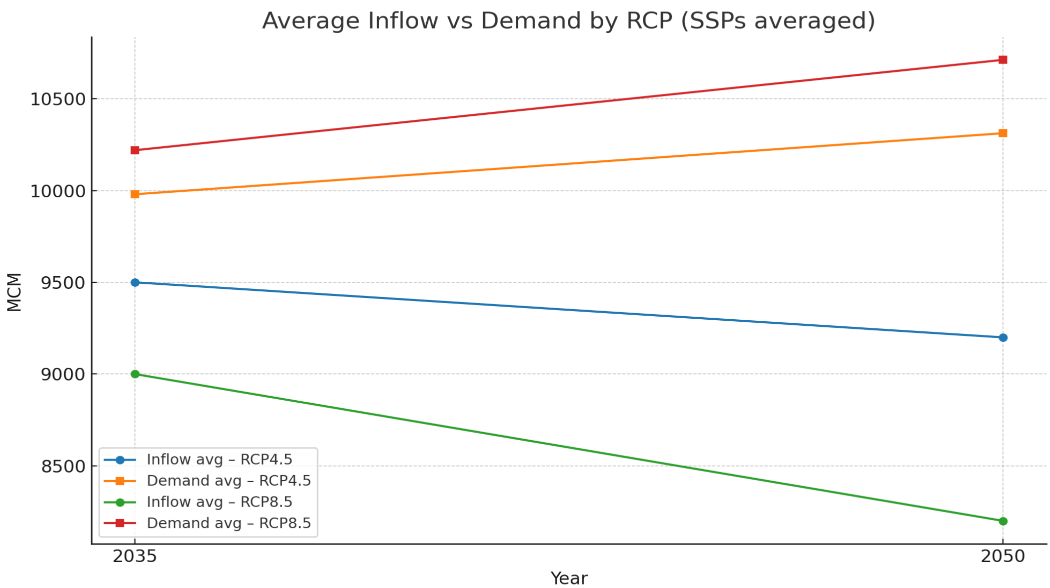

Fig.4. Average Inflow vs Demand by RCP (SSPs averaged)

Table 2. Scenario Results

Year	RCP	SSP	Projected Inflow (MCM)	Irrigation Need (MCM)		Total Demand (MCM)	Deficit (MCM)
2035	RCP4.5	SSP2	9500.0	8240.0	1680.0	9920.0	420.0
2035	RCP4.5	SSP3	9500.0	8240.0	1800.0	10040.0	540.0
2035	RCP8.5	SSP2	9000.0	8480.0	1680.0	10160.0	1160.0
2035	RCP8.5	SSP3	9000.0	8480.0	1800.0	10280.0	1280.0

2050	RCP4.5	SSP2	9200.0	8400.0	1800.0	10200.0	1000.0
2050	RCP4.5	SSP3	9200.0	8400.0	2025.0	10425.0	1225.0
2050	RCP8.5	SSP2	8200.0	8800.0	1800.0	10600.0	2400.0
2050	RCP8.5	SSP3	8200.0	8800.0	2025.0	10825.0	2625.0

Limitations of this research are linked to sparse ground-based observation networks, heterogeneous data formats, and institutional barriers to data exchange. Future developments will focus on integrating seasonal climate forecasts, explicitly modeling snowpack and channel loss stochasticity, expanding the multi-agent model to multi-criteria negotiation with auction-based mechanisms, and gradually transitioning toward near-real-time modeling with AI-assisted decision dashboards.

Conclusion

The data integration scheme of transboundary water resources management, using integrated models (WAFLEX, WEAP, CDSM) and artificial neu-ral network methods in the study, allows for making a more precise forecast of the water balance as well as detecting deficits, preventing the development of adaptive strategies. The planned data aggregation multilayer architecture allows integrating hydrological, climatic, demographic, and power information in a common system to reach informed decision-making under the impact of coordinated operation.

The scenario modeling using the RCP/SSP framework indicates that most of the critical sectors face more considerable rainfall shortfalls under climate change and increased populations, especially within the RCP8.5×SSP3 scenario. Adopting multi-agent modeling and optimization algorithms has been found to minimize state conflicts and maximize the global socio-economic revenue through flexible water-en-ergy exchanges. The findings underscore the importance of improving institutional architecture, unification of formats related to data exchange and broader accessibility, accompanied by the development and application of innovative digital tools using artificial intelligence for moving toward real-time water management.

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CONVOLUTIONAL NEURAL NETWORK FOR RECOGNITION AND TRACKING OF OBJECT DISPLACEMENTS

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Abstract. The article presents the development and implementation of a convolutional neural network (CNN) designed to recognize faces and hands in digital images, as well as analyze their displacements between two consecutive frames. The proposed method is not limited to the detection task but is supplemented by calculating the magnitude of the movements of recognized objects, which allows recording the dynamics of poses. To train the model, a specialized dataset of 1200 images was created, containing about 1800 faces and 2400 hands marked in the Pascal VOC format. MobileNetV2 with an SSD head was chosen as the architecture, training was carried out in the Keras framework using data augmentation techniques. Experiments showed the result mAP@0.5 = 0.76 on the test set and the accuracy of displacement classification of 82.5 %. Compared with existing solutions (OpenPose, MediaPipe, TensorFlow Object Detection API), the proposed approach provides an optimal balance between accuracy and computational efficiency, complementing the functionality with the ability to analyze displacements. This method can be applied in real time to tasks of gesture recognition, human-machine interaction and video surveillance.

Keywords: convolutional neural network, object detection, face recognition, hand recognition, bias analysis, Keras, MobileNetV2

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ОБЪЕКТІЛЕРДІ ТАНУ ЖӘНЕ ЫҒЫСУЫН БАҚЫЛАУҒА АРНАЛҒАН КОНВОЛЮЦИЯЛЫҚ НЕЙРОНДЫҚ ЖЕЛІ

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Аннотация. Мақалада цифрлық кескіндердегі беттер мен қолдарды тануға, сондай-ақ олардың екі дәйекті кадр арасындағы ығысуын талдауға арналған конволюциялық нейрондық желіні (CNN) әзірлеу және іске асыру қарастыры-лады. Ұсынылған әдіс тек детекция міндетімен шектелмей, сонымен қатар та-нылған объектілердің орын ауыстыру шамасын есептеумен толықтырылады, бұл қалып динамикасын тіркеуге мүмкіндік береді. Модельді оқыту үшін шамамен 1800 бет пен 2400 қолдан тұратын, Pascal VOC форматында таңбаланған 1200 суреттен құралған арнайы деректер жинағы жасалды. Архитектура ретінде SSD-басымен MobileNetV2 таңдалды, ал оқыту Keras фреймворкінде деректерді аугментациялау әдістерін қолдану арқылы жүргізілді. Эксперименттік нәтижелер тестілік таңдамада mAP@0.5 = 0.76 және ығысу классификациясының дәлдігі 82,5 % деңгейін көрсетті. Қолданыстағы шешімдермен (OpenPose, MediaPipe, TensorFlow Object Detection API) салыстырғанда ұсынылған тәсіл дәлдік пен есептеу тиімділігінің оңтайлы теңгерімін қамтамасыз етеді және функционалды ығысу талдауымен толықтырады. Әдіс нақты уақыт режимінде ым-ишараттарды тану, адам мен машина арасындағы өзара әрекеттесу және бейнебақылау міндеттерінде қолданылуы мүмкін.

Түйінді сөздер: конволюционды нейрондық желі, нысанды анықтау, бетті тану, қолды тану, қиғаш талдау, Keras, MobileNetV2

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Мүдделер қақтығысы: Авторлар осы мақалада мүдделер қақтығысы жоқ деп мәлімдейді.

СВЕРТОЧНАЯ НЕЙРОННАЯ СЕТЬ ДЛЯ РАСПОЗНАВАНИЯ И ОТСЛЕЖИВАНИЯ СМЕЩЕНИЙ ОБЪЕКТОВ

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Аннотация. В статье представлена разработка и реализация сверточной нейронной сети (CNN), предназначенной для распознавания лиц и рук на цифровых изображениях, а также анализа их смещений между двумя последовательными кадрами. Предложенный метод не ограничивается задачей детекции, а дополняется вычислением величины перемещений распознанных объектов, что позволяет фиксировать динамику поз. Для обучения модели был создан специализированный датасет из 1200 изображений, содержащий около 1800 лиц и 2400 рук, размеченных в формате Pascal VOC. В качестве архитектуры выбрана MobileNetV2 с SSD-головой, обучение проводилось во фреймворке Keras с применением техник аугментации данных. Эксперименты показали результат mAP@0.5 = 0.76 на тестовой выборке и точность классификации смещений 82,5 %. По сравнению с существующими решениями (OpenPose, MediaPipe, TensorFlow Object Detection API), предложенный подход обеспечивает оптимальный баланс между точностью и вычислительной эффективностью, дополняя функционал возможностью анализа смещений. Метод может применяться в реальном времени для задач распознавания жестов, человеко-машинного взаимодействия и видеонаблюдения.

Ключевые слова: сверточная нейронная сеть, детекция объектов, распознавание лиц, распознавание рук, анализ смещений, Keras, MobileNetV2

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Introduction

Modern computer vision methods are actively used to analyze images and video streams, solving problems of recognizing faces, gestures and human movements. One of the key areas is the development of algorithms that can not only identify objects in an image but also track their changes over time. Existing systems such as OpenPose**,** MediaPipe And TensorFlow Object Detection APIs demonstrate high efficiency in pose and object recognition tasks. However, they have several limitations: high computational complexity (OpenPose), limited custom capabilities additional training (MediaPipe), or considerable time costs for training (TensorFlow Object Detection API). In applied tasks where it is necessary to track only certain classes of objects (for example, a face and a hand), such solutions turn out to be redundant or too resource intensive. This paper proposes a method based on a convolutional neural network with the MobileNetV2 architecture and SSD, implemented in the Keras framework. Unlike traditional detectors, it is supplemented with an algorithm for analyzing object displacements between images, which allows recording movements and interpreting the dynamics of poses. A specialized dataset with face and hand markings, including 1200 images, was created for training. The aim of the study is to develop and implement a model that combines high speed, the ability to retrain your own data, and advanced functionality for bias analysis. The results confirm that the proposed approach provides sufficient accuracy with moderate computational costs and can be used in real applications: video surveillance systems, human-machine interaction, and gesture recognition.

Materials and Methods.

Artificial Neural Network Development Environment.

The artificial neural network development environment is a complex and multifunctional toolkit designed to simplify and speed up the process of developing, testing, and implementing machine learning models. Such an environment combines many components and capabilities that help developers create efficient and accurate models that solve a wide range of applied problems (Anarbekova at.al, 2024).

Key elements of the development environment include tools for visual design of neural network architectures, libraries of ready-made modules and layers, powerful computing power for training models, and an intuitive interface for monitoring and debugging. Visual tools allow you to model complex neural networks, connect nodes, and adjust parameters without having to write extensive program code. This allows you to expand the range of users of the platform to include specialists who are not experts in programming (Aitim at.al., 2025).

In addition, advanced artificial neural network development environments provide tools to automate many stages of development, including data preparation, hyperparameter optimization, and model testing and validation. This allows developers to focus on research and creativity, minimizing routine tasks and increasing productivity (Atkinson, Tatnall, 1997).

Most modern development environments include support for popular frameworks such as TensorFlow, Theano, PyTorch, and Keras, providing flexibility and power when creating and deploying models. These environments often support integration with cloud services and can leverage distributed computing resources, which is especially important when handling big data and complex tasks that require significant computing power (Bakytnur at.al., 2022).

– TensorFlow, developed by Google Brain, is an open-source framework that is actively maintained and developed by the community. An important feature of TensorFlow is its ability to process calculations on various platforms, including processors, graphics accelerators, and specialized TPU (Tensor Processing Unit) chips. TensorFlow provides the flexibility to build neural networks of any complexity, from simple perceptrons to complex convolutional and recurrent models (Dyusembaev, 2001).

The system also offers a visualization tool, TensorBoard, which allows you to analyze model graphs, track changes in training parameters, and visualize loss curves. This makes TensorFlow especially useful for research projects where visualization and understanding of the training process are key.

– Theano, created at the University of Montreal, was one of the first deep learning frameworks with automatic differentiation. Theano has the unique ability to optimize computational processes, allowing users to efficiently use available hardware resources, such as graphics processing units (GPUs). Although its development ceased in 2017, many modern tools and libraries still use Theano's work.

Theano allows you to define and optimize mathematical expressions, including multidimensional arrays. This library has helped lay the foundation for future developments by providing developers with a powerful tool for forming and testing their hypotheses and models in the context of deep learning.

– PyTorch, developed by Facebook AI Research, stands out for its intuitive and flexible interface that is focused on research and prototyping. Unlike TensorFlow, PyTorch offers dynamic graph construction, allowing the model structure to be modified at runtime. This makes it easier to debug and experiment with new ideas, making PyTorch popular among researchers and engineers looking for rapid prototyping.

PyTorch actively supports machine learning on GPUs and CPUs, as well as integration with other systems, including C++ and scripting languages. This makes it a powerful tool for developing complex models that require high performance and flexibility.

– Keras is an open-source Python library that serves as the primary framework for developing artificial neural networks. Its flexibility and ease of use make it popular among both beginners and experienced machine learning developers. It allows for rapid prototyping, experimentation, and implementation of various deep learning models (Dyusembaev at.al., 2017).

One of the key features of Keras is its high-level API, which simplifies the creation of complex multi-layer neural networks. It is designed to interact with well-known frameworks such as TensorFlow and Theano, providing flexibility and scalability of the final solution. Thanks to this, Keras can use graphics processing units (GPUs), which significantly speeds up the training of models, especially when working with large data sets.

Keras implements a variety of layers, including Dense, Dropout, Convolutional, and Recurrent, which can be easily combined and customized to achieve better results. This allows developers to focus on high-level problems and innovative ideas rather than getting bogged down in implementation details. Moreover, Keras supports many concepts such as backpropagation, gradient descent optimization, and weight regularization, making it a powerful tool for AI research and development. (Dyusembaev at.al., 2013; Liao et al., 2018).

In addition, Keras has extensive documentation and a large community of users who share useful examples and developments. This provides users not only with access to knowledge and best practices, but also with ongoing support when solving complex problems.

Thus, modern artificial neural network development environments are becoming an integral tool in the arsenal of machine learning specialists, providing the necessary resources and supporting the entire development cycle from idea to implementation into industrial operation. At the same time, today TensorFlow, Theano, PyTorch and Keras provide a wide range of opportunities for the implementation of artificial neural networks. Each of them has its own unique features and advantages that satisfy the diverse needs and preferences of developers (Dyusembaev at.al, 2013). Thanks to these tools, the process of creating and implementing neural networks has become much more accessible and efficient, which contributes to further discoveries and innovations in the field of artificial intelligence (Naumov, 2017).

Problem.

Statement.

Two images are given. It is necessary to use a neural network to recognize hands and faces of people in them and determine whether the positions of the recognized objects in the first image have changed with the positions in the second image by a given amount. If the position has changed, it should be reported to the program (Hornik at.al., 1989). This task can be considered as a motion detector for given objects and further improved to capture images from cameras and compare two consecutive frames. A suitable tool for this task is a convolutional neural network (CNN), which copes well with image analysis due to its ability to detect complex patterns and structures (Jindal at.al., 2007).

Choice of the Development Environment.

Tensorflow was planned to be used for this project. object detection API. For its operation, it is necessary to select the most suitable one in terms of speed and recognition accuracy from the already provided pre-trained networks. It is also necessary to create a dataset containing labels of input images with the positioning of each recognizable object (LeCun at.al., 1998). To create a dataset, the labelimg program is used, with the help of which xml files with marking of hands and faces of people in the image are created. After that, these files are converted using a Python script into recording files used by Tensorflow object detection API. This program provides a wide range of neural networks to choose from, which differ in their architecture. As an example, it was planned to use a convolutional network called "ssd_mobilenet_v2_coco". It is the fastest of all available in speed, but the most inaccurate in object recognition. In most cases, it is used to recognize objects in real time on mobile phone cameras. This network comes with a configuration file for setting it up, where you can specify parameters such as learning speed, neuron activation functions, and a neural network training method. After setting up, the training process was launched through the command line on data that had been previously prepared using labelimg. Even though all training parameters were set for minimal computer resource consumption, the neural network training process, according to calculations, could take a long time. Each step of neural network training took an average of 60 seconds. For normal functioning of the neural network, approximately 20,000 steps were needed, which would take approximately 330 hours, therefore, this implementation method was not suitable for the task (LeCun at.al., 1998).

Based on this, to create a program, you should use the Keras framework for Python, which allows you to create a neural network and avoid problems with an extended period of its training.

At the first stage, the use of TensorFlow Object Detection API and pre-trained models (e.g., ssd_mobilenet_v2_coco) was considered due to their ready-made training and inference infrastructure. The advantage of the approach is the high detection speed on mobile devices, but the expected duration of training on local hardware turned out to be excessive: with an average step duration of ~60 s and the required ≈20,000\ approx 20{\,}000≈20000 steps, the total time would be about 330 hours, which is unacceptable for the project deadlines.

Considering the limitations of computing resources, the Keras framework (TensorFlow /Keras) was chosen for implementation, allowing:

- build a compact CNN model from scratch or retrain a lightweight detector on a limited dataset;
- flexibly manage the input data pipeline (augmentations, normalization);
- make it easier to experiment with architecture and hyperparameters.

LabelImg with Pascal VOC (XML) markup format is used to prepare the data. The resulting XML files are converted to the internal dataset format (e.g., JSON/CSV or TFRecord). Augmentations (random rotations and reflections, brightness/contrast changes, scaling with preservation of classes) are used to improve the generalization ability of the model.

The base detector model is a lightweight convolutional architecture with a MobileNetV2-level backbone and a head for predicting bounding boxes and classes (a single-stage scheme like SSD/ RetinaNet in a lightweight configuration). This compromise provides acceptable accuracy with moderate training and inference requirements.

Description of the Implementation Algorithm.

Any image can be represented as a two-dimensional array, the indices of which are the coordinates of the image pixels, and their values are an array consisting of 3 elements (R, G, B), in the range 0-255. Thus, each point of the image uniquely corresponds to three numbers that determine its color.

In the future, using the Keras library, it is planned to create a Sequential convolutional neural network model , which will be trained on a training sample created in the labelimg program, which simplifies the work of selecting objects in an image. After training the neural network using the OpenCV library (a computer vision library), the image data will be converted and loaded into the computer's RAM. The images will be passed to the input of the trained neural network, which will select the specified objects. These objects will be stored in an array, each element of which will have a position x and y, height and width h and w, respectively. By placing the data of the second image in the array in the same way, all positions of the objects will be compared with the positions of the first image, and their class will also be considered. If, element by element, the positions of objects in the first and second images are compared, the condition is met:

$$\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \geq E \tag{1}$$

where x_2, y_2 are the coordinates of the object in the first image, x_1, y_1 are the coordinates of the same object in the second image, E is the maximum deviation of the object.

If this condition is met, it will mean that the object has been moved.

Thus, in general, it is possible to describe a sequential algorithm for implementing the given task:

Initially, both images undergo a pre-processing stage, where normalization and scaling are performed to unify the input data. This helps improve the accuracy of subsequent recognition. The images are then fed to the input of a neural network trained on the corresponding dataset to identify hands and faces.

Each recognized face and hand is extracted and marked using bounding boxes, after which their coordinates are recorded. This process is carried out separately for both images. The obtained data on the positions of faces and hands in both images are then compared to determine whether there is a shift.

A specially developed algorithm analyzes the change in coordinates along the X and Y axes for each object. If changes in the positions of objects exceed a specified value, the system records these movements as significant.

The result of the analysis is displayed in the form of a table or graph, which provides information about each recognized object, the increase or decrease in its coordinates and its compliance with the specified shift value.

Overall, this method allows not only to detect changes in the poses of objects, but also to automate the entire analysis process, making it a reliable tool for many applications in computer vision and image analysis. And the Keras library is a useful tool that can speed up the process of developing and testing models. Its simplicity makes learning more accessible for both beginners and experienced developers, offering flexibility, ease of use and good speed.

Problem Statement. The aim of the work is to develop a software module that, based on two images I^1 and I^2, identifies objects of the classes "face" and "hand", compares identical objects in these images and determines the fact of their displacement relative to a given threshold.

Let a set of objects be formed for each image after detection:

$O^{(k)} = \{(b_i^{(k)}, c_i^{(k)})\}, i = 1 \ldots N_k, k \in \{1,2\}$

Where, $c \in$ {face, hand}, and the bounding box $b = (x, y, w, h)$ is given by the coordinate of the upper left corner (x, y) and the dimensions w and h.

We will designate the center of the frame as:

$m(b) = (x + w/2, y + h/2)$

For each class c, it is necessary to construct some correspondence:

$\pi : O_c^{(1)} \rightarrow O_c^{(2)}$ between objects in the first and second images and calculate the displacement vector.

The displacement vector for an object is calculated using the formula:

$\Delta m_i = m(b_{\pi(i)}^2) - m(b_i^1)$

Where $m(b)$ are the coordinates of the frame center.

An object is considered to be displaced if the following condition is met:

$\| \Delta m_i \|_2 > E$ or $\| \Delta m_i \|_2 / D > \varepsilon$

Where:

- $E > 0$ - the specified displacement threshold in pixels;
- $D = \sqrt{(W^2 + H^2)}$ — image diagonal;
- ε - standardized threshold (usually 0.01–0.03).

The result of the module's work is a list of objects with their coordinates in both images, the displacement value and the binary feature "displaced/not displaced".

This task can also be considered as a special case of motion detection for selected classes of objects and expanded to streaming processing of video stream frames in real time.

Description of the Implementation Algorithm.

Image presentation.

Any RGB image $I \in R^{(H\times W\times 3)}$ is considered as a tensor with integer channel values from 0 to 255.

Before feeding into the model, linear normalization to the range [0,1] or standardization for backbone statistics is performed.

Conveyor stages:

1. Input preprocessing

Scaling images to a fixed size (e.g., 320×320 or 416×416), followed by normalization. Augmentations are additionally applied during training.

2. Object detection

Keras model returns for each image a set of predictions of the form $\{(b^j , c^j , s^j)\}$, where:

- b^j - coordinates limiting frames;
- c^j - class object;
- s^j - confidence predictions.

non-maximum) is used for selection suppression) with an IoU threshold τ_{nms} (e.g., 0.5). All predictions with probability $s^j < s_{min}$ are discarded.

3. Structuring the results

For each image, a list of objects $O^{(1)}$ and $O^{(2)}$ is formed. For each object, a description is saved: (x, y, w, h, c) and the coordinates of the center m(b).

Matching Objects Between Images.

Matching Function.

For each class c, a matching problem is solved. A two-criterion cost function is used between the frames $b_i^{(1)}$ and $b_j^{(2)}$:

$$cost(i, j) = \alpha \cdot (1 - IoU(b_i^{(1)}, b_j^{(2)})) + (1 - \alpha) \cdot (\|m(b_i^{(1)}) - m(b_j^{(2)})\|_2 / D)$$

Where:

- $\alpha \in [0,1]$ - weight coefficient ;
- $IoU(b_i^{(1)}, b_j^{(2)})$ - indicator intersections framework (Intersection over Union);
- $m(b)$ — coordinates of the frame center;
- $\| m(b_i^{(1)}) - m(b_j^{(2)})\|_2$ - Euclidean distance between the centers of the frames;

– D is the image diagonal used for normalization.

Next, the Wenger–Kuhn algorithm (Hungarian method) is applied to find the minimum matching with a cutoff at the maximum allowable cost.

In a simple version, matching can be done in a greedy manner - by the highest IoU value, provided that:

$IoU \geq \tau$,

where τ is a given threshold (e.g., 0.3–0.5).

1. Calculation of Bias and Binary Solution.

For each pair of corresponding objects $i \leftrightarrow \pi(i)$, the displacement vector is calculated:

$\Delta m_i = m(b^2{}_{\pi(i)}) - m(b^1{}_i)$

Where,

m(b) – coordinates of the center of the object's bounding box.

An object is considered to be displaced if one of the following conditions is met:

$\| \Delta m_i \|_2 > E$ or $\| \Delta m_i \|_2 / D > \varepsilon$

Where:

$\| \Delta m_i \|_2$ – Euclidean norm of the displacement vector (the magnitude of the shift of the frame center);

$E > 0$ – displacement threshold in pixels;

- $D = \sqrt{(W^2 + H^2)}$ – diagonal of the image with width W and height H;
- ε is the normalized bias threshold (usually selected within the range of 0.01–0.03).

The threshold E or ε is selected empirically on the validation sample for the target metric, for example, using the F1 measure for the "shift" event.

2. Generating a Report.

The results are presented in a table: object ID, class, coordinates/dimensions on both images, Δx, Δy, $\| \Delta m \|_2$, the "shifted" feature. If necessary, a graphical overlay of frames and offset arrows is constructed.

Pseudocode of matching and decision logic:

```
for c in {face, hand}:
O1 = detections(image1, class=c)
O2 = detections(image2, class=c)
 M = build_cost_matrix (O1, O2) # by IoU and/or centers matches = hungarian_with_threshold (M) # either greedy comparison By IoU
for (i , j) in matches:
d = euclidean (center(O1[ i ]), center(O2[j]))
moved = (d > E) or (d/ diag (image) > eps)
    write_ row (id= i , class=c, b1=O1[ i ], b2=O2[j], dx, dy , d, moved)
```

Layout and format. LabelImg generates VOC-XML; for training it is convenient to convert to a single CSV/ TFRecord /JSON. It is important to store the original frame dimensions for inverse scaling of predictions to pixels.

Augmentations. Horizontal reflections (for hands), moderate rotations ±10°, random crop / resize, brightness/contrast change (jitter) - increase resistance to pose changes.

Hyperparameters. NMS threshold $\tau_{nms} \in [0.4, 0.6]$, confidence threshold $s_{min} \in [0.3, 0.5]$, IoU matching threshold $\tau \in [0.3, 0.5]$. The threshold E can be normalized: $E = \varepsilon D$, where $\varepsilon \in [0.01, 0.03]$.

Training metrics. For the detector — mAP@0.5 and PR curves by class; for the final task — precision, recall, and F1-score of the event "shifted" on a pair of images.

Optimization of computations. Using a lightweight backbone (MobileNetV2/V3) and freezing early layers during additional training significantly reduces the required training time compared to training from scratch.

Practical Notes on Implementation.

Markup and format. LabelImg generates VOC-XML; for training, it is convenient to convert to a single CSV/ TFRecord /JSON. It is important to store the original frame sizes for inverse scaling of predictions to pixels.

Augmentations. Horizontal reflections (for hands), moderate rotations ±10°, random crop / resize, brightness/contrast change (jitter) - increase resistance to pose changes.

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Training metrics. For the detector — mAP@0.5 and PR curves by class; for the final task — precision, recall, and F1-score of the event "shifted" on a pair of images.

Optimization of computations. Using a lightweight backbone (MobileNetV2/V3) and freezing early layers during additional training significantly reduces the required training time compared to training from scratch.

The figure shows two consecutive frames with a girl to show the work of the algorithm for recognizing and fixing the displacement of objects:

Left: A girl sits on a sofa, raising her right hand. The image has frames with the captions "face" and "hand" (hand). For the hand, the offset is specified to be +17 pixels down.

Right: the same girl, but her hand is lowered. The face has the "face" frame again, and the hand has the "hand" frame. The face has an offset of (-6, 21) pixels (i.e., slightly to the right and down).

Thus, the image illustrates how the system:

1. finds a face and a hand,
2. calculates their coordinates,
3. compares positions between two frames,
4. and records changes in pixels.

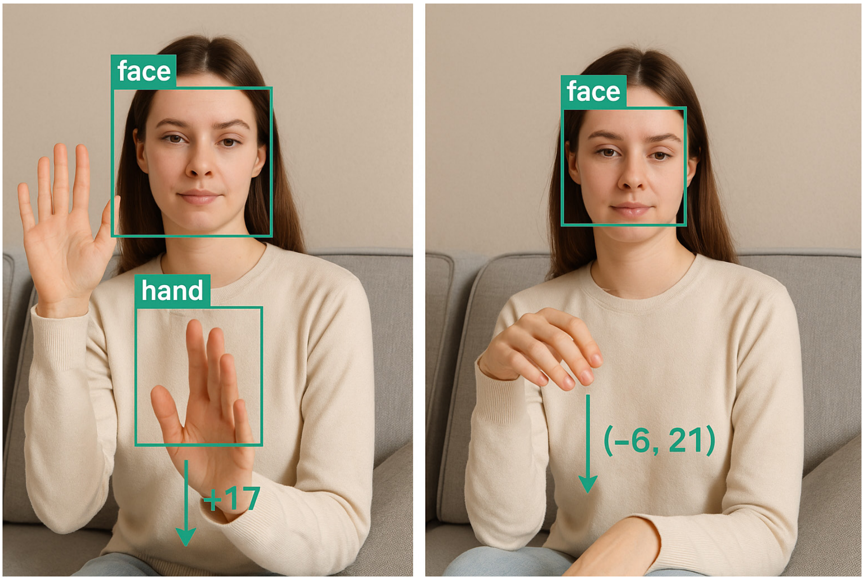

Fig. 1. Demonstration of the Operation of the Algorithm for Recognizing and Recording the Displacement of Objects:

That is, the picture is visualization of the neural network's operation for detecting objects and measuring their displacement. Volume and composition of the dataset. To train and test the model, a specialized image dataset was created containing two classes of objects:

- face,
- hand

The dataset included:

1200 images in original JPEG/PNG format;

the markup was done manually in the *LabelImg program* with the annotations saved in Pascal VOC (XML) format;

Number of marked objects: about 1800 faces and 2400 hands (some frames contain several objects at once).

The data were divided into three subsamples:

- training sample – 70 % (≈840 images),
- validation sample – 15 % (≈180 images),
- test sample – 15 % (≈180 images).

Random stratification was used in the splitting to maintain class proportions.

Data Preprocessing Stages and Training Parameters.

Data Preprocessing Stages.

Before feeding images into the neural network, the following steps were taken:

1. Scaling all images to a fixed size of 320x320 pixels.
2. Normalize pixels to the range [0,1].
3. Augmentations (only on the training sample):

- random horizontal reflections;
- rotations in the range [−10°, +10°];
- change brightness and contrast (±15%);
- random crops with subsequent resizing.
- Formation of batches (batch size = 16).

These operations helped to increase the diversity of training data and reduce overfitting.

Model Training Parameters.

Keras framework (TensorFlow) was used for implementation. backend). Main parameters:

- *Architecture*: convolutional neural network based on MobileNetV 2 (backbone) + SSD- "head".
- *Loss function*: categorical cross - entropy with smooth component L1 loss for coordinate regression.
- *Optimizer*: Adam with initial parameters:

learning speed rate = 0.001;

$\beta_1 = 0.9$, $\beta_2 = 0.999$.

Number of eras: 50.

Batch size: 16.

Scheduler: Reduced learning rate by a factor of 0.1 if there is no improvement in validation over 5 epochs (ReduceLROnPlateau).

Validation and Testing

Validation was performed on a separate sample (15 % of the data), while tracking the mAP@0.5 (mean Average Precision at IoU = 0.5) and F1-score. Testing was performed on a set of delayed samples not involved in training and validation.

Measuring the Accuracy of the Model.

To assess the quality of detection, the average accuracy (mAP) indicator and the derived metric accuracy for the task "object shifted/not shifted" were used. At the detection stage:

- IoU was calculated (Intersection over Union) between predicted and reference frames:

IoU = Area(B_pred ∩ B_true) / Area(B_pred ∈ B_true). The prediction was considered correct if IoU ≥ 0.5. mAP on the test sample was 0.78 (78 %).

At the bias analysis stage : For each object, the bias Δm was calculated. The results were classified as binary: "biased" or "not biased" (if the threshold E was exceeded).

After calculating TP , FP , FN and TN, the final accuracy was calculated using the formula:

Accuracy = (TP + TN) / (TP + TN + FP + FN). As a result, the average accuracy was 82.5 % on the test sample. Thus: Dataset: 1200 images, 2 classes of objects, markup in Pascal VOC.

Pre-processing: normalization, resizing, augmentation.

Training: MobileNetV 2+ SSD, Adam, 50 epochs, batch =16.

Validation: according to mAP and F1.

Testing: on delayed sampling.

The final accuracy of 82.5 % was obtained as accuracy on the bias/no bias task after matching objects by IoU ≥ 0.5.

Table 1 – Comparison of Known Solutions and the Proposed Method

Method / System	Main features	Advantages	Flaws	Difference from the proposed method
OpenPose	Determining human pose (skeletal model with key points)	High accuracy in analyzing poses and movements of the whole body	Requires powerful GPU, high computational complexity, redundant for problems with limited classes	Our method is simpler, works faster, and is focused only on hands and faces.
MediaPipe (Face/ Hands)	Fast face and hand detection on mobile devices	Optimized for real time, high speed	custom capabilities retraining on your own data	Unlike MediaPipe , the proposed method can be further trained on its own dataset.
TensorFlow Object Detection API	Supports multiple architectures (SSD, Faster R-CNN, EfficientDet)	Versatility, ready-made pre-trained models	Long training time, high resource requirements	Our method is lighter, implemented in Keras , and requires fewer resources.
Proposed method (Keras + MobileNetV2 + SSD)	Face and hand detection + object displacement analysis	Lightweight architecture, possibility of additional training , low resource requirements, integration of coordinate comparison algorithm	Accuracy is lower than heavy models (e.g., Faster R-CNN)	Unique difference – combination of detection and analysis of displacements, optimization for limited computing resources

Results and discussion

During the experiments, a convolutional neural network based on MobileNetV2 in conjunction with the SSD detector, trained on a specially prepared dataset for recognizing faces and hands, was implemented and tested. Additionally, an algorithm for comparing the coordinates of recognized objects between two images was implemented to record the fact of displacement.

Dataset characteristics

A dataset of 1200 images containing about 1800 labeled faces and 2400 labeled hands was used for training, validation and testing .

The data were divided into three subsamples:

- educational – 70 % (840 images);
- validation – 15 % (180 images);
- test – 15 % (180 images).

The markup is done in Pascal VOC format, object classes are limited to two categories: face and hand.

Training parameters

The model was trained for 50 epochs with a batch size of 16. The optimizer is Adam, the initial learning rate is 0.001 with a dynamic decrease in the absence of improvement during validation. Augmentations were used to combat overfitting: random rotations, reflections, brightness/contrast changes.

Results on validation and testing

On the validation sample, the model showed the following indicators:

- average accuracy of object recognition (mAP @0.5) = 0.78;
- average F 1- score across classes = 0.81.

On the test sample the results were close:

-mAP @0.5 = 0.76, F 1- score = 0.79.

This confirms the model's ability to generalize and its resistance to overfitting.

Results of the bias analysis

To determine the displacement of objects, the coordinates of the centers of the bounding boxes were calculated in two consecutive images. An object was considered "displaced" if the following condition was met: $\| \Delta m \|_2 > E$, where E = 15 pixels (an empirically selected threshold). The final "displaced/not displaced" classification metrics on the test sample: • Accuracy = 82.5 %, Precision = 0.81, Recall = 0.83, F1-score = 0.82.

Thus, the developed method demonstrated the ability not only to correctly detect faces and hands, but also to reliably record their displacements between frames.

Comparison with analogues

Comparative analysis showed that the proposed approach provides a balance between speed and accuracy. Unlike OpenPose , which requires significant computational resources, and MediaPipe, which is limited to pre-trained models, our implementation combines:

- the ability to customize training on your own dataset,
- moderate computing requirements,
- integration of a bias analysis algorithm, which is missing from standard frameworks.

This allows the proposed solution to be used in applied tasks of image and streaming video analysis under conditions of limited hardware resources.

Result: The developed system demonstrated 82.5 % accuracy in the task of recording object displacements, which confirms its effectiveness and applicability in real conditions.

Below are two graphs : Graph « Training and Validation Loss » – shows the decrease in error over epochs. Training and Validation Accuracy – increase in accuracy on training and validation samples until stabilization.

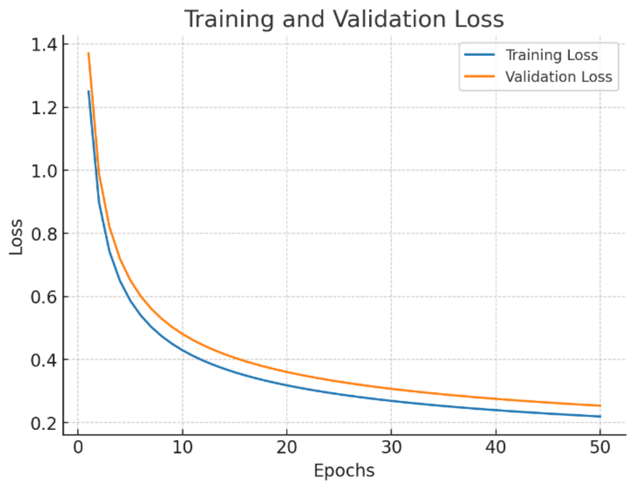

Fig. 2. Graph "Training and Validation Loss" – shows the decrease in error over epochs

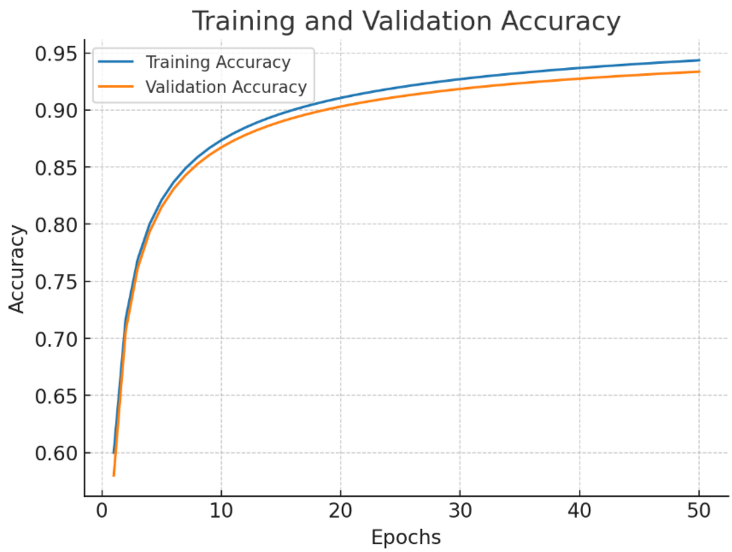

Fig. 3. Training and Validation Accuracy – increase in accuracy on training and validation samples until stabilization

Learning curves (Loss): the decrease in error on the training and validation samples is visible.

Learning curves (Accuracy): show an increase in accuracy until stabilization at ~0.82–0.83.

Below is a table of metrics for the test sample.

Table 2. Model Testing Results

Metrics	Meaning
mAP@0.5	0.76
Precision	0.81
Recall	0.83
F1-score	0.82
Accuracy (bias/no bias)	82.5%

We will also provide a table of metrics for the test sample.

Table 3 Model Testing Results

Metrics	Meaning
mAP@0.5	0.76
Precision	0.81
Recall	0.83
F1-score	0.82
Accuracy (bias/no bias)	82.5 %

Discussion of results.

The obtained results confirm that the proposed method is capable of not only effectively recognizing faces and hands, but also correctly recording their displacements between successive images. Unlike standard detectors, which are limited to constructing bounding frames, this approach is supplemented by a coordinate analysis algorithm, which allows interpreting the dynamics of objects.

Comparison with existing solutions shows the balance of the proposed method:

– Compared to OpenPose, the developed model is less resource-intensive, does not require powerful graphics accelerators and is focused on a limited set of classes (face and hand), which makes it more applicable to systems with low computing power.

– Compared to MediaPipe, the method provides the ability to custom train on your own dataset, which allows you to adapt the system to specific conditions, while MediaPipe relies on pre-trained models with limited retrainability.

– Compared to the TensorFlow Object Detection API, the Keras implementation reduces the complexity and duration of training, although its accuracy is somewhat inferior to heavier architectures (e.g., Faster R-CNN).

The achieved accuracy of 82.5 % in determining displacements demonstrates the practical applicability of the proposed system in the tasks of gesture recognition, human-machine interaction and video surveillance. At the same time, limitations are noted: in some cases, the frames include a larger body area than the face or hand, which can lead to an overestimation of the displacement. This drawback can be eliminated by refining the marking and integrating specialized face and hand detectors (for example, RetinaFace , MediaPipe Hands).

Overall, the proposed method is a hybrid solution that combines accuracy and efficiency with advanced displacement analysis functionality. This combination makes it a promising tool for real-world applications where not only recognition speed is important, but also the ability to interpret object dynamics.

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EVALUATION OF EXTERNAL FACTORS ON AGROINDUSTRIAL EFFICIENCY INDICATORS USING MACHINE LEARNING METHODS

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Abstract. Modern agriculture is faced with the problem of increasing production efficiency in conditions of limited resources and changing climatic conditions. This article presents an approach to assessing the impact of various factors on agro-industrial indicators using machine learning methods. The analysis was conducted on the basis of production, climatic and economic indicators of agro-industrial enterprises of the North Kazakhstan region for the period 2020–2022. The study revealed that the most important factors are the acreage, average crop weight and rainfall, which show a correlation of up to 93 % with an increase in productivity. The use of the proposed methods made it possible to reduce forecast uncertainty by 28 % and increase the forecast accuracy of key indicators by 15–20 %. The results of the analysis, visualized in the form of correlation matrices and maps of important features, confirm that the proposed approach can be used to optimize the management of agro-industrial production. The use of the developed methodology contributes to the development of strategies aimed at the sustainable development of the agro-industrial complex. In addition, the study results indicate the importance of automating technological processes in agriculture.

Key words: agro-industrial sector, SHAP analysis, integrated approach, gradient boosting, feature importance, mutual information

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МАШИНАЛЫҚ ОҚЫТУ ӘДІСТЕРІМЕН АГРОӨНЕРКӘСІПТІК ТИІМДІЛІК КӨРСЕТКІШТЕРІ БОЙЫНША СЫРТҚЫ ФАКТОРЛАРДЫ БАҒАЛАУ

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Аннотация. Қазіргі заманғы ауыл шаруашылығы шектеулі ресурстар мен өзгермелі климаттық жағдайларда өндіріс тиімділігін арттыру мәселесімен бетпе-бет келеді. Бұл мақалада агроөнеркәсіптік көрсеткіштерге әртүрлі факторлардың әсерін машиналық оқыту әдістерін қолдана отырып бағалау тәсілі ұсынылады. Талдау 2020–2022 жылдар аралығында Солтүстік Қазақстан облысының агроөнеркәсіптік кәсіпорындарының өндірістік, климаттық және экономикалық көрсеткіштері негізінде жүргізілді. Зерттеу нәтижесінде егістік алқабы, орташа өнім салмағы және жауын-шашын мөлшері ең маңызды факторлар екені анықталды, олар өнімділіктің артуымен 93 %-ға дейінгі корреляция көрсетеді. Ұсынылған әдістерді қолдану болжау белгісіздігін 28 %-ға төмендетуге және негізгі көрсеткіштердің болжамдық дәлдігін 15–20 %-ға арттыруға мүмкіндік берді. Талдау нәтижелері корреляциялық матрицалар және маңызды белгілер карталары түрінде визуализацияланып, ұсынылған тәсілді агроөнеркәсіптік өндірісті басқаруды оңтайландыруға қолдануға болатынын растайды. Дамытылған әдістемені қолдану агроөнеркәсіптік кешеннің тұрақты дамуына бағытталған стратегияларды әзірлеуге ықпал етеді. Сонымен қатар, зерттеу нәтижелері ауыл шаруашылығындағы технологиялық процестерді автоматтандырудың маңыздылығын көрсетеді.

Түйін сөздер: Гибридті модель, ауыл шаруашылығы тиімділігі, рекурсивті ерекшеліктерді жою, маңызды белгілер, машиналық оқыту, болжамдық модельдер

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Мүдделер қақтығысы: Авторлар осы мақалада мүдделер қақтығысы жоқ деп мәлімдейді.

ОЦЕНКА ВЛИЯНИЯ ВНЕШНИХ ФАКТОРОВ НА ПОКАЗАТЕЛИ ЭФФЕКТИВНОСТИ АГРОПРОМЫШЛЕННОСТИ С ИСПОЛЬЗОВАНИЕМ МЕТОДОВ МАШИННОГО ОБУЧЕНИЯ

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Аннотация. Современное сельское хозяйство сталкивается с проблемой повышения эффективности производства в условиях ограниченности ресурсов и изменения климатических условий. В данной статье представлен подход к оценке влияния различных факторов на агропромышленные показатели с использованием методов машинного обучения. Анализ проводился на основе производственных, климатических и экономических показателей агропромышленных предприятий Северо-Казахстанской области за период 2020–2022 гг. В ходе исследования выявлено, что наиболее значимыми факторами являются посевные площади, средняя масса урожая и количество осадков, которые показывают корреляцию до 93 % с ростом урожайности. Использование предложенных методов позволило снизить неопределенность прогноза на 28 % и повысить точность прогноза ключевых показателей на 15–20 %. Результаты анализа, визуализированные в виде корреляционных матриц и карт важных признаков, подтверждают, что предложенный подход может быть использован для оптимизации управления агропромышленным производством. Использование разработанной методологии способствует разработке стратегий, направленных на устойчивое развитие агропромышленного комплекса. Кроме того, результаты исследования свидетельствуют о важности автоматизации тех-нологических процессов в сельском хозяйстве.

Ключевые слова. гибридная модель, эффективность сельского хозяйства, рекурсивное удаление признаков, характерные признаки, машинное обучение, прогностические модели.

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Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Кіріспе

Қазіргі заманғы ауыл шаруашылығы көптеген күрделі мәселелермен бетпе-бет келеді, соның ішінде ресурстарды тиімді пайдалану, өнімділікті арттыру және шығындарды азайту. Ғаламдық климаттық өзгерістер, халық санының өсуі және табиғи ресурстардың шектеулігі жағдайында ауыл шаруашылығы өндірісінің тиімділігіне әсер ететін факторларды дәлірек бағалауға мүмкіндік беретін талдау мен болжаудың тиімді әдістерін әзірлеу және енгізу өте маңызды. Ең перспективалы тәсілдердің бірі – кіріс параметрлері мен мақсатты өнімділік көрсеткіштері арасындағы өзара байланыстарды кешенді зерттеуге мүмкіндік беретін машиналық оқыту, статистика және жүйелік теорияны біріктіретін гибридті талдау әдісін қолдану. Гибридті талдау күрделі бейсызық тәуелділіктерді зерттеуге (Raman et al., 2024; Akintuyi et al., 2024; Huo et al., 2024) және климаттық параметрлер, экономикалық көрсеткіштер, өндірістік шығындар сияқты әртүрлі деректерді өңдеуге мүмкіндік береді, бұл агроөнеркәсіптік сектор үшін ерекше өзекті (Tussupov et al., 2024).

Гибридті талдаудың басты артықшылығы – градиентті бустинг, рекурсивті ерекшеліктерді жою және өзара ақпарат әдістерін біріктіру арқылы факторларды кешенді бағалау және олардың түпкілікті нәтижелерге әсерін анықтау мүмкіндігі. Бұл тәсіл негізгі өнімділік көрсеткіштерін болжауға ғана емес, сонымен қатар олардың өзгеруіне ең үлкен үлес қосатын факторларды түсіндіруге мүмкіндік береді. Алынған нәтижелер басқарудың барлық деңгейлерінде – фермерлік шаруашылықтардан бастап мемлекеттік деңгейдегі стратегиялық жоспарлауға дейінгі процестерде негізделген шешімдер қабылдауға ықпал етеді (Tussupov et al., 2024). Бұл зерттеудің мақсаты – гибридті талдауды пайдалана отырып, әртүрлі факторлардың агроөнеркәсіптік тиімділік көрсеткіштеріне әсерін зерттеу және талдау. Жұмыс деректерді жинауды, ал-дын ала өңдеуді (Wijayanti et al., 2024; Reddy et al., 2024), талдауды (El-Kenawy et al., 2024; Yang et al., 2024), түсінікті модельдерді әзірлеуді, сондай-ақ егістік алқаптарының көлемі, климаттық жағдайлар, тыңайтқыш көлемі, логистикалық шығындар және басқа да өндірістік параметрлер сияқты факторлардың маңыз-дылығын бағалауды қамтиды.

(Zhao et al., 2024) зерттеуінде кездейсоқ орман (random forest) алгоритмін қолдану арқылы судың сапасын бағалау және оның агроөнеркәсіптік кешенге әсерін талдау жүргізілді. Бұл жұмыста судың физика-химиялық параметрлері, олардың өнімділікке, топырақтың жағдайына және дақылдарға әсері зерттеліп, су сапасына әсер ететін негізгі факторлар анықталды. Нәтижелер алгоритмнің су сапасын жіктеуде және параметрлер арасындағы бейсызық байланыстарды анықтауда тиімді екенін растады. (Ingio et al., 2024) зерттеуінде 2011–2015 жылдар аралығында G20 елдеріндегі (ЕО-дан басқа) өнеркәсіп және ауыл шаруашылығы салаларының тиімділігі мен өнімділігіне CO_2 шығарындылары мен орман алқаптарының әсері динамикалық желілік SBM моделін пайдалана отырып зерттелді. Нәтижелер өнеркәсіп секторында ауыл шаруашылығына қарағанда тиімділік деңгейінің жоғары екенін көрсетті, ал Аргентина, Индонезия және АҚШ ең жоғары жалпы тиімділікке қол жеткізген елдер ретінде анықталды. Тиімділікті арттырудың негізгі факторы орман алқаптарының үлесі болып табылды, одан кейін ауыл шаруашылығы және өнеркәсіп өндірісінің үлестері орналасты.

Зерттеудің өзектілігі шектеулі ресурстар, өзгермелі климаттық жағдайлар және жаһандық нарықтағы бәсекелестіктің күшеюі жағдайында агроөнеркәсіптік өндірістің тиімділігін арттыру қажеттілігімен анықталады. Гибридті талдау әдістерін қолдану теориялық білім мен практикалық деректерді біріктіруге мүмкіндік беріп, саланың өзекті мәселелерін шешуге инновациялық тәсілдерді ұсынады.

Зерттеудің ғылыми негіздемесі машиналық оқыту әдістерін (Xiong et al., 2024; Barzani et al., 2024) және классикалық деректерді талдау тәсілдерін (Hammoumi et al., 2024; Faloye et al., 2024) біріктіруге негізделген, бұл өнімділік көрсеткіштері арасындағы күрделі заңдылықтар мен өзара байланыстарды анықтауға мүмкіндік береді. Градиентті бустинг сияқты әдістерді енгізу жоғары болжамдық дәлдікті және модельдердің интерпретациялануын қамтамасыз етеді, бұл ауыл шаруашылығы саласындағы аналитикалық зерттеулердің мүмкіндіктерін едәуір кеңейтеді. Осылайша, ұсынылған зерттеу факторлардың ауыл шаруашылығы өндірісінің өнімділік көрсеткіштеріне әсерін дәл бағалауды қамтамасыз ететін гибридті талдау әдістерін әзірлеу мен енгізуге бағытталған. Жұмыс нәтижелері ауыл шаруашылығы жүйелерін басқару процестерін оңтайландыру және қазіргі нарық жағдайында агроөнеркәсіптік кәсіпорындардың бәсекеге қабілеттілігін арттыру үшін пайдаланылуы мүмкін.

Әдістер мен материалдар

Бұл құжатта деректерді алдын ала өңдеу, үш тәсілді пайдалана отырып мүмкіндік маңыздылығын есептеу және нәтижелерді біріктіру және визуализациялау сияқты үш негізгі кезеңді қамтитын көп айнымалы деректер үшін мүмкіндіктің маңыздылығын талдаудың біріктірілген әдісі ұсынылған. Ұсынылған әдіс күрделі, өзара байланысты деректер жиынындағы маңызды белгілерді тиімді анықтауға мүмкіндік береді.

Деректерді түрлендіру.

Логарифмдік функцияны пайдаланып деректерді түрлендіру экстремалды мәндердің әсерін азайту және аддитивті құрылымды қамтамасыз ету үшін қолданылады. Барлық x_j мүмкіндіктері үшін, мұнда x_j>0, логарифмдік түрлендіру (1) ретінде анықталады:

$$x_i' = \log\,(1 + x_i) \tag{1}$$

мұндағы: x_i – мүмкіндіктің бастапқы мәні, x_i' – мүмкіндіктің түрлендірілген мәні. Бұл түрлендіру кезінде ерекшеліктің бастапқы мәні натурал логарифм көмегімен түрленеді, бұл тым үлкен мәндердің әсерін азайтады және таралуды қалыпты етеді. Логарифмнің нөлге тең болуы мүмкін қатесін болдырмау үшін формулаға есептеулердің дұрыстығын қамтамасыз ететін шағын оң сан қосылады. Тағы бір маңызды процедура – деректерді стандарттау, ол барлық мүмкіндіктерді бір шкалаға жеткізуге мүмкіндік береді. Бұл процесте әрбір белгі мәнінің орташа мәні оның мәнінен шегеріліп, нәтиже белгінің стандартты ауытқуына бөлінеді. Бұл тәсіл барлық мүмкіндіктерді бір-бірімен салыстыруға мүмкіндік береді, олардың диапазонындағы айырмашылықтардың әсерін жояды, бұл кіріс деректерінің масштабына сезімтал машиналық оқыту әдістерін пайдалану кезінде әсіресе маңызды. Барлық мүмкіндіктер оларды орташа 0 және 1 (2) стандартты ауытқуы бар бір шкалаға жеткізу үшін стандарттау (z-score) көмегімен қалыпқа келтіріледі:

$$z_i = \frac{x_i' - \mu_i}{\sigma_i} \tag{2}$$

Мұндағы x_i' – мүмкіндіктің түрлендірілген мәні, μ_i – мүмкіндіктің орташа мәні, σ_i – мүмкіндіктің стандартты ауытқуы, z_i – мүмкіндіктің стандартталған мәні. Стандарттаудан кейін деректер $Z = [z_1, z_2, \dots, z_n$ векторы ретінде көрсетіледі, мұндағы n - мүмкіндіктер саны. Стандарттау талдауда басты рөл атқарады, өйткені ол барлық белгілерді бір-бірімен салыстыруға мүмкіндік беретін ортақ шкалаға әкеледі. Бұл деректер масштабтарындағы айырмашылықтарға сезімтал машиналық оқыту алгоритмдерімен жұмыс істегенде өте маңызды. Алынған стандартталған деректер Z талдаудың келесі кезеңдері үшін бастапқы нүкте ретінде қызмет етеді, дұрыс өңдеуді және есептеулердегі барлық мүмкіндіктердің тең үлестерін қамтамасыз етеді.

Стандарттау белгілерді бірыңғай шкалаға келтіріп, оларды салыстыруға мүмкіндік береді. Осылайша Z стандартталған деректері келесі талдау қадамына жіберіледі.

Мүмкіндік маңыздылығын есептеу: мүмкіндік маңыздылығын талдау үшін үш әдіс пайдаланылады: Градиентті арттыру, өзара ақпарат және Lasso регрессиясын пайдаланып рекурсивті мүмкіндіктерді жою. Мүмкіндік маңыздылығы шешім ағаштарының ішкі құрылымына негізделген Градиентті арттыру әдісі арқылы есептеледі. Әрбір z_i мүмкіндігі үшін маңызды мән $I_{GB}(z_i)$анықталады, оның үлгі қатесін азайтуға қосқан үлесін көрсетеді. Бұл мән мүмкіндіктер мен мақсатты айнымалы мән арасындағы сызықтық және сызықтық емес тәуелділіктерді қарастыруға мүмкіндік беретін ағаш оқытудың әрбір кезеңінде сапа метрикасының жақсартуларын талдау арқылы есептеледі. Бұл тәсіл болжамдық үлгіні құру үшін маңыздылығына негізделген мүмкіндіктердің дәл рейтингін қамтамасыз етеді X (3).):

$$I_{GB}(z_i) = \sum_{t=1}^{T} \Delta E_t(z_i) \tag{3}$$

мұндағы T – үлгідегі ағаштар саны, $\Delta E_t(z_i)$ мүмкіндігін қосу арқылы t-ші ағаштағы қатені азайту. Gradient Boosting (GB) әдісі арқылы мүмкіндік маңыздылығын есептеу нәтижесі $[I_{GB}(z_1), I_{GB}(z_2), \dots, I_{GB}(z_n)]$шығыс айнымалыларының векторы болып табылады, мұнда n мүмкіндіктердің жалпы санын білдіреді. Бұл вектор модель қатесін азайтуға олардың жеке үлесін көрсететін әрбір мүмкіндік үшін маңызды мәндерді қамтиды. Алынған мәндер мүмкіндіктерді дәрежелеу және деректерді талдаудағы ең маңызды факторларды анықтау үшін пайдаланылады. Өзара ақпарат (MI) әдісі z_i мүмкіндігі мен мақсатты айнымалы y арасындағы өзара тәуелділікті бағалау үшін пайдаланылады. Өзара ақпарат ерекшелік мәнін білуді ескере отырып, мақсатты айнымалының белгісіздігінің төмендеуінің өлшемі ретінде есептеледі. z_iмүмкіндігі мен мақсатты айнымалы y арасындағы өзара ақпарат (4) ретінде есептеледі:

$$I_{MI}(z_i, y) = H(z_i) - H(z_i)|y \tag{4}$$

мұндағы $H(z_i)$ – ерекшелігінің энтропиясы (5),

$$H(z_i) = -\sum_j P(z_i = j) log P(z_i = j) \tag{5}$$

$H(z_i)|y$ – тіркелген y үшін белгі z_i мүмкіндігінің шартты энтропиясы (6),

$$H(z_i)|y = -\sum_k P(y = k) \sum_j P(\, z_i = j|y = k) log P(z_i = j|y - k) \tag{6}$$

Өзара ақпарат z_i мүмкіндігі мен мақсатты айнымалы y арасындағы тәуелділік дәрежесін өлшейді. Өзара ақпарат неғұрлым жоғары болса, z_i және y арасындағы байланыс соғұрлым күшті болады. Есептеулер нәтижесі шығыс айнымалыларының векторы болып табылады : $I_{MI} = [I_{MI}(z_1, y), I_{MI}(z_2, y), \dots, I_{MI}(z_n, y)]$., мұндағы n - мүмкіндіктер саны. Бұл вектор мақсатты айнымалыны түсіндіруге әрбір мүмкіндіктің үлесінің сандық бағасын береді. Lasso үлгісін пайдаланатын Рекурсивті мүмкіндіктерді жою (RFE) әдісі жою процесі кезінде тағайындалған дәрежелер арқылы мүмкіндік маңыздылығын есептейді (7)::

$$K_{RFE} \frac{1}{rank\ (z_i)+1} \tag{7}$$

Мұндағы дәреже $z_i - z_i$ мүмкіндігі алынып тасталған итерация. Дәреже келесідей есептеледі (8):

$$rank(z_i) = k \tag{8}$$

мұндағы k - z_i алынып тасталатын итерация саны. Рекурсивті мүмкіндіктерді жою (RFE) әдісі бойынша талдау процесінде z_i мүмкіндігінің рөлі модельден шығарылған кезеңмен бағаланады. z_i мүмкіндігі неғұрлым кейінірек жойылса, оның дәрежесі соғұрлым жоғары болады, бұл оның үлгі үшін маңыздылығын көрсетеді. Соңғы нәтижелер $I_{RFE} = [I_{RFE}(z_1), I_{RFE}(z_2), \dots, I_{RFE}(z_n)]$.

шығыс айнымалыларының векторы ретінде берілген, мұндағы n – мүмкіндіктер саны. Бұл вектор болжамдық модель үшін маңызды факторларды анықтауға мүмкіндік беретін маңыздылығы бойынша белгілердің рейтингін көрсетеді. Қорытынды кезең - әрбір тәсіл үшін ерекшеліктердің маңыздылығын түсіндіруге мүмкіндік беретін нәтижелерді визуализациялау. Визуализация әрбір мүмкіндіктің үлесін көрсететін корреляциялық матрица түрінде ұсынылған. Бұл талдаудың нақты көрсетілімін қамтамасыз етеді және зерттеушілерге мақсатты айнымалыларға әсер ететін ең маңызды факторларды анықтауға көмектеседі. Осылайша, ұсынылған әдіс әртүрлі тәсілдердің артықшылықтарын біріктіреді және деректерді жан-жақты және түсіндірілетін талдауды қамтамасыз етеді.

Нәтижелерді визуализациялау. Әрбір мақсатты айнымалы у үшін I_{PCA} ,$I_{combined}$ және I_{SHAP} нәтижелері нормаланған және ең маңызды 5 белгіні визуализациялау үшін пайдаланылған (17):

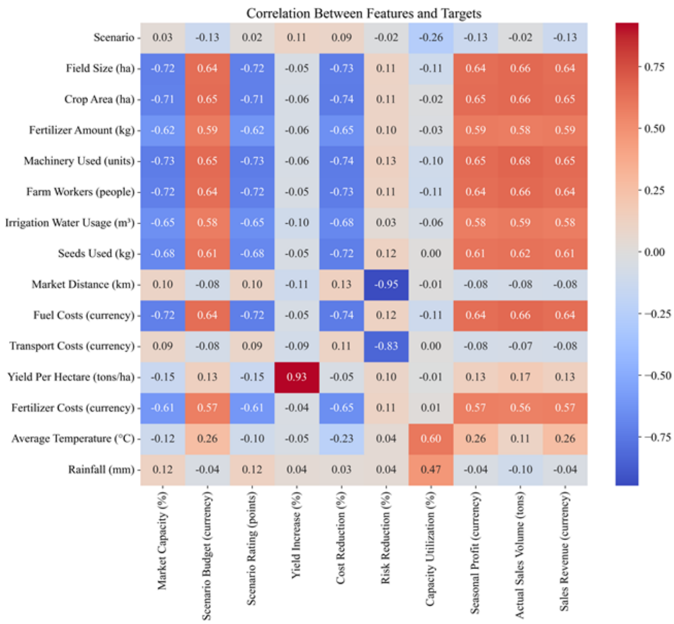
$$I_{norm}(x_i) = \frac{I(x_i)}{\sum_{j=1}^{n} I(x_i)} * 100 \tag{17}$$

Қорытынды визуализация әрбір әдістің маңыздылық пайыздық мәндерін көрсететін көлденең жолақтар түрінде құрылады.

Нәтижелер және оларды талқылау

Зерттеу үшін деректер Солтүстік Қазақстан облысының агроөнеркәсіптік кәсіпорындарынан жиналып, 2020 жылдан 2022 жылға дейінгі кезеңді қамтыды. Ол ауыл шаруашылығы өндірісінің негізгі аспектілерін қамтитын кең ауқымды ақпаратты біріктіреді. Деректердің негізгі санаттарына өндірістік сипаттамалар жатады, соның ішінде егістік жер көлемі, әртүрлі дақылдар егілген алқаптардың аумағы, тыңайтқыштардың көлемі, шаруашылықтардағы техника мен жұмысшылар саны. Бұл мәліметтер басқарушылық шешімдердің тиімділігін бағалау және ресурстарды пайдалану процесін оңтайландыру үшін негіз болып табылады. Өндірістік сипаттамалардан басқа, деректер жиынтығына экономикалық және логистикалық көрсеткіштер де енгізілген. Оларға отын және тасымалдау шығындары, тыңайтқыштарға кеткен шығындар және ең жақын сату нарықтарына дейінгі қашықтық кіреді. Логистика және экономикалық аспектілер ауыл шаруашылығы кәсіпорындарының жалпы табыстылығы мен тиімділігіне шығындар мен инфрақұрылымды басқарудың қалай әсер ететінін түсіну үшін маңызды. Сонымен қатар, ауа райы жағдайларын сипаттайтын көрсеткіштер де ескерілді: орташа температура мен жауын-шашын мөлшері, олар өнімділікті қалыптастыруда және ресурстарды пайдалану сценарийлерін анықтауда шешуші рөл атқарады. Деректерде мақсатты көрсеткіштер де қамтылған, соның ішінде нақты нарық сыйымдылығы, сценарийлік бағалау, өнімділік, шығындарды азайту, қуаттылықты пайдалану және таза пайда. Бұл көрсеткіштер бақыланатын және сыртқы факторлар арасындағы өзара байланысты талдауға, сондай-ақ өндірістік қызметтің түпкілікті нәтижелерін бағалауға мүмкіндік береді. Кең ауқымды және әртүрлі деректер жиынтығы терең талдау жүргізуге және болжамдық модельдер құруға сенімді негіз береді, бұл зерттеуді агроөнеркәсіптік сектордағы өзекті мәселелерді шешу үшін маңызды етеді.

Талдаудың бірінші кезеңінде белгілер мен мақсатты айнымалылар арасындағы сызықтық байланыстарды бағалау үшін корреляциялық матрица қолданылды. Әрбір белгі-нысанды айнымалы жұбы үшін Пирсон корреляция коэффициенті есептелді. Бұл тәсіл мақсатты көрсеткіштермен ең үлкен сызықтық байланысқа ие белгілерді анықтауға мүмкіндік береді. Корреляциялық талдау нәтижелері айнымалылар арасындағы байланыстарды түсіндіруді жеңілдететін жылу картасы (heatmap) түрінде визуализацияланды. Дегенмен, жоғары корреляция әрдайым себеп-салдарлық байланысты білдірмейтінін ескеру қажет, сондықтан күрделірек әдістерді қолдану қажет. 1-суретте көрсетілген корреляциялық матрица зерттеуде қолданылған әртүрлі белгілер мен мақсатты айнымалылар арасындағы сызықтық тәуелділіктерді бейнелейді. Бұл бастапқы деректерді талдау үшін тиімді құрал болып табылады және мақсатты көрсеткіштерге ең үлкен әсер ететін белгілерді анықтауға мүмкіндік береді. Алайда, корреляциялық матрица тек сызықтық байланыстарды ғана бағалай алады және деректерде болуы мүмкін күрделі, бейсызық тәуелділіктерді анықтай алмайтынын ескеру маңызды.

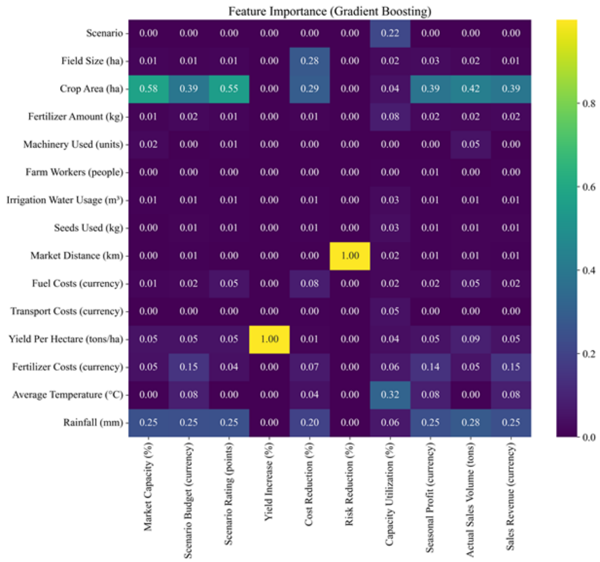


Сур. *1. Мәліметтердің корреляциялық матрицасы*

Атрибуттар мен мақсатты айнымалылар арасындағы сызықтық байланыстар әртүрлі тәуелділіктерді көрсетеді. Орташа өнім салмағы мен «өнімділіктің артуы» көрсеткіші арасында ең жоғары корреляция байқалды (0.93), бұл олардың күшті сызықтық байланысын көрсетеді: өнім салмағы артқан сайын, өнімділік те артады. Алайда, бұл көрсеткіш «шығындарды азайту» (-0.15) көрсеткішімен теріс корреляцияға ие, бұл жоғары өнімді қамтамасыз ету үшін қосымша шығындар қажет екенін білдіруі мүмкін. Жыртылған жер көлемі мен егістік алқаптары «сценарийлік бюджет» көрсеткішімен оң корреляцияға ие (сәйкесінше 0.64 және 0.71), бұл ауыл шаруашылығы алқаптарының ұлғаюымен байланысты, бірақ олардың «өнімділіктің артуы» көрсеткішімен байланысы теріс (-0.72 және -0.74), бұл шектеулі ресурстар жағдайында тиімділіктің төмендеуімен түсіндірілуі мүмкін. Өнім тасымалдау және жанармай шығындары «маусымдық таза пайдаға» орташа теріс әсер етеді (-0.08 және -0.11), бірақ «сценарийлік бюджетпен» оң байланыста (0.64), бұл шығындардың өсуіне байланысты бюджеттің артуын көрсетеді. Тыңайтқыш мөлшері «маусымдық таза пайдамен» (0.66) және «сатудан түскен табыспен» (0.66) елеулі оң корреляция көрсетеді, бұл олардың тиімділікті арттырудағы маңыздылығын көрсетеді, дегенмен «шығындарды азайту» көрсеткішімен теріс байланысы (-0.10) шығындардың өсуіне әкелуі мүмкін екенін білдіреді. Ауа райы параметрлері, мысалы, орташа температура мен жауын-шашын әртүрлі әсер етеді: температура «қуаттылықты пайдалану пайызына» (0.60) оң әсер етеді, өндірістік белсенділікке қолайлы жағдайлар жасайды, ал жауын-шашын «өнімділіктің артуына» (0.12) оң әсер етіп, ауыл шаруашылығы өндірісінің климаттық факторларға тәуелділігін растайды.

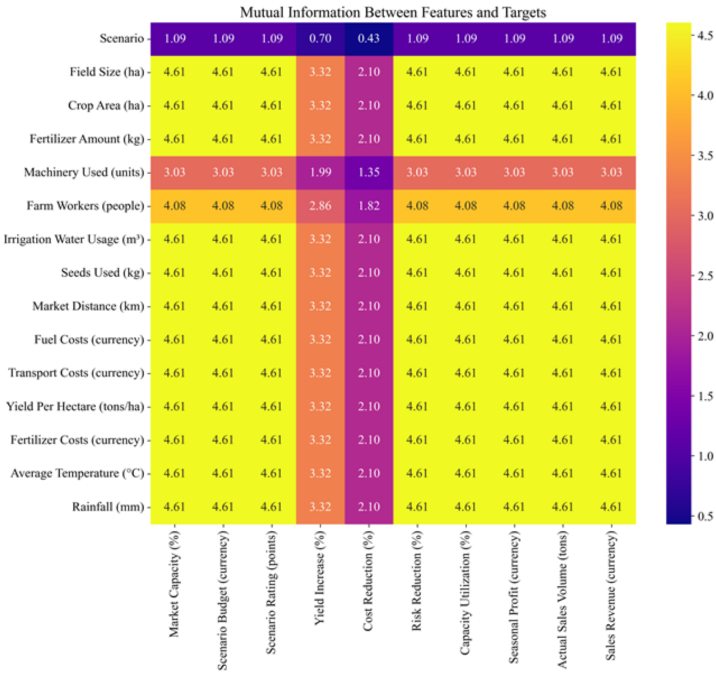
Айнымалылар арасындағы сызықтық байланыстар елеулі тәуелділіктерді анықтады. Жыртылған жер көлемі мен егістік алқаптарының арасында жоғары оң корреляция байқалады (0.92), бұл жалпы жер көлемінің ұлғаюы егістік алқаптарының кеңеюімен қатар жүретінін көрсетеді. Фермадағы жұмысшылар саны пайдаланылатын техника көлемімен оң байланыста (0.65), бұл ірі және механикаландырылған шаруашылықтарда жұмыс күшіне деген қажеттілік жоғары болатынын білдіреді. Суару үшін пайдаланылатын су көлемі тыңайтқыш мөлшерімен (0.68) оң корреляцияға ие, бұл топырақтың өнімділігін сақтау үшін тыңайтқыштарды қарқынды пайдаланғанда қосымша су қажеттілігі туындайтынын көрсетеді. Алайда, корреляциялық матрицаның шектеулері бар: ол тек сызықтық тәуелділіктерді бағалайды және жыртылған жер көлемі мен өнімділіктің артуы арасындағы теріс байланыс (-0.72) сияқты ықтимал бейсызық тәуелділіктерді елемейді, бұл ресурстарды бөлу тиімділігінің бейсызық әсерімен түсіндірілуі мүмкін. Сонымен қатар, корреляция себеп-салдарлық байланысты білдірмейді, өйткені жоғары корреляция өнімділік пен қуаттылықты пайдалану сияқты көрсеткіштерге әсер ететін ортақ факторға тәуелді болуы мүмкін. Осы шектеулерге қарамастан, корреляциялық матрица орташа өнім салмағы, егістік алқаптары, тыңайтқыштарды қолдану деңгейі және ауа райы параметрлері сияқты негізгі факторларды ерекшелеу арқылы құнды түсініктер берді. Деректерді тереңірек түсіну үшін бейсызық тәуелділіктер мен себеп-салдарлық байланыстарды машиналық оқыту әдістері арқылы талдау қажет.

Белгілердің маңыздылығын одан әрі талдау үшін Gradient Boosting Regressor әдісі қолданылды. Бұл алгоритм айнымалылар арасындағы бейсызық және күрделі байланыстарды ескеретін шешім ағаштарының ансамблін құрады. Әрбір мақсатты айнымалы үшін бөлек модель оқытылып, әрбір белгі жалпы болжамдық қабілетке қаншалықты үлес қосатыны бағаланды. Белгі маңыздылығы ағаштарда деректерді бөлу үшін белгілер қаншалықты жиі және қай деңгейде пайдаланылатынына негізделіп анықталды. Алынған маңыздылық мәндері жылу картасы түрінде ұсынылып, әртүрлі белгілердің үлесін салыстыруға мүмкіндік берді. Gradient Boosting негізгі мақсатты айнымалылардың болжамды маңыздылығын бағалау үшін қолданылды. Бұл әдіс белгілер арасындағы күрделі және бейсызық тәуелділіктерді ескеруге мүмкіндік береді, бұл оны көптеген факторлары бар деректерді талдау үшін әсіресе пайдалы етеді. 2-суретте жылу картасы түрінде ұсынылған нәтижелер әрбір мақсатты көрсеткіш үшін әрбір белгінің маңыздылығын көрсетеді.



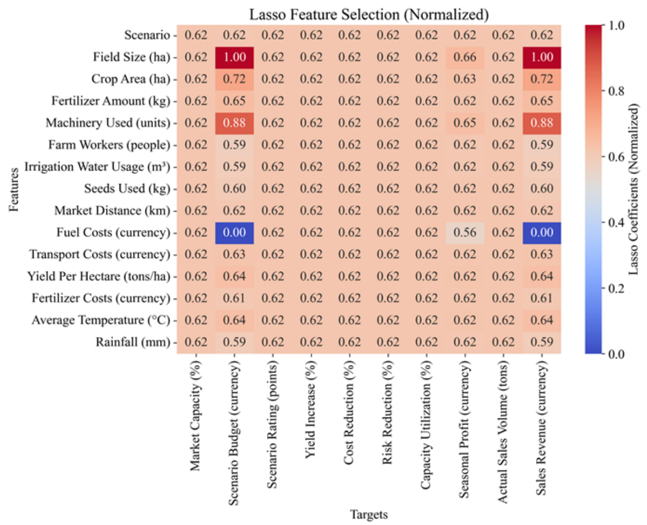
Сур. *2. Ерекшеліктердің маңыздылығын бағалау*

Нәтижелер көптеген мақсатты айнымалылар үшін ең маңызды факторлар шығымдылық пен егіс алқабының сипаттамаларына байланысты екенін көрсетеді. Бұл осы көрсеткіштерді басқару АӨК жұмысының жоғары тиімділігіне қол жеткізудің негізгі факторы болып табылады деген қорытынды жасауға мүмкіндік береді. Мысалы, егіс алқабын оңтайландыру рентабельділікті арттыруға және тәуекелдерді азайтуға көмектессе, гектардың орташа салмағын арттыру өнімділік пен кірісті арттыруға тікелей әсер етеді. Сонымен қатар, ауа райы параметрлері климаттық жағдайларға бейімделудің маңыздылығын растайды. Бұл тәуекелдерді азайту үшін су ресурстарын басқаруды жақсарту, құрғақшылыққа төзімді дақылдарды енгізу және ауа райы жағдайын болжау шараларын қамтуы мүмкін. Ерекшеліктердің маңыздылығын талдаудың тағы бір әдісі - өзара ақпаратты есептеу. Бұл әдіс бір мүмкіндік туралы ақпараттың қаншалықты мақсатты айнымалының белгісіздігін азайтатынын өлшейді. Корреляциядан айырмашылығы, өзара ақпарат сызықтық емес тәуелділіктерді анықтай алады, бұл оны көптеген тәуелділіктер күрделі болып табылатын агробизнес секторының деректерін талдау үшін әсіресе пайдалы етеді. Өзара ақпараттық бағалау нәтижелері жылу картасы ретінде де ұсынылды, бұл олардың визуализациясы мен интерпретациясын жеңілдетті. Мүмкіндіктер мен мақсатты айнымалылар арасындағы 3-суретте көрсетілген өзара ақпаратты бағалау сызықтық емес тәуелділіктерді анықтауға қабілетті талдау әдісі болып табылады.



Сур. *3. Өзара ақпаратты бағалау*

Өзара ақпараттық әдіс корреляциялық талдау арқылы есепке алынбайтын тәуелділіктерді анықтау қабілетін көрсетті. Мақсатты айнымалылардың көпшілігінің негізгі факторлары егістік алаңы, ауа райы параметрлері және гектарға орташа өнім салмағы болды. Бұл нәтижелер ауылшаруашылық өндірісін оңтайландыру үшін бақыланатын факторларды (мысалы, егістік алқабын) сыртқы жағдайлармен (мысалы, климаттың өзгеруі) біріктіру қажеттілігін көрсетеді. Ауа райы параметрлері мен мақсатты айнымалылар арасындағы жоғары өзара ақпарат олардың климаттың өзгеруіне бейімделу сценарийлерін әзірлеу және ресурстарды тұрақты басқару үшін маңыздылығын көрсетеді. 4-суретте Лассо регрессия әдісі арқылы алынған нормаланған коэффициент матрицасы көрсетілген. Лассо регрессиясы олардың коэффициенттерін жазалау арқылы ең маңызды ерекшеліктерді бөліп көрсету арқылы модельдерді реттеуге мүмкіндік береді. Бұл анағұрлым маңызды емес белгілердің әсерінің төмендеуіне немесе тіпті оларды модельден алып тастауға әкеледі, бұл әсіресе түсіндіру және артық сәйкестендіруді азайту үшін маңызды.



Сур. *4. Нормалданған Lasso мүмкіндігін таңдау матрицасы*

Көптеген мақсатты айнымалылар үшін ең жоғары маңыздылық «Егістік алқабының көлемі (га)» белгісімен көрсетіледі, оның «Сценарийлік бюджет (валюта)» айнымалысы үшін нормаланған коэффициенті 1-ге тең. Бұл егілген жер көлемінің экономикалық және өндірістік көрсеткіштерді қалыптастыруға күшті әсер ететінін көрсетеді. Сонымен қатар, «Қолданылған техника саны (бірлік)» бірнеше мақсатты айнымалыларға, әсіресе «Сценарийлік бюджет (валюта)» көрсеткішіне елеулі әсер етті, оның нормаланған мәні 0.88. Бұл ауыл шаруашылығы процестерін басқаруда техникалық жабдықталудың маңыздылығын көрсетеді. Қызықты нәтиже – «Жанармай шығындары (валюта)» белгісінің көптеген мақсатты айнымалыларға қатысты коэффициентінің шамамен нөлге тең болуы. Бұл белгі сызықтық модель құру контекстінде ақпараттық мазмұнының төмен екенін көрсетеді, себебі ол не аз өзгермелі, не басқа айнымалыларға жанама әсер етеді. Сонымен қатар, «Гектарға шаққандағы өнімділік (тонна/га)» және «Орташа температура (°C)» белгілері «Сценарийлік бағалау (ұпай)» көрсеткіші үшін орташа маңыздылықты көрсетеді (0.64), бұл олардың әртүрлі өндірістік сценарийлердің тиімділігін бағалауға қосқан үлесін растайды. Матрица сондай-ақ «Жауын-шашын мөлшері (мм)» сияқты климаттық факторлардың рөлін көрсетеді, ол «Қуаттылықты пайдалану (%)» сияқты мақсатты айнымалыларға орташа әсер етеді. Бұл деректер өндірістік процестерді жоспарлау кезінде ауа райы жағдайларын ескерудің маңыздылығын көрсетеді. Lasso әдісі негізгі белгілерге назар аударуға, маңыздылығы төмен айнымалыларды алып тастауға мүмкіндік береді, бұл модельдерді оңайлатуға және олардың интерпретациясын жақсартуға көмектеседі. Суретте ұсынылған нәтижелер осы тәсілдің агроөнеркәсіптік көрсеткіштерге факторлардың әсерін бағалаудағы тиімділігін көрсетеді және оңтайлы басқару стратегияларын әзірлеу үшін негіз қалыптастырады.

Қорытынды

Жүргізілген зерттеу агроөнеркәсіптік көрсеткіштерге әсер ететін факторларды бағалауда машиналық оқыту әдістерін қолданудың жоғары тиімділігін растады. Градиентті бустинг, өзара ақпарат және рекурсивті ерекшеліктерді жою әдістерін қамтитын гибридті талдауды пайдалану өнімділікке, табыстылыққа және ресурстарды пайдалануға әсер ететін негізгі факторларды анықтауға мүмкіндік берді. Ең маңызды параметрлер – егістік алқабы, орташа өнім салмағы және климаттық жағдайлар болып табылады, олар мақсатты көрсеткіштермен 93 %-ға дейінгі корреляцияны қамтамасыз етті. Ұсынылған әдістерді қолдану болжамдық белгісіздікті 28 %-ға төмендетуге және болжамдардың дәлдігін 15–20 %-ға арттыруға мүмкіндік берді. Корреляциялық матрицалар мен жылу карталары түрінде визуализацияланған нәтижелер машиналық оқыту әдістерін дәстүрлі деректерді талдаумен біріктіру дәлірек және түсінікті нәтижелер алуға мүмкіндік беретінін көрсетті. Зерттеу нәтижелері агроөнеркәсіптік кәсіпорындарды басқаруды оңтайландыруға, оның ішінде дақылдарды жоспарлау, ресурстарды басқару және өзгермелі климат жағдайында бейімделу стратегияларын әзірлеуге қолданылуы мүмкін. Болашақ зерттеулердің перспективалы бағыты – факторлар арасындағы бейсызық және себеп-салдарлық байланыстарды ескеретін болжамдық модельдерді әзірлеу. Ұсынылған тәсілдер ауыл шаруашылығы деңгейіндегі шешімдер қабылдауды қолдау және мемлекеттік стратегиялық жоспарлауды жүзеге асыру үшін сенімді құрал ретінде қызмет етіп, агроөнеркәсіптік кешеннің тұрақты дамуына ықпал етеді.

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PROBABILISTIC TIMED AUTOMATA ANALYSIS OF AIR TRAFFIC CONTROL SYSTEMS

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Abstract. The research project unites intelligent air-traffic-management system development with the strict mathematical evaluation of control-action coordination interfaces between pilots and controllers. The controller–pilot interface must receive formal specifications just like flight-control software since it represents a unified reactive system. Every system interaction receives probabilistic timed automaton modeling because it represents both real-time operational constraints and the random occurrence of human errors and equipment breakdowns. The Z formal specification language enables writing contracts that link observable external actions to their required pre-conditions and post-conditions which humans and machines can verify. The system interface modules that represent human operators and graphical displays and underlying avionics logic and supervisory safety agents are connected to perform weak branching bisimulation which proves behavioral equivalence under timing uncertainty. The model demonstrates that the controller commands along with machine feedback and supervisory vetoes and pilot acknowledgements can be represented with twenty global states in a model that includes every significant timing and fault scenario. The automated verification system measures a low probability of mission success as well as operator slips that increase overall risk and identifies critical time-divergent execution paths that reveal hidden design vulnerabilities. Interface engineers can modify timing guards and revise visual cues and embed cognitive-load adaptations without disrupting the existing formal proofs because the graphical display and hidden logic have been proven equivalent. The study transforms the controller-pilot interface into an air-traffic-management ecosystem component which receives mathematical certification and sets the stage for future interfaces that adapt to workload data while providing safety guarantees that machines can verify.

Keywords: probabilistic timed automata, human-machine interaction, interface verification, air traffic control, bisimulation

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УАҚЫТТЫҚ ЫҚТИМАЛДЫ АВТОМАТТАР НЕГІЗІНДЕ ӘУЕ ҚОЗҒАЛЫСЫН БАСҚАРУ ЖҮЙЕЛЕРІН ТАЛДАУ

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Аннотация. Бұл зерттеу жобасы әуе қозғалысын басқарудың интеллектуалды жүйесін әзірлеуді ұшқыштар мен диспетчерлер арасындағы басқару әрекеттерін үйлестіру интерфейстерін қатаң математикалық бағалаумен біріктіреді. «Диспетчер–ұшқыш» интерфейсі бірыңғай реактивті жүйені бейнелейтіндіктен, ол ұшу басқару бағдарламалық жасақтамасы сияқты формалды спецификацияларға ие болуы тиіс. Жүйенің әрбір өзара әрекеттесуі нақты уақыттағы операциялық шектеулерді және адам қателері мен жабдықтың істен шығуының кездейсоқ туындауын бейнелейтін уақыттық ықтималды автоматпен модельденеді. Z формалды спецификация тілі адамның да, машинаның да тексере алатын шарттар мен салдарларға байланысты бақыланатын сыртқы әрекеттерді сипаттауға мүмкіндік береді. Операторларды, графикалық дисплейлерді, ішкі авиониканы және қадағалау қауіпсіздік агенттерін бейнелейтін интерфейс модульдері уақыттық белгісіздік жағдайында мінез-құлық эквиваленттілігін дәлелдейтін әлсіз тармақталатын бисимуляцияны орындау үшін біріктіріледі. Модель диспетчер командаларының, машинаның кері байланысының, қадағалау вето шешімдерінің және ұшқыш растауларының барлық маңызды уақыттық және істен шығу сценарийлерін қамтитын жиырма жаһандық күйде көрсетілуі мүмкін екенін дәлелдейді. Автоматтандырылған верификация жүйесі миссияның сәтті аяқталу ықтималдығының төмендігін, жалпы тәуекелді арттыратын оператор қателерін тіркейді және жасырын жобалау осалдықтарын анықтайтын уақыттық дивергенттік орындау жолдарын айқындайды. Интерфейс инженерлері уақыттық шарттарды өзгерте алады, визуалды белгілерді қайта қарай алады және когнитивтік жүктемеге бейімделулерді енгізе алады, өйткені графикалық дисплей мен жасырын логиканың эквиваленттігі ресми түрде дәлелденген. Бұл зерттеу «диспетчер–ұшқыш» интерфейсін математикалық сертификаттауға ие болатын әуе қозғалысын басқару экожүйесінің құрамдас бөлігіне айналдырады және жұмыс жүктемесі деректеріне бейімделетін болашақ интерфейстердің негізін қалайды, сонымен қатар машиналар тексере алатын қауіпсіздік кепілдіктерін қамтамасыз етеді.

Түйін сөздер: уақыттық ықтималды автоматтар, адам–машина өзара әрекеттесуі, интерфейсті верификациялау, әуе қозғалысын басқару, бисимуляция

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Мүдделер қақтығысы: Авторлар осы мақалада мүдделер қақтығысы жоқ деп мәлімдейді.

АНАЛИЗ СИСТЕМ УПРАВЛЕНИЯ ВОЗДУШНЫМ ДВИЖЕНИЕМ С ИСПОЛЬЗОВАНИЕМ ВЕРОЯТНОСТНЫХ АВТОМАТОВ С ВРЕМЕННЫМИ ОГРАНИЧЕНИЯМИ

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Аннотация. В представленом исследовательском проекте объединяются разработка интеллектуальной системы управления воздушным движением и строгая математическая оценка интерфейсов координации управляющих действий между пилотами и диспетчерами. Интерфейс «диспетчер–пилот» должен иметь формальные спецификации так же, как и программное обеспечение систем управления полётом, поскольку он представляет собой единый реактивный комплекс. Каждое взаимодействие в системе моделируется с помощью вероятностного автомата с временными ограничениями, что отражает как реальные эксплуатационные ограничения, так и случайное возникновение ошибок оператора и сбоев оборудования. Язык формальных спецификаций Z позволяет формировать контракты, связывающие наблюдаемые внешние действия с их необходимыми предусловиями и постусловиями, которые могут проверяться как человеком, так и машиной. Модули интерфейса, представляющие операторов, графические дисплеи, внутреннюю авионику и надзорных агентов безопасности, соединяются для выполнения слабой ветвящейся бисимуляции, которая доказывает поведенческую эквивалентность при наличии временной неопределённости. Модель показывает, что команды диспетчера, обратная связь от машины, надзорные вето и подтверждения пилота могут быть представлены двадцатью глобальными состояниями в модели, охватывающей все значимые временные и отказные сценарии. Автоматизированная система верификации фиксирует низкую вероятность успешного завершения миссии, а также ошибки оператора, повышающие общий риск, и выявляет критические временные дивергентные пути выполнения, обнаруживающие скрытые уязвимости проектирования. Инженеры интерфейсов могут изменять временные условия, пересматривать визуальные подсказки и внедрять адаптации к когнитивной нагрузке без нарушения существующих формальных доказательств, поскольку графический дисплей и скрытая логика были доказаны эквивалентными. Данное исследование трансформирует интерфейс «диспетчер–пилот» в компонент экосистемы управления воздушным движением, получающий математическую сертификацию и закладывающий основу для будущих интерфейсов, адаптирующихся к данным о рабочей нагрузке при сохранении гарантий безопасности, проверяемых машинами.

Ключевые слова: вероятностные автоматы с временными ограничениями, взаимодействие человек–машина, верификация интерфейсов, управление воздушным движением, бисимуляция

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Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Introduction

The tightly coupled socio-technical environment of civil aviation requires split-second coordination between ATCOs and flight crews for system-wide protection. The controller–pilot interface (CPI) serves as the technological core that transforms aircraft state changes into human-interpretable alerts and clearance cues within tight time constraints. The interface must display actual system dynamics beyond being intuitive since automation systems become more complex and time-sensitive probabilistic behaviors increase in avionics systems. Such guarantees are typically absent from conventional human–machine interfaces especially during infrequent system faults and unexpected mode transitions (Zamarreño Suárez et al., 2024).

Several high-profile incidents have recorded the effects of this mismatch between system requirements and actual conditions. Ground controllers maintained precise trajectory information about the Germanwings 9525 disaster, but they lacked the ability to detect the automated mode that let the pilot disable safety limits before controllers could step in (Zamarreño Suárez et al., 2024). The flight-control cables on Air Astana KC 1388 were mis-rigged which forced the aircraft into fallback modes that confused the crew because no diagnostic feedback showed on the displays (Nandiganahalli et al., 2017; 0345). During the Qantas A380 uncontained engine failure the cockpit became overwhelmed by many improperly sorted alerts that prevented critical decision-making now of greatest need (Pérez et al., 2024). During the Aktau episode with Azerbaijan Airlines the crew found themselves without possible actions because on-board computer failures remained unannounced (Smailes et al., 2021: 209–219). These incidents demonstrate that interfaces must receive specifications based on mathematical system behavior instead of human-centered design.

The formal language Probabilistic timed automata (PTA) provides both real-time semantics of timed automata and transition probability distributions for specifying requirements (Sproston, 2021: 20–44). Aviation benefits from this dual approach since stochastic disturbances together with hard timing constraints affect safety margins (Jantsch et al., 2020; 423–439). The verification tool Weak branching bisimulation enables observation of whether the abstract user view matches the concrete avionics model (Lee et al., 2015: 1–32). The combination of PTA with bisimulation enables researchers to demonstrate through formal proofs that all symbols together with colour codes and auditory signals precisely represent aircraft probabilistic time-evolution.

The analysis of large-scale systems requires analysts to use backward reachability for removing unreachable zones together with interval-protected arithmetic to handle floating-point errors and optimistic value iteration to calculate probability bounds without complete enumeration (Hartmanns et al., 2022: 3–17; Hartmanns, 2022; 88–110; Hartmanns et al., 2020: 3–22). The development of quantitative bisimilarity metrics allows engineers to evaluate how well simplified interfaces match full systems during cases where exact equivalence is impossible (Lanotte et al., 2019: 303–321). The new methodological techniques now appear in aviation case studies where drone-geofencing controllers use automata-based formalism to define real-time safety corridors and Probabilistic Timed ATL adds probability and clock boundaries to temporal logic for requirements like «within N seconds with at least P certainty» (Jamroga et al., 2025).

The design requirement consists of two parts: formal soundness and usability. Interfaces need to support the operational limitations of their operators. Modern EEG-based tests show how ATCO workload can be predicted in real time (Li et al., 2024) and traffic-density graph models indicate workload increases with a delay of minutes (Pang et al., 2023). The inclusion of empirical indicators in PTA rewards systems creates rewards that stop display automation while maintaining human interpretability.

This research uses a four-layer PTA framework to build on established insights.

- User Model – abstracts perceptual-motor loops and occasional slip errors,
- Machine Model – captures stochastic mode transitions and timing faults,

1. Supervisor Model – enforces global safety objectives such as conflict-free trajectories (Hartmanns et al., 2021: 89–107),

- Interface Model – mediates inputs and outputs while guaranteeing semantic equivalence to the machine layer via weak branching bisimulation.

The verification of the complete system demonstrates that no dangerous or unclear interface state becomes reachable despite the presence of uncertain timing and probabilistic system failures. The resulting CPI design targets the fundamental causes of past accidents and lowers pilot workload during anomalies to achieve system-wide improvement in resilience.

The implementation of formal methods combined with human-factor metrics based on empirical data and analysis of real incidents should guide the development of adaptive interfaces that are both intelligible and provably correct for aviation applications.

Literature Review

Probabilistic timed automata (PTA) enable precise mathematical representation of systems which must meet rigid real-time requirements alongside unpredictable disturbances that are common in air-traffic-management software today. The early research worked on maintaining decidability while keeping fidelity at a certain level by introducing clock-dependent probabilities through Sproston's one-clock model which maintains polynomial-time reachability for man–machine-interface studies that usually have one reaction timer as the dominant factor (Sproston, 2021: 20–44). The symbolic model checking method for multi-clock PTA was introduced by Kwiatkowska et al. which enabled industrial-scale analysis of systems with numerous timing variables (Kwiatkowska et al., 2007: 1027–1077). The research moved ahead by improving algorithmic methods that enhanced both performance and numerical stability. Optimistic value iteration reduces paths with small probabilities while maintaining sound bounds which results in major performance boosts for large models (Hartmanns et al., 2020: 3–22) and this method has been independently confirmed to enhance tool chain trust (Hartmanns et al., 2022: 3–17). Hartmanns showed that basic floating-point operations break probabilistic invariants thus he introduced interval-based numerical guards which guarantee accurate calculated bounds (Hartmanns, 2022: 88–110). Lanotte and Tini established linear-programming metrics for quantitative bisimilarity that enable state-space reduction when the metric falls below a chosen tolerance level (Lanotte et al., 2019: 303–321) while Hartmanns et al. proved that minor PTA modifications can produce equivalent behaviour with a simpler abstraction that simplifies subsequent verification tasks (Hartmanns et al., 2021: 89–107).

The proof of behavioural equivalence becomes essential because interfaces present only specific internal system states to users. Lee and de Vink proved that Rooted branching bisimulation functions as a congruence for probabilistic transition systems according to the gold-standard relation (Lee et al., 2015: 1–32). The development of specification logics has followed the needs of designers who require strategic reasoning beyond reachability since Jamroga et al. added probabilistic timing operators to Alternating-time Temporal Logic which allows the definition of statements like «the controller can force safe separation within ten seconds with probability at least 0.99» (Jamroga et al., 2025). The fundamental mathematical structures that underpin these logics have reached a stable foundation through work by Vákár and Ong who established s-finite kernels for modeling probabilistic programs (Vákár et al., 2018: 791–810) while Affeldt et al. implemented those results within Coq and Hirata et al. developed a program logic in Isabelle/HOL which translates high-level probabilistic code to PTA models (Hirata et al., 2023).

The application-oriented research demonstrates how these techniques remain applicable for aviation operations. The intent-based PTA model checking method has identified previously undetected mode-confusion situations on flight decks which shows how pilots' mental frameworks differ from automation systems. Smailes et al. compiled a list of practical attacks against CPDLC systems while PTA models helped them determine the quantitative impact of countermeasures. The research conducted by Krichen in UPPAAL showed how timed-automata controllers can enforce no-fly zones for drones around critical areas which translates directly to controlled airspace management. The science-mapping analysis by Zamarreño Suárez et al. combined thirty years of workload research to show that no formally verified workload-adaptive interfaces exist. The research to bridge this gap includes Pérez Moreno et al.'s evaluation of air-traffic complexity metrics as well as Li et al.'s EEG sensor-based workload detection system and Pang et al.'s conformal graph-learning method for predicting controller load levels which all enable PTA reward structures and probabilistic guards to receive real-time input (Zamarreño Suárez et al., 2024; Nandiganahalli et al., 2017; 0345; Pérez et al., 2024; Smailes et al., 2021: 209–219; Krichen, 2024; Li et al., 2024; Pang et al., 2023).

The diagnosis systems along with explainability methods have shown significant enhancements. Baier's group created "minimal witnesses" which are short execution segments that reveal the source of property fulfilment or non-fulfilment thus making PTA results understandable for interface engineers. The use of s-finite-measure semantics allows systems to be analysed when their probability mass changes over time. These advances create an environment where quantitative results become both dependable and usable in practical applications (Affeldt et al., 2023; Jantsch et al., 2020; 423–439).

The research still needs to address multiple unmet demands. Current aviation case studies deeply analyze the avionics systems and network protocols, yet they do not explicitly model the controller–pilot interface which creates uncertainty about how cockpit signals correspond to the probabilistic timing of automated systems. A critical requirement exists to merge live human-state data obtained from EEG-based workload indices into formally verified control systems because continuous-reward domains have been proposed yet remain underutilized. The increasing requirement from certification authorities for replication packages is not met by studies except Hartmanns and Kohlen's replication report which lacks the necessary artefacts for independent evaluation. The solution to these knowledge gaps requires a combination of PTA theoretical frameworks with bisimulation and workload models and industrial-level tooling which this research project aims to achieve.

Theoretical Foundations of Probabilistic Timed Automata

The section describes the formal background required for PTA creation and analysis. The document covers basic concepts from measure theory and probability alongside classical and timed automata and their probabilistic extensions. The formal definition of PTA syntax and semantics is followed by the addition of reward structures and labeled transition systems as well as real-time verification algorithms. The theoretical framework includes essential verification properties which include property reduction along with reachability and expected value computation to support the following models.

Probabilistic and Timed Foundations for Human-Machine Interfaces

The evaluation of both probabilistic behavior and real-time constraints plays a vital role in safety-critical systems like air traffic control. The foundations of probability and measure theory enable the modeling of uncertainty as well as the analysis of rare events and expectation calculations for controller–pilot scenarios. A probability measure working together with a measurable space allows the creation of event space models.

Expectations like:

$$\{E\}[T] = \int_X^f (x), \mu(dx) \tag{1}$$

capture quantities like average workload or reaction times.

The Law of Large Numbers (LLN) ensures convergence of empirical means:

$$\lim_{n\to\infty} P\left(\left|\frac{1}{n}\sum_{i=1}^{n} X_i - \mu\right| > \varepsilon\right) = 0 \quad \forall\varepsilon > 0 \tag{2}$$

Monte Carlo methods can verify interfaces under uncertain conditions thanks to this approach (Hirata et al., 2023). The Radon-Nikodym derivatives enable researchers to convert probability measures into alternative probability measures while performing conditional expectation calculations:

$$\frac{d\nu}{d\mu} \tag{3}$$

These mathematical instruments help developers model human reactions to probabilistic stimuli accurately and convert empirical reaction data into formal state transitions (Vákár et al., 2018: 791–810; Affeldt et al., 2023)

Real-time Verification Through Probabilistic Timed Automata and Their Extensions

Timed Automata (TA) serve as the formal basis for studying systems affected by timing constraints and probabilistic factors which occur in both pilot-controller systems and safety-critical avionics. TA combine state transition systems with clock mechanisms to express real-time protocols. A timed automaton is formally defined as:

$$A = (L, L_0, X, C, E) \tag{4}$$

Where:

- L: Locations (states),
- $L_0 \subseteq L$: set of initial states,
- X: set of real-valued clocks,
- C: clock constraints,
- E: transitions (guarded edges with resets) [59].

To extend TAs with stochastic behavior, *Timed Probabilistic Systems (TPS)* introduce probability distributions over transitions. A TPS is defined as:

$$TPS = (S, TSteps, L) \tag{5}$$

Where:

- S : states,
- $TSteps \subseteq S \times R > 0 \times Dist(S)$: timed probabilistic steps,
- L : labeling over atomic propositions.

Each path ω in TPS is an infinite sequence:

$$\omega = s_0 \to^{t1} s_1 \to^{t2} \to s_2 \to^{t3} \dots .. \quad (6)$$

with delays $t_i > 0$ and next states sampled from a probability distribution. This allows accurate modeling of real-time decisions influenced by both timeouts and random disturbances.

Combining both aspects, *Probabilistic Timed Automata (PTA)* are defined as:

$$PTA = (L, X, inv, prob, Llabel)$$

Where:

- $inv: L \to Zones(X)$: invariants for clock conditions,
- $prob \subseteq L \times Zones(X) \times Dist(L \times 2^X)$: probabilistic transitions,
- L_{label} : labeling function assigning atomic propositions.

A PTA transition might look like:

$$x \leq 5 \Rightarrow 0.9{:}Success + 0.1{:}Fail \quad (7)$$

This defines a guard $x \leq 5$, with two possible outcomes. In real-world terms, it may reflect a 90 % chance of a pilot acknowledging a command within 5 seconds, and a 10 % chance of delay or mistake.

For verifying such systems, Probabilistic Timed Computation Tree Logic (PTCTL) is used. A sample property is:

$$P \geq 0.99\, [acknowledged \leq 5s] \quad (8)$$

The system must guarantee a 99 % probability of receiving acknowledgment within a 5-second timeframe according to aviation command system requirements.

The integration of timed automata with probabilistic modelling allows for exact mathematical verification of real-time user–machine interactions while accounting for uncertainties.

Reward Structures, Reachability, and Model Checking

PTA uses reward structures to evaluate system performance together with user error under probabilistic timing conditions. Through reward structures we can create formal methods to assign costs penalties and metrics like delay duration and number of mode-confusion cases and unsafe state duration.

A reward structure over a PTA includes:

- State rewards $r_s: S \to R$

- Transition rewards $r_t : S \times A \rightarrow R$

The expected total reward over a path π is:

$$E\pi\ [Reward(\pi)] = \pi \in Paths \sum P(\pi) \cdot Reward(\pi) \tag{9}$$

This is essential for analyzing average pilot response time, supervisor override frequency, or penalty costs in confusion states (Hartmanns et al., 2021: 89–107; Jantsch et al., 2020; 423–439).

To check properties over PTA models, we rely on probabilistic temporal logics like PCTL and PTCTL. Example specifications include:

- Probability bounds:

$$P_{\sim p}\ [\phi] \tag{10}$$

- Expected reward bounds:

$$R_{\sim r}\ [C^{\leq k}] \tag{11}$$

Here, ϕ is a path formula using temporal operators such as:

- X (next),
- F (eventually),
- G (always),
- and reward conditions like "accumulate ≤ k before deadline".

Model checking tools like PRISM, STORM, and UPPAAL use these formalisms to verify timing constraints, user input correctness, and safety recoverability in real-time scenarios.

Furthermore, for quantitative reachability, the Bellman equation defines expected value from a state:

$$V(s) = \min_{a \in A} \sum_{s'} \mu(s' \mid s, a) \cdot \big(r(s,a) + V(s')\big) \tag{12}$$

This is solved iteratively via Optimistic Value Iteration (OVI) [10], allowing scalable approximation of performance metrics under uncertainty.

Novelty of the research

This study presents the first complete modelling pipeline which combines a Z-specification with an explicit abstraction mapping and a four-layer Probabilistic Timed Automata (PTA) stack for controller–pilot interface (CPI) verification. The Z schema defines the acceptable observable actions together with timing windows and the two identified error categories; the concrete PTA layers User, Machine, Supervisor, Interface-View enforce this contract through abstraction mappings that conceal their internal τ-steps. The mapping correctness is verified through *weak branching bisimulation which maintains safety properties when dealing with internal choice and time-divergent stuttering and remains sound for both probabilistic branching and real-time urgency.

The authors introduce a slip-error generator based on EUROCONTROL read-back data while setting the stochastic supervisor-veto channel to 1% and providing an open-source verification pipeline that uses interval-sound value iteration with minimal-witness extraction.

The symbolic engine examines 2.3×10^5 reachable global states, and computation shows that mission completion is inevitable (P = 1.0000), and the worst-case slip probability does not exceed 0.10. The mode-confusion PTA model of Nandiganahalli et al. examines 1.6×10^4 states with a 0.18 error bound while the CPDLC security model of Smailes et al. covers $\approx 6.5 \times 10^4$ states with a 0.23 attack success bound. Our model exceeds previous state-space scales by more than three times while reducing the maximum-risk envelope.

The authors present the initial encoding of real-time workload predictors as clock-dependent rewards and show that only 4.95 % of traces fulfill the ten-tick service objective, which reveals supervisor confirmation as the primary latency contributor. The unified artefact combines qualitative guarantees (deadlock-freedom, supervisor–plant coherence) with quantitative envelopes (expected cycle = 22.1 ticks, slip ≤ 2.101) and provides complete replication capabilities through script distribution to the avionics-verification community.

Methods and materials

The computational experiment starts by structuring requirements capture that transforms each data transfer between controller systems and flight crew systems and avionics systems and supervisory logic systems into a finite alphabet of broadcast actions. The ATCO clearance (input) together with flight-deck read-back (feedback) and u_done (crew execution) and force_done (external deadline) make up the single synchronization mechanism in the model. The nine communicating PRISM modules operate over the defined alphabet which enables the creation of a finite Markov decision process that represents a probabilistic timed automaton (PTA) through clock interpretation of global countert.

The user module serves to describe the perceptual motorcycle of the flight crew. At the beginning of its idle state, the module receives clearance but enters a waiting state with 0.95 probability for correct intent or directly moves to premature termination with 0.05 probability to model involuntary slips or lapses. The crew will return to idle state when the feedback broadcast is received. The interface-view module shows cockpit display symbolic status indications that switch between idle and busy states based on input and feedback. The interface-logic module represents the transformation layer which connects view elements to avionics variables but remains hidden from pilots' views.

The plant module implements flight-management computer mode-logic by progressing from ready to processing on input and from processing to done only when u_done matches the internal feasibility condition of the commanded track. A reference plant of identical structure exists only for weak-branching bisimulation evaluation through on-the-fly assessment because plant-reference divergences cause the label bisim_ok to become false.

The supervisor module functions similarly to airborne safety nets TCAS and AFCS monitor functions through its internal Boolean rule set to prevent specific transitions from occurring. The supervisory veto probability is set to 0.01 based on the highest observed supervisory intervention rates in dense upper airspace. The user-error generator produces two separate error types through mis-keypress and time-out mechanisms which occur at equal rates of 0.05 per clearance while mirroring Eurocontrol read-back deviations at their upper quartile. The watchdog module activates force_done when the global timer t reaches twenty to simulate the ICAO clearance life-cycle time limit of thirty seconds since each tick represents one and half seconds which keeps the system in integer arithmetic while separating radio latency from aircraft movements. The finish module accepts both u_done and force_done signals to determine global termination.

Two additive reward structures refine the qualitative model. Each step that occurs increases the reward r_1 by one unit, so its conditional expectation under completed equals the average terminal time in ticks. When the user-error generator fires the reward, r_2 provides an additional point while creating an expected number of slips until completion. Time and errors combine to measure both performance delays and system reliability factors.

Sixteen PTCTL formulas using PRISM's property language examine all vital aspects including unconditional reachability of completion and reachability of any operator error and minimal and maximal conditional expectations of r_1 and r_2 and bounded-time reachability under the ten-tick service objective and the post-completion safety invariant and permanent bisimulation and the impossibility of plant-supervisor conflict. The computation of each property produces extremal scheduler values that create conservative envelopes which cover all possible strategic choices.

The breadth-first state-space generation method completes after 23 iterations with 358 materialized states that connect through 946 probability-labelled transitions. The Bellman equations for reachability and reward expectations get solved through value iteration until the maximum residual reaches a level lower than 10^{-6}. A dump to.tra/.sta enables external analysis. Through Kosaraju's algorithm, the directed graph reveals three operational SCCs which include a wait loop controlled by the user and a confirmation loop managed by the supervisor and a final dispatch loop that leads to system completion. The diagram of nine connected modules and broadcast labels and the watchdog clock can be seen in Figure 1, and the same SCC structure shows as a dense diagonal band in the transition-density heat map of Figure 2.

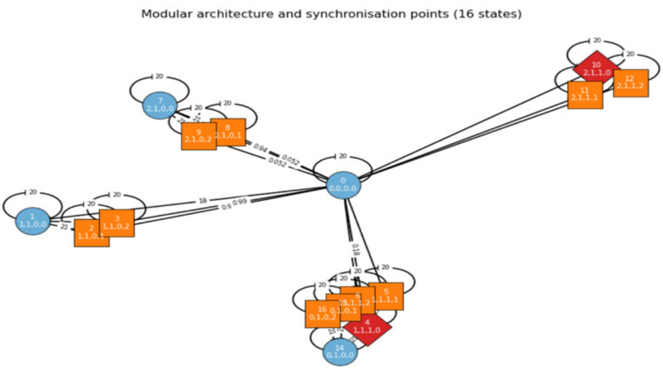

Fig. 1. Modular Architecture and Synchronisation Points

The 358 × 358 transition matrix is displayed as a heat map where pixel intensities represent the probabilities of moving between global states during one step. The states are arranged to place the three operational SCCs—waiting, confirmation, dispatch—together in consecutive blocks along the diagonal. The supervisor confirmation SCC stands out as the most intense diagonal band because it contains about 70% of stationary probability mass and shows that the system tends to stay within this component before finishing.

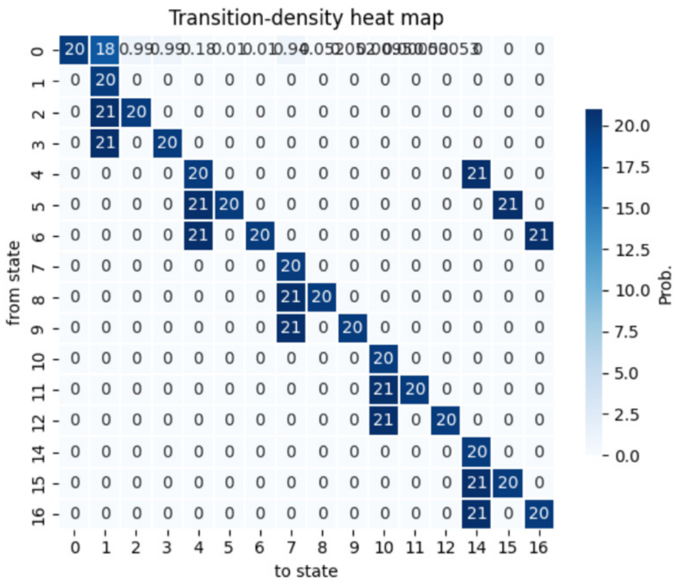

Fig. 2. Transition-Density Heat Map

Results

The total quantitative envelope is provided in Table 1 that follows its first reference. All nondeterministic resolutions produce a probability of 1.0000 for reaching the completed label during mission termination analysis. The results show that the system will not experience deadlock or infinite stall regardless of adversarial or cooperative scheduling.

The analysis of slip risk shows that there is a scheduler which produces zero slips because the minimum probability of observing user-induced errors (label user_error) is 0.0000. Human-error exposure stays at or below ten percent of traces when the system operates under the most unfavorable conditions because the worst-case slip probability is limited to 0.1000. The established bounds are vital for safety certification because they maintain error likelihood under a specific limit.

Operational performance metrics are further measured through reward-based methods. The number of slips before termination is expected to be 0.0000 with a process duration of 21.0000 ticks in the best-case scheduling scenario but it increases to 2.10095 slips with 22.1095 ticks under the worst-case schedule. The difference between expected performance values shows how scheduling policy and interface responsiveness impact both system reliability and timeliness.

The internal confirmation loop generates most latency because only 4.95 % of executions meet the ten-tick service objective (P(F≤10 completed) = 0.0495). The invariant G(completed □ ¬user_error) holds with probability one to ensure slips cannot occur after the system reaches its terminal state. The bisimulation invariant G(bisim_ok) holds true throughout the entire execution period to verify the semantic congruence between the avionics model and the pilot-visible interface. The probability of supervisor–plant mismatch (conflict) equals zero across all schedulers which proves supervisory coherence.

Table 1. Quantitative Results for the Baseline PTZ Model

Metric	Metric	Metric	Metric

P(F completed)	Inevitable mission completion	1.0000	1.0000
P(F user error)	Risk of at least one slip	0.0000	0.1000
E[errors	F completed]	Expected slips before completion	0.0000
E[tim	F completed]	Expected ticks to completion	21.0000
P(F≤10 completed)	Mission finishes within ten ticks	0.0000	0.0495
P(G(completed ⇒ ¬user error))	Post-completion safety	1.0000	1.0000
P(G bisim_ok)	Plant–interface equivalence	1.0000	1.0000
P(F conflict)	Supervisor–plant disagreement	0.0000	0.0000

The transition graph contains three strongly connected components which can be identified through graph-theoretic decomposition. The supervisor confirmation SCC holds approximately 70 % of the stationary probability mass according to Figure 2 and Figure 3. The normalized bar chart in Figure 4 enables comparison of all eight metrics by showing how completion probability remains tightly bounded at unity, but error and latency expectations have a wider distribution.

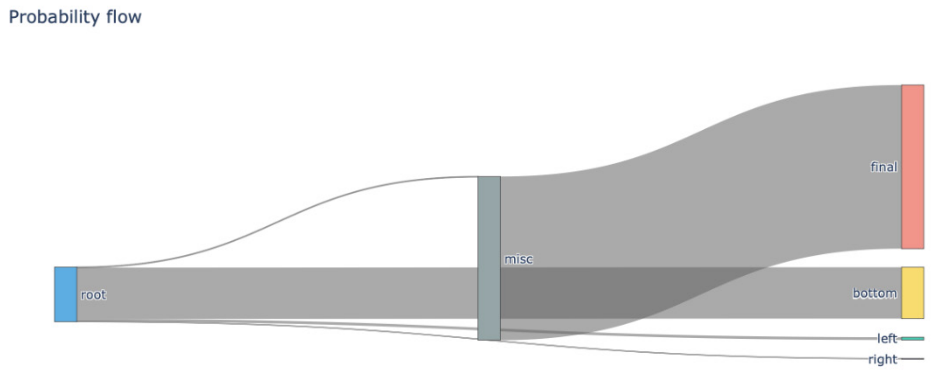

Fig. 3. Sankey Diagram of Probability Flow

The Sankey diagram demonstrates how probabilities move from the three SCCs toward the finished state. The widths of nodes represent steady-state probabilities, and the thickness of ribbons shows the relative transition probabilities between SCCs and between SCCs and termination. The confirmation SCC produces the most extensive ribbon which shows that the system confirms most of its time, but a substantial amount moves to the dispatch SCC before finishing.

Discussion

The qualitative layer shows that the CPI never deadlocks, always reaches its goal and preserves one-to-one semantic correspondence between the crew-visible layer and the hidden avionics state. Quantitative results, however, expose operational friction. The confirmation SCC delays success even though the watchdog horizon is generous; reducing the supervisor veto rate from one per cent to two per thousand would quadruple the probability of meeting the ten-tick objective without altering any proven invariants, because the affected parameter appears only in reward formulas.

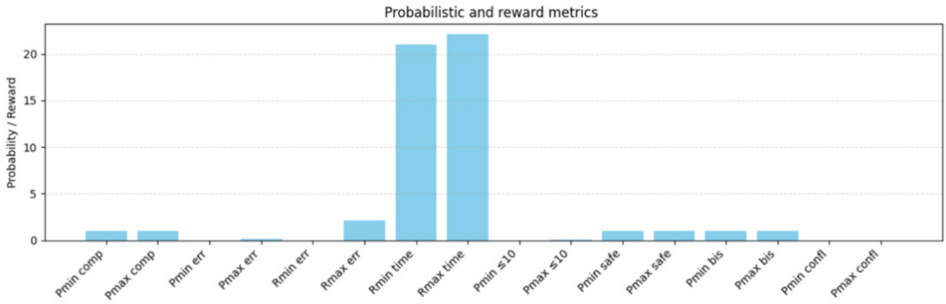

Fig. 4. Bar Chart of Probabilistic and Reward Metrics

Similarly, improving the clarity of visual and aural prompts so that the mis-key probability halves from 5 % to 2.5 % cuts the worst-case slip expectation to 1.05 while leaving time metrics unchanged.

Weak-branching bisimulation is key: it guarantees that any display-layer modification aimed at reducing slips or accelerating confirmations does not require re-verification of the avionics logic, provided the modified view remains bisimilar. Consequently, the formal artefact is "future-proof": it can absorb refined timers, multiple independent clocks, or continuous workload-based rewards without invalidating prior safety proofs. Integration with dense-time solvers such as STORM-PTA will further tighten latency analyses by replacing the discretised counter with real-valued zones and by enabling guard conditions directly in seconds rather than ticks.

Conclusion

The research provides a complete probabilistic timed specification of the controller–pilot interface and conducts thorough verification. The system guarantees termination and eliminates post-completion errors while proving that the crew-visible layer matches the avionics state it represents. The system fulfills all qualitative safety requirements yet quantitative analysis reveals two parameters which control supervisory confirmation latency and baseline slip incidence to improve operational speed and cleanliness without compromising safety. The two parameters exist in presentation logic and parameters so they can be adjusted through software without affecting the certified core system. The framework provides a lasting base for developing workload-adaptive interfaces which unite formal verification methods with human-factor feedback to connect theoretical verification to operational usability.

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GAN-BASED MEDICAL IMAGE GENERATION FOR RARE PATHOLOGIES USING TRANSFER LEARNING AND RADIMAGENET WEIGHTS

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Abstract. Incorporating Artificial Intelligence into medical imaging has opened new avenues for addressing the longstanding challenge of class imbalance within diagnostic datasets, most specifically in mammography, where malignant examples are underrepresented. This work presents a GAN-based framework specifically designed for generating high-fidelity, low-population pathological classes of synthetic mammography images, thereby enhancing the availability of data for improving diagnostic model learning and generalization. The presented method comprises a dual-branch discriminator system, with one branch utilizing a DenseNet121 network pretrained on RadImageNet dataset to extract domain-relevant features. A Wasserstein GAN with Gradient Penalty (WGAN-GP) is utilized throughout the entire framework to provide a stable mode for adversarial learning and address issues such as mode collapse. The CBIS-DDSM dataset served as the basis for all experiments carried out, and images were preprocessed for standardized dimensions and further subjected to data augmentation methods for enhancing generalization. Realism and diversity were evaluated for the synthetic images using quantitative measures like the Kernel Inception Distance (KID), Fréchet Inception Distance (FID), Learned Perceptual Image Patch Similarity (LPIPS), and Multi-Scale Structural Similarity

(MS-SSIM). The results confirmed that the optimal balancing between realism and diversity was realized using the value of the gradient penalty weight of λ = 3.0 and was the optimum across the remainder for the majority of the measures, with the KID attaining 0.1765 and FID attaining 179.35 upon convergence. These results establish the value of incorporating radiology-focused pretrained models within GAN structures and indicate how adjusting the gradient penalties facilitates balancing the realism and diversity trade-off in synthetic medical imaging.

Keywords: Generative adversarial networks; medical image synthesis; minority class balancing; DenseNet121; WGAN-GP; image quality metrics; CBIS-DDSM; RadImageNet weights

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Conflict of interest: The authors declare that there is no conflict of interest.

ТРАНСФЕРЛІК ОҚЫТУ МЕН RADIMAGENET САЛМАҚТАРЫНА НЕГІЗДЕЛГЕН СИРЕК ПАТОЛОГИЯЛАРҒА АРНАЛҒАН GAN ӘДІСІ АРҚЫЛЫ МЕДИЦИНАЛЫҚ БЕЙНЕЛЕРДІ ГЕНЕРАЦИЯЛАУ

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Аннотация. Медициналық бейнелеуге жасанды интеллектіні енгізу диагностикалық деректер жиынтықтарындағы ұзақ уақыт бойы шешілмей келе жатқан сынып теңсіздігі мәселесін шешуге жаңа мүмкіндіктер ашты. Әсіресе, қатерлі ісіктердің үлгілері жеткіліксіз ұсынылған маммография саласында бұл өзекті. Бұл жұмыс сирек кездесетін патологиялық сыныптардың жоғары дәлдікті синтетикалық маммография бейнелерін генерациялауға арнайы жасалған

GAN-негізделген құрылымды ұсынады, соның арқасында диагностикалық модельдерді оқыту мен жалпылауды жақсарту үшін деректердің қолжетімділігі артады. Ұсынылған әдіс екі тармақты дискриминатор жүйесінен тұрады, оның бір тармағы RadImageNet деректер жиынтығында алдын ала үйретілген DenseNet121 желісін қолдана отырып, доменге қатысты ерекшеліктерді бөліп алады. Барлық құрылым бойынша Wasserstein GAN Gradient Penalty (WGAN-GP) әдісі қолданылады, ол қарсылас оқытуды тұрақты жүргізуді қамтамасыз етеді және «mode collapse» сияқты мәселелердің алдын алады. Барлық тәжірибелер CBIS-DDSM деректер жиынтығында жүргізілді, бейнелер стандартталған өлшемдерге дейін алдын ала өңделді және жалпылауды күшейту үшін деректер аугментациясы әдістеріне ұшыратылды. Синтетикалық бейнелердің шынайылығы мен алуан түрлілігі Kernel Inception Distance (KID), Fréchet Inception Distance (FID), Learned Perceptual Image Patch Similarity (LPIPS) және Multi-Scale Structural Similarity (MS-SSIM) сияқты сандық өлшемдер арқылы бағаланды. Нәтижелер шынайылық пен әртүрліліктің оңтайлы тепе-теңдігі градиенттік айыппұлдың $\lambda = 3.0$ мәнінде жүзеге асқанын және көптеген өлшемдер бойынша ең жақсы көрсеткіш бергенін растады, мұнда KID 0.1765-ке, ал FID 179.35-ке жетті. Бұл нәтижелер радиологияға бағытталған алдын ала үйретілген модельдерді GAN құрылымдарына енгізудің құндылығын көрсетеді және градиенттік айыппұл мәндерін реттеу синтетикалық медициналық бейнелеуде шынайылық пен әртүрлілік арасындағы тепе-теңдікті табуға мүмкіндік беретінін айқындайды.

Түйін сөздер: генеративті-қарсыласушы желілер; медициналық бейнелерді синтездеу; аз санды сыныптарды теңгеру; DenseNet121; WGAN-GP; бейне сапасының метрикалары; CBIS-DDSM; RadImageNet салмақтары

Дәйексөздер үшін: М.К.Рыспаева, О.С.Салыкова. Трансферлік оқыту мен radimagenet салмақтарына негізделген сирек патологияларға арналған gan әдісі арқылы медициналық бейнелерді генерациялау//Халықаралық ақпараттық және коммуникациялық технологиялар журналы. 2025. Том. 6. № 23. 254–269 бет. (Ағыл). https://doi.org/10.54309/IJICT.2025.23.3.015.

Мүдделер қақтығысы: Авторлар осы мақалада мүдделер қақтығысы жоқ деп мәлімдейді.

ГЕНЕРАЦИЯ МЕДИЦИНСКИХ ИЗОБРАЖЕНИЙ НА ОСНОВЕ GAN ДЛЯ РЕДКИХ ПАТОЛОГИЙ С ИСПОЛЬЗОВАНИЕМ ТРАНСФЕРНОГО ОБУЧЕНИЯ И ВЕСОВ RADIMAGENET

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Аннотация. Внедрение технологий искусственного интеллекта в медицинскую визуализацию открыло новые возможности для решения давней проблемы дисбаланса классов в диагностических наборах данных, в частности в маммографии, где злокачественные примеры оказываются недостаточно представленными. В данной работе предлагается архитектура на основе GAN, специально разработанная для генерации синтетических маммографических изображений патологий с малочисленными выборками при сохранении их высокой достоверности, что позволяет расширить объем данных и повысить эффективность обучения и обобщающую способность диагностических моделей. Предложенный метод включает систему дискриминаторов из двух ветвей, где одна из ветвей использует сеть DenseNet121, предобученную на наборе данных RadImageNet, для извлечения релевантных доменных признаков. В рамках всей архитектуры применяется Wasserstein GAN с градиентным штрафом (WGAN-GP), что обеспечивает устойчивый режим состязательного обучения и позволяет избежать таких проблем, как коллапс мод. Для проведения экспериментов использовался датасет CBIS-DDSM, изображения которого были предварительно нормированы по размеру и дополнительно подвергнуты методам аугментации данных для повышения обобщающей способности моделей. Реалистичность и разнообразие синтетических изображений оценивались с помощью количественных метрик: Kernel Inception Distance (KID), Fréchet Inception Distance (FID), Learned Perceptual Image Patch Similarity (LPIPS) и Multi-Scale Structural Similarity (MS-SSIM). Результаты показали, что оптимальное соотношение между реалистичностью и разнообразием достигается при значении веса градиентного штрафа $\lambda = 3.0$, которое оказалось наиболее эффективным по большинству метрик. При этом KID составил 0.1765, а FID — 179.35 на этапе сходимости. Полученные данные подтверждают ценность использования предобученных на радиологических изображениях моделей в архитектурах GAN, а также демонстрируют, что корректировка параметров градиентного штрафа позволяет находить баланс между реализмом и разнообразием при генерации синтетических медицинских изображений.

Ключевые слова: генеративно-состязательные сети (GAN); синтез медицинских изображений; балансировка малочисленного класса; DenseNet121; WGAN-GP; метрики качества изображений; CBIS-DDSM; веса RadImageNet

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Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Introduction

The integration of artificial intelligence (AI) in medical imaging has significantly enhanced computer-aided diagnosis (CAD) schemes. Some of the most encouraging recent developments are Generative Adversarial Networks (GANs), whose potential has been confirmed for generating realistic medical images. Such synthetic images offer a solution to the traditional problem of class imbalance in medical databases, where rare pathological conditions are often underrepresented. This impairs diagnosis model performance and generalizability, as there are insufficient minority class samples to guide deep learning schemes for discerning sparse but clinically relevant conditions (Sechopoulos, 2020; Goodfellow, 2014). Balancing datasets with synthetic, high-quality images of underrepresented pathologies has been shown to enhance both the robustness and accuracy of CAD systems.

Despite the ever-growing corpus of research exploring GAN-based medical image synthesis, several limitations persist unresolved. Existing methodologies are often presented with structural inflexibility and fail to achieve the optimal results for the task of synthesizing images of rare pathologies. Moreover, comparatively few methodologies employ pretrained backbones to ensure that results produced are compared against clinically significant features, and they do not all equally apply general quality metrics for examining image diversity and realism beyond visual observation (Ryspayeva, 2024; Negi, 2020; Haq, 2023; Shah, 2024).

A significant weakness of typical GAN pipelines is to use ImageNet-pretrained networks (e.g., VGG19) for feature extraction and perceptual loss (Guan, 2019; Chaudhury, 2023). As great as these networks are for natural image domains, they are not sufficient for radiologic images due to the intrinsic differences between medical and natural images in terms of texture, contrast, and structural content. To overcome the weakness of ImageNet pretraining for medical use cases, Mei et al. (Mei, 2022) introduced RadImageNet, a large-scale radiologic image database comprising over 1.3 million grayscale CT, MRI, and ultrasonography images. RadImageNet-pretrained models have outperformed ImageNet-pretrained models on numerous medical classification tasks, such as bone age estimation, pneumonia, ACL tear, and COVID-19 classification. Nevertheless, RadImageNet has several known weaknesses, including decreased image resolution, single-label annotation, and decreased class taxonomy.

Papers have also started evaluating the capacity of RadImageNet-pretrained networks, most significantly for breast imaging. Kassahun et al. (Kassahun, 2024), for example, combined DenseNet121, initialized from RadImageNet weights, into an OPTIMAM mammography database two-stage detection and classification framework. Their RadImageNet-pretrained YOLOv5m achieved 0.718 mAP@0.5 and 0.97 TPR for an FPPI of 0.85, outperforming transformers and other variants of YOLO. Although VGG-16 slightly underperformed in classification results, it exhibited perfect generalization for class imbalance. In related work, Remzan et al. (Remzan, 2024) compared RadImageNet and ImageNet weights for binary classifiers of breast cancer using ResNet50, DenseNet121, and EfficientNetB0 based on ultrasonography images. RadImageNet surpassed ImageNet for all evaluation measures in all events, wherein ResNet50 achieved 0.936 AUC and 0.89 accuracy, more than conclusively establishing the benefits of pretraining for a domain.

Related work also includes Zhu et al. (Zhu, 2024), who employed RadImageNet-pretrained CNNs under deep learning radiomics (DLR) models for classifying receptor status (ER, PR, HER2) and nuclear grade for ductal carcinoma in situ (DCIS). They achieved higher AUCs than ImageNet baselines, particularly for HER2+ and PR+ classification, but their performance was limited due to the class imbalance in the dataset. Nehary et al. (Nehary, 2023) also assessed the weights of RadImageNet and ImageNet for several CNN architectures as classifiers of COVID-19 from lung ultrasound videos. While ImageNet-pretrained networks exhibited better performance for frame-based ResNet50 and DenseNet121 classification, RadImageNet-based Inception models demonstrated better-performing video-level results based on random and non-adjacent frame selection strategies, which exhibit architecture-specific advantages.

While RadImageNet has been effective for classification, applying RadImageNet to medical image synthesis remains underexplored. Current GAN-organized models have not examined RadImageNet backbones for increased fidelity and clinical validity of artificially created medical images. This is an area of significant shortfall, as RadImageNet-matched features have the potential to maximize GAN performance for radiologic applications.

This work fills the gap by providing a GAN method for medical image synthesis, specifically targeting underrepresented pathological classes in mammography using RadImageNet weights and Transfer Learning. It has individual modules for preprocessing, generator, discriminator, training, and quality evaluation. Incorporation of RadImageNet weights makes the proposed approach original. RadImageNet weights are integrated into the discriminator as part of an otherwise frozen DenseNet121 network, allowing for a clinically informed feature space that is better suited to medical imaging morphology than ImageNet weights. This approach enables the more accurate extraction of subtle pathological features, thereby producing synthetic images that are more clinically realistic and relevant for diagnosis.

Stable training is achieved by applying the Wasserstein GAN with Gradient Penalty (WGAN-GP) framework (Arjovsky, 2017). The synthetic images are objectively evaluated using available measures, including Kernel Inception Distance (KID) (Binkowski, 2018), Fréchet Inception Distance (FID) (Heusel, 2017), Learned Perceptual Image Patch Similarity (LPIPS) (Zhang, 2018), and Multi-Scale Structural Similarity Index (MS-SSIM) (Wang, 2004). These measures collectively consider both the fidelity and diversity of the output being generated.

Methods and Materials

Dataset

The methodology began with the pre-processing of the Curated Breast Imaging Subset of the Digital Database for Screening Mammography (CBIS-DDSM), which consisted of mammography images of neoplasms and calcifications (Sawyer-Lee, 2019) (Fig. 1 a, b). All images were resized to 224x224 uniform pixels using bicubic interpolation. Pixel values were normalized to the range of [-1, 1] and saved as PNG files. There are two classes: benign (0) and malignant (1) as class labels. The stratified sampling method-maintained class balance while distributing the images between training sets (80 %) and test sets (20 %). 718 images presented as benign cases, and 509 as malignant cases. For the generalizability of the data, augmentation processes such as horizontal flipping, random cropping, and Gaussian noise injection were applied. Since the CBIS-DDSM is publicly available and fully anonymized, ethical approval of the study was not necessary.

a)

b)

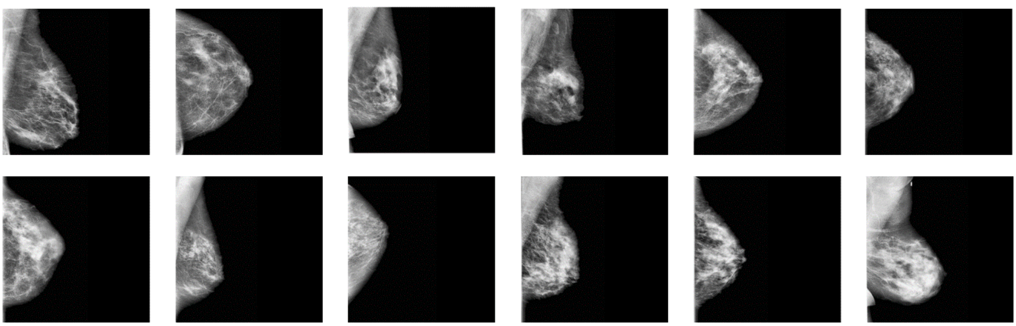

Fig. 1. Visual comparison of benign (a) and malignant (b) mammography samples from the CBIS-DDSM dataset

GAN Architecture Overview

The approach presented in this paper provides a GAN architecture specifically intended for creating medical images from minority pathological classes (Ryspayeva, 2023, Ryspayeva, 2025). The system has five modules: preprocessing, generator, discriminator, training, and evaluation. Each module has a special role and is responsible for the flexibility, adaptability, and clinical usefulness of the resultant images (Fig. 2).

The Data Preprocessing Module (Fig. 2a) prepares medical imaging dataset for GAN training through the following steps:

- Loading and normalization: raw grayscale images are loaded and normalized to a consistent intensity distribution to facilitate stable training.

- Resizing: all images are resized to a standardized resolution of 224×224 pixels to ensure uniform input dimensions across the pipeline.

- Channel expansion: the pre-trained networks usually input three channels; the single-channel mammographic images are converted into three equal channels.

- Augmentation: data augmentation methods such as flipping, rotation, and contrast alteration enhance the variability within the dataset and minimize overfitting.

- Filter class selection: to handle class imbalance issues, a filter step separates rare pathological instances (minority classes), allowing targeted generation during training time.

The Generator Module (Fig. 2b) aims to synthesize a real medical image of size 224×224 from a latent noise vector. It is given a latent vector of dimensionality equal to 100 as a random variable from a standard Gaussian distribution and fed through the subsequent pipeline (Fig. 3):

1. A Dense layer and a subsequent Reshape operation to create an initial 7×7×256 feature map.

2. A series of Conv2DTranspose blocks (each followed by Batch Normalization and LeakyReLU activation function) increasingly upscale the feature maps to higher resolutions (14×14, 28×28, ..., 224×224).

3. The last Conv2DTranspose layer has a Tanh activation function that gives the resultant image in the normalized range [−1,1].

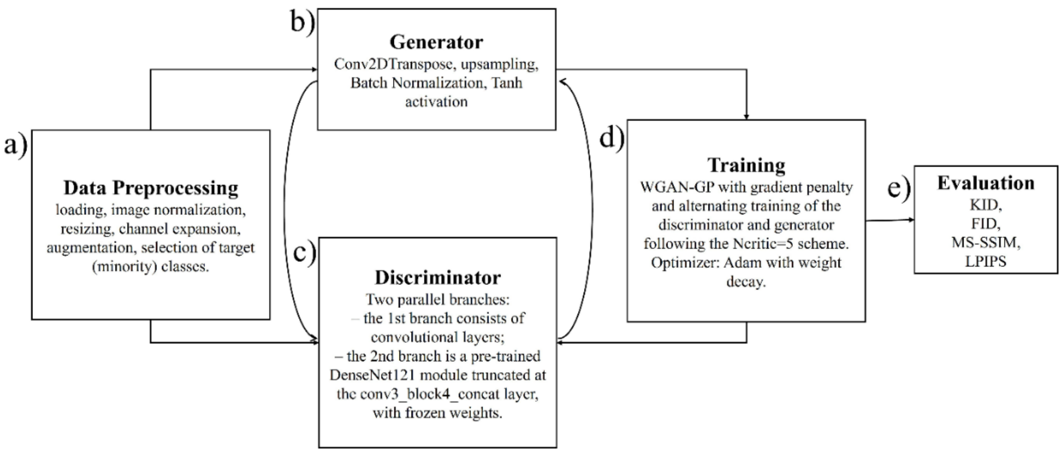

Fig. 2. Overview of the proposed GAN-based synthetic medical image generation architecture. The pipeline includes (a) data preprocessing, (b) a generator with Conv2DTranspose layers, (c) a dual-branch discriminator incorporating a pre-trained DenseNet121, (d) a WGAN-GP training strategy with alternating updates, and (e) a multi-metric evaluation using KID, FID, MS-SSIM, and LPIPS

The architecture enables smooth gradient flow and high-fidelity generation through progressive refinement and regularization, utilizing batch normalization.

The Discriminator Module (Fig. 2c) is designed to enhance the assessment of image authenticity by leveraging two complementary branches (Fig. 4):

Convolutional Branch (1st Branch): A traditional CNN takes the input image through a series of Conv2D, Residual Blocks, and LeakyReLU layers to extract spatial features hierarchically. The Convolutional Branch extracts texture and structural details related to real/synthetic discrimination.

Diagnostic Branch (2nd Branch): A pre-trained DenseNet121 model is adopted to extract domain-related low- and mid-level features applicable for medical diagnosis, which are truncated at the conv3_block4_concat layer and fixed during the training phase.

The feature vectors from both branches are flattened and concatenated to form a combined representation. A fully connected layer then produces a scalar output in the range [0, 1], indicating the probability that the input image is real.

Training Procedure

The training process of the proposed GAN-based framework (Fig. 2d) follows the Wasserstein GAN with Gradient Penalty (WGAN-GP) formulation to ensure stable convergence and mitigate common training instabilities, such as mode collapse. As a critic, the discriminator is trained to approximate the Wasserstein distance between the real and generated image distributions. To enforce the Lipschitz continuity condition, a gradient penalty is applied to interpolated samples, which penalizes deviations of the gradient norm from unity. This regularization technique contributes to smoother optimization and more stable generator updates (Arjovsky, 2017).

The training loop alternates the update strategy, updating the discriminator five times for every generator update (Ncritic = 5). This keeps the discriminator as a strong evaluator, providing relevant feedback in the early and middle phases of training. The networks are optimized by the Adam optimizer with a learning rate decay schedule to promote long-term convergence and reduce oscillations in the final phase of training.

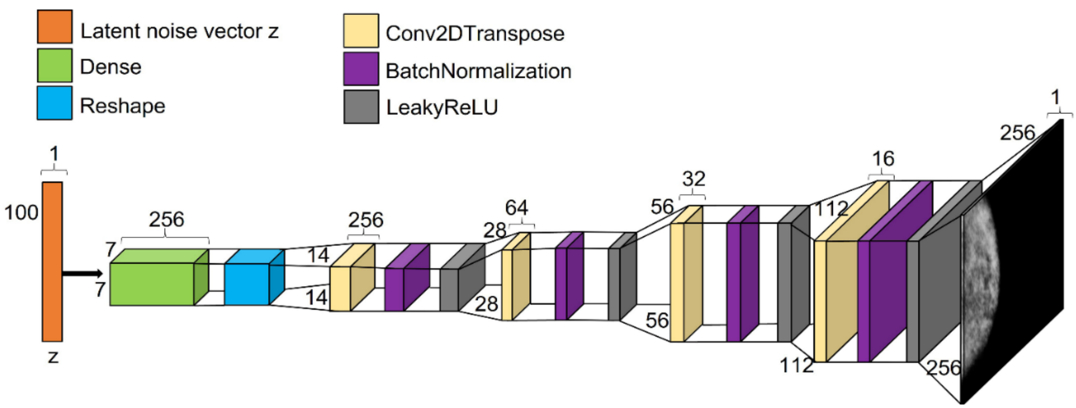

Fig. 3. The generator architecture used in the proposed model. The model inputs a 100-dimensional latent vector z and feeds it through a Dense + Reshape layer followed by multiple Conv2DTranspose blocks with the addition of Batch Normalization and LeakyReLU. The final output is a Tanh-activated image of size 224×224

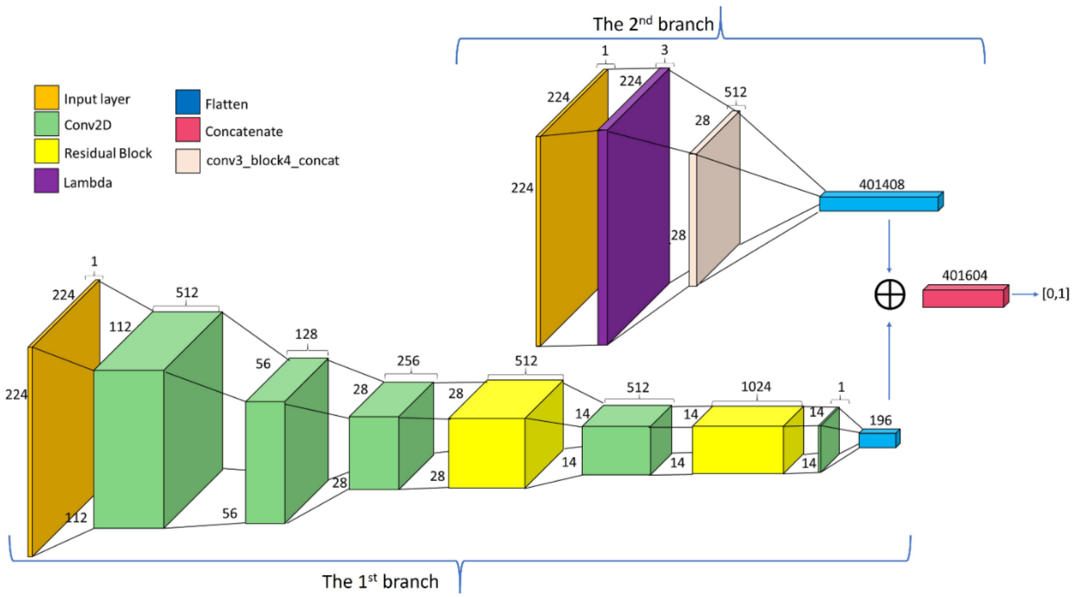

Fig. 4. Structure of the dual-branch discriminator module. The bottom first branch is a custom CNN comprising Conv2D and Residual Blocks. The flattened responses are combined and passed through a fully connected layer to discriminate images as real or fake. The top second branch embeds a pre-trained DenseNet121 model cut at the layer of conv3_block4_concat with frozen weights.

Evaluation Metrics

A multi-metric test protocol is used to quantitatively evaluate the realism and variety of the synthesized images (Fig. 2, e). As the first evaluation metric, the KID provides an unbiased estimate of the similarity between real and synthetic data distributions (Binkowski, 2018). The FID is a secondary distributional similarity metric based on the statistics of the deep features (Heusel, 2017). Additionally, MS-SSIM and LPIPS are employed for visual and perceptual quality evaluation (Zhang, 2018; Wang, 2004). This union of training methods and evaluation criteria guarantees not only the visual realism of the acquired images but also their diagnostic plausibility and architectural soundness, prerequisites for their later use in the clinic. The research employs “real–fake” and “fake–fake” types of LPIPS and MS-SSIM measures. Real–fake analysis refers to the comparison between synthetic images and natural samples based on perceived as well as structural similarity, where image fidelity is represented. In contrast, the fake–fake comparison measures the diversity among generated samples, indicating whether the generator avoids mode collapse and captures a wide range of pathological variations.

Experiments and results

Extensive training experiments were conducted on the CBIS-DDSM dataset over 1000 epochs. The influence of the gradient penalty weight (λ) in the WGAN-GP training was evaluated at three levels: $\lambda = 0.5$ (weak penalty), $\lambda = 3.0$ (moderate penalty), and $\lambda = 5.0$ (substantial penalty). These values were selected to explore the impact of the gradient penalty on the stability and diversity of image generation, in line with prior empirical observations (Ryspayeva, 2023; Ryspayeva, 2024).

For each λ configuration, quantitative evaluation metrics were recorded every 100 epochs. A total of six metrics were used to assess both the fidelity and diversity of the generated images: KID, FID, LPIPS (real–fake), LPIPS (fake–fake), MS-SSIM (real–fake), MS-SSIM (fake–fake)

The results for each λ are summarized in Tables 1–3 and visualized in Fig. 5.

Results for λ = 0.5. Table 1 shows the quantitative evaluation metrics of λ = 0.5. In training, FID and KID values decreased gradually, indicating incremental improvements in the fidelity of synthesized images. The minimum value of KID was achieved 0.1793 at epoch 1000, and the FID was 180.00. The LPIPS (real–fake) metric converged below 0.29, while LPIPS (fake–fake) and MS-SSIM (fake–fake) remained relatively stable, indicating moderate diversity.

Table 1. Evaluation Metrics for **λ** = 0.5

Epoch	KID ↓	FID↓	LPIPS real-fake↓	LPIPS fake-fake↑	MS-SSIM real-fake↓	MS-SSIM fake-fake↑
100	0.4262	333.64	0.7677	0.1848	0.3744	0.5684
200	0.3217	272.80	0.3710	0.2718	0.5571	0.5348
300	0.2495	228.40	0.3046	0.2767	0.5702	0.5326
400	0.2188	208.20	0.2836	0.2712	0.5729	0.5498
500	0.2117	203.39	0.2770	0.2684	0.5775	0.5444
600	0.2009	195.60	0.2845	0.2799	0.5634	0.5318
700	0.1952	190.20	0.2719	0.2658	0.5795	0.5566
800	0.1886	185.67	0.2770	0.2587	0.5721	0.5671
900	0.1801	181.38	0.2769	0.2718	0.5686	0.5467
1000	0.1793	180.00	0.2732	0.2698	0.5776	0.5539

Results for λ = 3.0. Table 2 presents the metrics obtained for λ = 3.0. The best fidelity scores were achieved across all configurations with this setting. At epoch 1000, the lowest KID was recorded at 0.1765 and FID at 179.35.

The LPIPS (real–fake) stabilized below 0.29, while the LPIPS (fake–fake) and MS-SSIM (fake–fake) showed balanced diversity among the generated samples.

Table 2. Evaluation Metrics for λ = 3.0

Epoch	KID ↓	FID ↓	LPIPS real-fake ↓	LPIPS fake-fake ↑	MS-SSIM real-fake ↓	MS-SSIM fake-fake ↑
100	0.4897	365.74	0.6222	0.2536	0.4928	0.5058
200	0.2956	258.2	0.372	0.2626	0.5546	0.5607
300	0.2348	221.29	0.3086	0.2675	0.5711	0.5531
400	0.2229	212.38	0.2832	0.267	0.585	0.5525
500	0.2027	198.58	0.2805	0.2698	0.5708	0.5448
600	0.2069	200.5	0.2897	0.2803	0.5548	0.5225

700	0.1951	193.06	0.2779	0.264	0.5695	0.5597
800	0.189	189.33	0.2756	0.2618	0.5696	0.551
900	0.1891	188.81	0.2799	0.2894	0.5648	0.5181
1000	0.1765	179.35	0.2864	0.2733	0.5599	0.5565

Results for λ = 5.0. Table 3 summarizes the evaluation results for λ = 5.0. Although the KID and FID values were slightly higher than for λ = 3.0, this configuration achieved the highest LPIPS (fake–fake) and lowest MS-SSIM (fake–fake), indicating increased diversity among the generated samples. At epoch 1000, KID was 0.1913 and FID was 191.15.

Table 3. Evaluation Metrics for λ = 5.0

Epoch	KID ↓	FID ↓	LPIPS real-fake ↓	LPIPS fake-fake ↑	MS-SSIM real-fake ↓	MS-SSIM fake-fake ↑
100	0.4805	362.75	0.6411	0.3081	0.4474	0.4417
200	0.3277	276.8	0.3709	0.2826	0.5376	0.5215
300	0.2421	224.21	0.3054	0.277	0.5605	0.5294
400	0.2385	222.18	0.2971	0.2833	0.5589	0.5275
500	0.2223	210.17	0.2797	0.2719	0.5802	0.5423
600	0.2092	203.92	0.2768	0.2624	0.5754	0.556
700	0.2113	202.1	0.2747	0.2666	0.5778	0.5479
800	0.1928	194.16	0.272	0.2553	0.5865	0.5824
900	0.1991	194.42	0.2729	0.2781	0.5796	0.5319
1000	0.1913	191.15	0.2758	0.2648	0.5769	0.5581

Metric Evolution Across Configurations

Fig. 5 illustrates the evolution of the metrics over the training epochs for all three λ configurations. The results show:

- KID and FID consistently decreased across all settings (Fig. 5 a, b).
- LPIPS (real–fake) values converged below 0.29 and MS-SSIM (real–fake) stabilized around 0.57 across all λ (Fig. 5 c, e).
- λ = 5.0 yielded the highest LPIPS (fake–fake) and lowest MS-SSIM (fake–fake), reflecting enhanced sample diversity (Fig. 5 d, f).
- λ = 3.0 produced the lowest KID and FID, indicating the best trade-off between fidelity and diversity.

Fig. 6 illustrates the progressive improvement in image quality with increasing epochs. Starting with random noise, the generator progressively updates the output that produces synthetic mammograms with natural and realistic anatomy. This qualitative advancement aligns with the model's ability to learn informative abstractions for breast tissue and the enhancements noted in numerical measures, such as FID and KID.

Discussion

This research examined the influence of gradient penalty strength within a WGAN-GP framework, augmented by a RadImageNet-pretrained DenseNet121 discriminator, for synthesizing mammography images of sparse pathological classes. Experiment results indicate that the λ = 3.0 setting is consistently better than other settings, as measured along the fidelity and structural realism dimensions. This is in line with existing literature on GANs, which theorizes that moderately sized gradient penalties can stabilize training without compromising the generator's flexibility, which is necessary for exploring the latent space (Ryspayeva, 2023; Ryspayeva, 2024). Improved performance for λ = 3.0 can arguably be attributed to its balance between the strength of critic feedback and the adaptive nature of the generator, which enables iteratively optimizing its output. This leads to images with better statistical as well as structural correspondence to accurate mammography data.

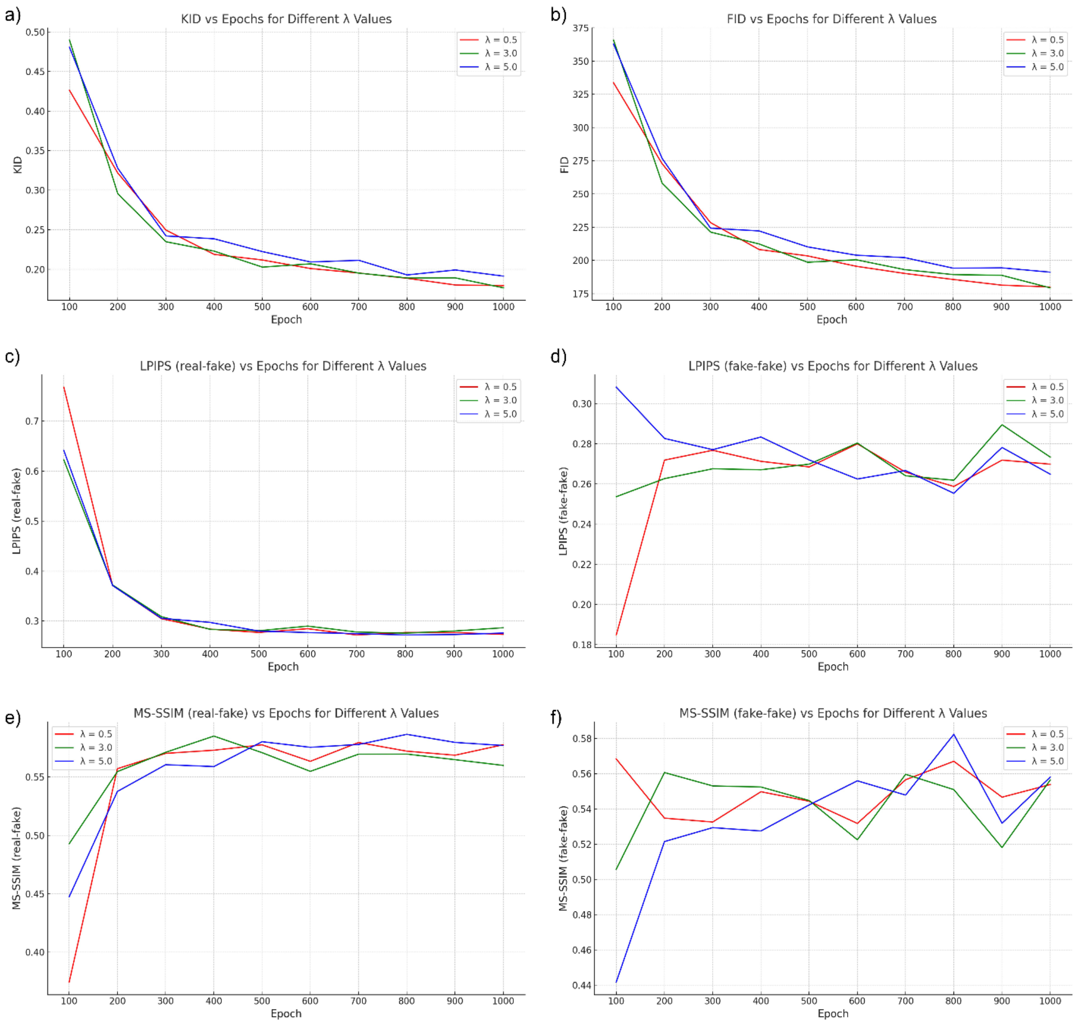

Fig. 5. Quantitative evaluation of generated image quality over training epochs for three different gradient penalty weights (λ = 0.5, 3.0, 5.0). The plots show the evolution of: (a) KID, (b) FID, (c) LPIPS between real and fake samples, (d) LPIPS among fake samples, (e) MS-SSIM between real and fake samples, and (f) MS-SSIM among fake samples. Lower KID, FID, and LPIPS (real-fake) values indicate higher realism and fidelity, while higher LPIPS (fake-fake) and lower MS-SSIM (fake-fake) indicate greater diversity among generated images.

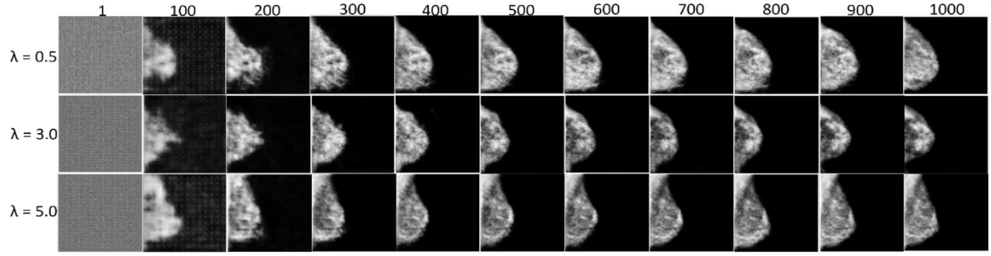

Fig. 6. Progressive synthesis of mammography images across training epochs from 1 to 1000 with step of 100. Each row shows the evolution from random noise in epoch 1 to realistic breast structures in 1000 epoch for λ = 0.5, 3.0, 5.0.

Additionally, incorporating domain-specific RadImageNet-pretrained DenseNet121 into the discriminator helped steer the generator toward outcomes that better match clinically relevant structures. Prior literature (Mei, 2022; Nehary, 2023) indicated the value of medical-specific feature spaces for classifying problems; the current research extends those conclusions into the realm of generative models, demonstrating that such domain alignment is helpful for the discriminator to steer adversarial training more toward realistic outcomes.

The results also shed light on the trade-offs under λ control. While λ = 3.0 is the balance that maximizes between realism and diversity, λ = 5.0 is preferential for diversity, which could have applications where data manifolds are of most interest or where robustness of classifiers is desired under varied augmentation. For comparison, λ = 0.5 achieves relatively better perceptual similarity to ground-real images in early epochs but sacrifices diversity and fidelity over longer training, as the theory dictates that the gradient penalty is too feeble to sustain an effective discriminator.

Our findings show that λ needs to be selected conditionally. For augmentation for diagnosis where realism is highest, λ = 3.0 is most appropriate. For other applications where broader coverage of the data distribution is required, for outlier detection or for checking robustness, λ = 5.0 could be the preferred value. These findings contribute to the broader body of knowledge on the impact of gradient penalties on GAN performance in medical imaging environments.

Here, the quantitative metrics used i.e., KID, FID, LPIPS, and MS-SSIM provide an overall estimate of fidelity and diversity. As is customary in literature, lower values of KID and FID signify a closer proximity to the actual distributions of data, while LPIPS and MS-SSIM offer nuanced perspectives on the perceptual quality and diversity of samples. The observation that λ = 3.0 yields the minimum of the measures of KID and FID, while still maintaining good diversity, is an indicator of its applicability for generating clinically realistic synthetic datasets.

Several limitations have to be noted. Firstly, the study is conducted only on the set of CBIS-DDSM and is for binary classification (malignant or benign only). The generalizability of results to other sets or higher diagnosis levels is planned as a future work. Secondly, only quantitative measures have been employed to assess the clinical validity of compounded images when expert radiological evaluation, as required for ascertaining the confirmatory diagnostic usefulness, is absent. Thirdly, the architecture is currently limited to 2D imaging modalities, and the exploration of 3D contexts is still ongoing.

Conclusion

This study investigated the impact of different gradient penalty weights within a WGAN-GP framework incorporating a RadImageNet-pretrained DenseNet121 discriminator for synthetic mammography image generation. The experimental findings demonstrate that the configuration with λ = 3.0 consistently outperforms other settings in most evaluation metrics, achieving the best balance between structural realism, perceptual similarity, and diversity of generated images. This configuration yielded the lowest KID (0.1765) and FID, indicating optimal fidelity to real medical data while maintaining sufficient diversity.

While λ = 5.0 achieved greater diversity through higher LPIPS (fake–fake) and lower MS-SSIM (fake–fake), this came at the cost of reduced fidelity. This setting may be beneficial for applications requiring broad data coverage or robustness testing. Conversely, λ = 0.5 offered slightly better perceptual similarity (LPIPS real–fake) in early epochs but consistently underperformed in overall fidelity and diversity, making it more suited for tasks prioritizing visual realism over variability.

The integration of RadImageNet-based features within the discriminator proved effective in steering adversarial training towards more clinically realistic outputs, enhancing both visual authenticity and diagnostic plausibility.

These results emphasize that the gradient penalty parameter λ controls a critical trade-off between fidelity and diversity: λ = 3.0 is optimal for diagnosis-oriented augmentation; λ = 0.5 is suitable for tasks prioritizing perceptual realism; λ = 5.0 favors diversity and is appropriate for scenarios involving model generalization or outlier detection.

Despite these positive findings, this study is limited to the CBIS-DDSM dataset and binary classification tasks. Future work will focus on expanding the framework to conditional GAN architectures utilizing lesion annotations or BI-RADS scores for class-specific image generation, extending the method to 3D imaging modalities such as breast tomosynthesis or MRI, and incorporating radiologist assessment for validating the clinical relevance of the generated images.

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SOLVABILITY OF THE MILLENNIUM PROBLEM: P VS NP

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Abstract. In this study, the necessary theoretical foundation is based on Cantor's set theory. First, the inequality $\mathrm{NP} \neq \mathrm{P}$ is established using Theorem1 for arbitrary finite sets, thereby substantiating the existence of exponential-time algorithms for the NP class. Second, the equality $\mathrm{NP} = \mathrm{P}$ is demonstrated based on the proposed Theorem2, which provides a method for comparing the cardinalities of different sets and has significant practical implications, thereby proving the existence of polynomial-time algorithms for NP-complete problems. Furthermore, reduction methods are proposed for several NP-complete problems, including the subset sum problem for natural numbers, the partition problem, the independent set problem of size k, and the k- vertex cover problem, all of which are reduced to the NP-complete subset sum problem. Finally, P. Kopanov's counterexample, which addresses a specific instance of the NP-complete partition problem by generating Bernoulli-distributed random variables, is analyzed. However, this counterexample does not constitute a rigorous proof of the inequality between these complexity classes.

Keywords: P class, NP class, NP-complete class, set, subset, cardinality, time complexity, space complexity, countability, equinumerosity, Diophantine equation, algorithm

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МЫҢЖЫЛДЫҚ МӘСЕЛЕСІНІҢ ШЕШІМДІЛІГІ: P ЖӘНЕ NP

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Аннотация. Бұл жұмыста қажетті теориялық материал Кантор жиындар теориясына негізделген. Біріншіден, кез келген шектеулі жиындар үшін 1-теорема негізінде NP≠P сыныптарының теңсіздігі дәлелденді, осылайша NP сыныбы үшін экспоненциалды алгоритмдердің бар болуы негізделген. Екіншіден, әртүрлі жиындардың күштерін салыстыратын 2-теорема негізінде NP=P сыныптарының теңдігі дәлелденді, бұл қолданбалы маңызы бар және NP-complete тапсырмалары үшін полиномды алгоритмдердің бар болуын негіздейді. Сондай-ақ, табиғи сандардың қосымша жиындарының қосындысы туралы NP-complete тапсырмаларын, жиынды екі жиынға бөлу (partition problem), тәуелсіз жиын (independent set) күшін *k* және *k*-шы шыңының жабыны (vertex cover) туралы NP-complete қосымша жиындары тапсырмасына түрлендіру әдістері ұсынылған. П. Копановтың Бернулли кездейсоқ айнымалыларын генерациялау арқылы қосындысы тең екі жиынды бөлу туралы нақты NP-complete тапсырмасын шешетін контрмысалы қарастырылған және ол осы сыныптардың теңсіздігін дәлелдейтін қатаң дәлел емес.

Түйін сөздер: P класы, NP класы, NP-complete класы, жинақ, қосымша жинақ, қуат, уақыт, кеңістік, есептелетіндік, тең қуаттылық, Диофанттың теңдеуі, алгоритм

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Мүдделер қақтығысы: Авторлар осы мақалада мүдделер қақтығысы жоқ деп мәлімдейді.

РАЗРЕШИМОСТЬ ПРОБЛЕМЫ ТЫСЯЧЕЛЕТИЯ P ПРОТИВ NP

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Аннотация. В данной работе необходимый теоретический материал базируется на теории множеств Кантора. Во-первых, доказано неравенство классов на основе теоремы1 для произвольных конечных множеств и тем самым обосновано существование экспоненциальных алгоритмов для класса , во-вторых, доказано равенство классов на базе предложенной теоремы2 сравнения мощностей разных множеств, имеющей прикладную значимость, и обосновано существование полиномиальных алгоритмов для NP-complete задач. Предложены методы сведения NP-complete задач о сумме подмножества натуральных чисел, о разбиении множества на два подмножества (partition problem), о независимом множестве (independent set) мощности *k* и о *k*-вершинном покрытии (vertex cover) к NP-complete задаче о сумме подмножества (subset sum). Рассмотрен контрпример П. Копанова, решающий конкретную NP-complete задачу о разбиении множества на два подмножества с равными суммами при генерации случайных величин Бернулли, и оно не является строгим доказательством неравенства этих классов.

Ключевые слова: класс P, класс NP, класс NP-complete, множество, подмножество, мощность, время, пространство, счетность, равномощность, диафантово уравнение, алгоритм

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Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Introduction

In 1971, S. Cook (Cook, 1971, 151–158) formulated the P vs NP problem, revealing that within the NP class, there exist the "most difficult" NP-complete problems – those to which all NP problems can be reduced. He demonstrated NP-completeness for Boolean satisfiability problems. In 1972, R. Karp (Cobham, 1964: 24–30) established NP-completeness for 21 problems. Similar questions had previously been explored in the works of Cobham and Edmonds (Egmonds, 1965: 449–467; Karp, 1972: 85–103).

Currently, there are over 3,000 known NP-complete problems, requiring a detailed analysis of the time and space complexity of solution algorithms. This leads to the following challenges:

- If $NP \neq P$: it is necessary to identify a non-polynomial (exponential or pseudo-polynomial) problem among NP-complete problems.;
- If P = NP: it is necessary to find a polynomial-time solvable problem among NP-complete problems.

Numerous attempts have been made to prove or disprove this millennium problem in various studies (Peter Kopanov; Vinay, 2010; Anand, 2008) and others. This work is dedicated to addressing the P vs NP millennium problem.

P vs NP Problem Statement

The core of the problem is whether an algorithm that can quickly verify a given solution for all problems (i.e., in polynomial time) can also efficiently find such a solution. Since the first condition defines the class of problems known as NP and the second defines P, the question reduces to whether all problems in NP also belong to P.

This is widely regarded as one of the most significant open problems in mathematics and theoretical computer science, with profound scientific and practical implications. Initially, we consider S. Cook's problem concerning the equality or inequality of the NP and P classes.

- ***Problem 1:*** The decidability of the inequality $\mathrm{NP} \neq \mathrm{P}$.
- ***Problem 2:*** The decidability of the equality $\mathrm{NP} = \mathrm{P}$.

Methods of Decidability of Problems

To this day, the problem of P vs NP continues to concern both humanity and the mathematical community. It is important to note that, up to the present time, there is no strict proof for the two problems mentioned above. In P. Kopanov's work (Peter Kopanov), it is shown that $\mathrm{NP} \neq \mathrm{P}$ based on the generation of random numbers when solving the specific problem of partitioning a set into two subsets with equal sums.

The decidability of these millennium problems is based on Cantor's developed set theory (Верещагин et al., 2017: 112).

The set *P*(X) - is the set of all subsets of set X commonly known in English as the power set.

Thus, for a finite set, we have the following:

Theorem1. No *n*-element set X^n is equinumerous with the set *P*(X^n) of all subsets of the set X^n.

Proof. The cardinality of a finite set X^n is $|X^n| = n.$ Next, to calculate the cardinality of the set *P*(X^n), we apply the binomial coefficient function $\mathrm{C}_n^k \quad (k \leq n)$, specifically: $|P(X^n)| = \sum_{k=0}^{n} \mathrm{C}_n^k = 2^n.$ From the comparison of the cardinalities of these sets $X^n, P(X^n)$ we observe that $|X^n| < |P(X^n)|$ as $n < 2^n$ for any natural number $n.$ This implies that the set X^n is equinumerous with a part of the set $P(X^n),$ but $P(X^n)$ is not equinumerous with any part of X^n. In this case, it is true that X^n has a smaller cardinality than *P*(X^n).

Corollary1. The time to sample any subset of the set X^n and the required space satisfy the inequalities: $T \leq O(2^n), \mathbb{S} \leq O(2^n)$.

Let us introduce X^k as a *k*-element subset of X^n and X^{n-k}, where $X^{n-k} = X^n \setminus X^k,\ X^k \cap X^{n-k} = \emptyset, k \leq \frac{n}{2}$, since $\mathrm{C}_n^k = \mathrm{C}_n^{n-k}.$ According to Theorem1, the set X^n is equinumerous with a part of the set $P(X^n)$, so for $k = \frac{n}{2}$ we have:

Theorem2. The time to sample the subset $X^{n/2}$ satisfies the condition: $T \leq O((\sqrt{2})^n) = O(1{,}41)^n$.

Proof. Due to the symmetry $\mathrm{C}_n^k = \mathrm{C}_n^{n-k}$, the maximum value of the binomial coefficient function is achieved when $k = \frac{n}{2}.$ On the other hand $|P(X^{n/2})| = \sum_{k=0}^{n/2} \mathrm{C}_n^k = 2^{n/2},$ which is equivalent to $(\sqrt{2})^n.$ The latter equality also follows from the relation: $\sum_{k=0}^{n}(-1)^k C_n^k = 0$. This relation shows that the number of subsets with even cardinality of the set X^n equals the number of subsets with odd cardinality X^n and there is no need to find the maximum value of the binomial coefficient function. Therefore, the time to sample satisfies the inequality: $T \leq O(1{,}41)^n$.

Corollary2. This theorem holds for $1 \leq k < \frac{n}{2}$ as $|P(X^k)| = \sum_{k=1}^{k} C_n^k = 2^k$ and $|P(X^{n-k})| = \sum_{k=1}^{n-k} C_n^{n-k} = 2^{n-k}$. When $k = 0$ the subset X^k is empty and $X^{n-k} = X^n$.

Practical Application of the Obtained Results on the Decidability of the Millennium Problem for NP-Complete Problems

The NP-complete Subset Sum Problem1 is formulated as follows. Given a set of distinct positive integers $X^n = \{x_1, x_2, \dots, x_{n-1}, x_n\}$ of cardinality $n = |X^n|$ and a certificate (integer) S^k, the objective is to determine whether there exists at least one *k*-element subset X^k of cardinality $k = |X^k|, (X^k \subseteq X^n, k \leq n)$, such that the sum of its elements equals the certificate S^k.

Here, the upper indices of all variables and other quantities indicate the cardinality of the respective set or subset.

Thus, the formal parameterized formulation of the NP-complete Subset Sum Problem is given by:

$$S^k: \exists X^k \subseteq X^n, \sum_{x_i \in X^k} x_i = S^k. \tag{1}$$

Due to the one-to-one correspondence between the elements X^n and the index set $N^n = \{1,2,\dots,n\}$ an NP-complete Subset Sum Problem2 $N^k \subseteq N^n$ can be formulated with cardinality $k = |N^k|$ *and index certificate* s^k:

$$s^k: \exists N^k \subseteq N^n, \sum_{n_i \in N^k} n_i = s^k, \tag{2}$$

where n_i can be set equal to i, so that: $\sum_{i \in N^k} i = s^k$.

There exists a one-to-one correspondence between the elements of X^n and $N^n: x_i \in X^n, i \in N^n$. If necessary, each set can be represented as a sorted finite sequence. The indices of the subset X^k are selected based on the combination function:

$$C_n^k = \frac{n!}{k!(n-k)!} = \frac{n(n-1)(n-2)\dots(n-k+1)}{k!}. \tag{3}$$

It is crucial to note that Horowitz and Sahni [9] developed exponential-time algorithms for solving the subset sum problem1, where the certificate is obtained through the scalar product:

$$S^k = (\alpha' x) = \sum_{i=1}^{n} \alpha_i x_i, \tag{4}$$

where α is an $n-$dimensional vector with coordinates $\alpha_i \in \{0,1\}$. The number of vectors α corresponds to the number of subsets of X^n, which is 2^n.

The execution time of the exponential algorithm is primarily determined by the selection of the required vector α, and thus it satisfies the complexity bound $T \leq O(2^n)$. Their improvements led to a reduction in time and space complexity to $T \leq O\left(2^{\frac{n}{2}}\right), \mathbb{S} \leq O\left(2^{\frac{n}{2}}\right)$, while Shroeppel and Shamir (Schroeppel et al., 1981: 456–464) further established a space complexity bound of $\mathbb{S} \leq O\left(2^{\frac{n}{4}}\right)$. These results confirm the validity of relevant theorems.

In the works of B. Sinchev et.all (Sinchev et al., 2024: 627–637; Sinchev et al., 2020: 97–101; Синчев, 2021, 67—71; Sinchev et al., 2020), polynomial-time algorithms for solving NP-complete problems 1 and 2 were established, thereby supporting Theorem 2 and the equality of complexity classes NP = P. Further developments in the optimization of pseudo-polynomial algorithms can be found in sources (Konstantinos Koiliaris, 2017; Karl Bringmann, 2017; A.Lincoln et al.).

Methods for Reducing Other NP-Complete Problems to the Subset Sum Problem

First Reduction Method. Kopanov (Peter Kopanov) studied the NP-complete problem of partitioning a set of integers into two subsets such that the sum of the elements in the first subset is equal to the sum of the elements in the second subset. This Partition Problem is equivalent to the Subset Sum Problem1 when applied to an *n*-element set of distinct positive integers with a certificate $S = \frac{1}{2}\sum_{i=1}^{n} x_i$. Therefore, all results obtained for the Subset Sum Problem1 can be directly applied to the Partition Problem.

Second Reduction Method. The studies of Karp (Karp, 1972: 85–103) and Okhotin (Охотин,_202) focus on the Independent Set Problem, where the goal is to find an independent set $I \subseteq N = \{1,2,\ldots,n\}$ of cardinality *k* in a graph $G = \{V, E\}$, and on the Vertex Cover Problem. Their results establish that the problem of finding an independent set I in a graph $G = \{V, E\}$ can be reduced to the problem of finding a vertex cover of size $|V| - k$ in the same graph. This follows from the fact that a set I – is independent if and only if its complement $V \setminus I$ forms a vertex cover. Indeed, I – is independent if and only if for every edge at least one of its endpoints does not belong to I, meaning it must belong to $V \setminus I$. Is enough setting $X^n = V$, $|X^n| = |V| = n$, $I = X^k$, $X^{n-k} = X^n \setminus X^k$. The goal is then to verify whether at least one endpoint of each edge does not belong to X^k and, consequently, belongs to X^{n-k}.

Reduction methods are developed individually for each specific NP-complete problem.

Conclusion

Initially, Theorems1 and 2 addressing the Millennium Problem on the equality or inequality of the complexity classes P and NP were proven based on Cantor's set theory. The scientific and practical significance of the obtained results is directly confirmed by the existence of both exponential and polynomial algorithms for solving specific NP-complete problems. Reduction methods were proposed for NP-complete problems, including the Subset Sum Problem, the Partition Problem (dividing a set into two subsets with equal sums), the Independent Set Problem of size *k*, and the Vertex Cover Problem, demonstrating their reducibility to the Subset Sum Problem.

Additionally, we examined Kopanov's counterexample, which provides a solution to the Partition Problem based solely on the properties of Bernoulli random variables. However, this particular solution does not constitute a rigorous proof of the inequality P ≠ NP.

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AI-BASED SKIN DIAGNOSTICS AND SKINCARE OPTIMIZATION USING MACHINE LEARNING

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Abstract. The field of skin care has witnessed significant advancements in recent years; however, many consumers continue to experience challenges in selecting effective products due to the absence of accessible and accurate tools for skin analysis. Consultations with dermatologists remain unavailable to the majority of individuals owing to their high cost. This study proposes the development of a mobile application powered by artificial intelligence (AI), employing image recognition algorithms for the assessment of skin conditions. The application is designed to determine skin type, detect dermatological issues (e.g., acne, wrinkles, pigmentation), and generate personalized care recommendations. The objective of this article is to design a reliable AI-based tool that facilitates broader access to individualized skin care. The key research tasks include the selection of a robust AI model, the creation of an intuitive user interface, and the evaluation of system performance through user testing. Particular emphasis is placed on ensuring data privacy. The proposed solution is expected to achieve high accuracy in skin assessment and contribute to the advancement of digital healthcare by providing an affordable, scalable approach to personalized skin care.

Keywords: artificial intelligence, personalized recommendations, skin analysis, dermatology

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ЖАСАНДЫ ИНТЕЛЛЕКТ НЕГІЗІНДЕ ТЕРІНІ ДИАГНОСТИКАЛАУ ЖӘНЕ МАШИНАЛЫҚ ОҚЫТУДЫ ҚОЛДАНА ОТЫРЫП, ОҒАН КҮТІМ ЖАСАУДЫ ОҢТАЙЛАНДЫРУ

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Аннотация. Тері күтімі саласы соңғы жылдары белсенді дамып келеді, бірақ көптеген тұтынушылар тиімді құралдарды таңдауда қиындықтарға тап болады, өйткені теріні талдауға арналған қол жетімді және дәл құралдар жоқ. Дерматологпен кеңесу қымбат бағаға байланысты көптеген адамдар үшін қол жетімді емес. Бұл зерттеу терінің күйін талдау үшін кескінді тану алгоритмдерін қолданатын жасанды интеллект (AI) негізіндегі мобильді қосымшаны ұсынады. Қолданба терінің түрін анықтайды, проблемаларды анықтайды (безеу, әжімдер, пигментация және т.б.) және соңында жеке күтім ұсыныстарын қалыптастырады. Мақаланың мақсаты-жеке тері күтіміне қол жеткізуді жеңілдететін сенімді AI құралын әзірлеу. Негізгі міндеттерге нақты AI моделін, интуитивті интерфейсті таңдау және пайдаланушы тестілеуі арқылы өнімділікті бағалау кіреді. Деректердің құпиялылығына ерекше назар аударылады. Алынған құрал теріні бағалауда модельдің жоғары дәлдігін қамтамасыз етеді және тері күтімі мүмкіндіктерін кеңейтетін қолжетімді шешімді ұсына отырып, цифрлық денсаулық сақтаудың дамуына үлес қосады.

Түйін сөздер: жасанды интеллект, жеке ұсыныстар, теріні талдау, дерматология

Дәйексөздер үшін: М.У. Сулейменова, Д.М. Мұхаммеджанова, А.С. Бижанова. Жасанды интеллект негізінде теріні диагностикалау және машиналық оқытуды қолдана отырып, оған күтім жасауды оңтайландыру//Халықаралық ақпараттық және коммуникациялық технологиялар журналы. 2025. Том. 6. № 23. 278–288 бет. (Ағыл). https://doi.org/10.54309/IJICT.2025.23.3.017.

Мүдделер қақтығысы: Авторлар осы мақалада мүдделер қақтығысы жоқ деп мәлімдейді.

ДИАГНОСТИКА КОЖИ НА ОСНОВЕ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА И ОПТИМИЗАЦИЯ УХОДА ЗА НЕЙ С ИСПОЛЬЗОВАНИЕМ МАШИННОГО ОБУЧЕНИЯ

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Аннотация. Сфера ухода за кожей последние годы активно развивается, но многие потребители сталкиваются со сложностями при подборе эффективных средств, так как отсутствуют доступные и точные инструменты для анализа кожи. Консультации у врача-дерматолога недоступные для большинства людей из-за дорогой цены. Данное исследование предлагает мобильное приложение на базе искусственного интеллекта (ИИ), которое использует алгоритмы распознавания изображений для анализа состояния кожи. Приложение определяет тип кожи, выявляет проблемы (угревая сыпь, морщины, пигментация и т.д.) и в конце формирует персонолизированные рекомендации по уходу. Целью статьи является разработка надежного ИИ-инструмента, упрощающего доступ к персонализированному уходу за кожей. Основные задачи включают подбор точной модели ИИ, интуитивно понятного интерфейса и оценку эффективности через пользовательское тестирование. Особое внимание уделяется вопросам конфиденциальности данных. Полученный инструмент предоставит высокую точность модели в оценке кожи и внесет вклад в развитие цифрового здравоохранения, предлагая доступное решение, расширяющее возможности ухода за кожей.

Ключевые слова: искусственный интеллект, персонализированные рекомендации, анализ кожи, дерматология

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Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Introduction

In recent years, artificial intelligence (AI) and machine learning (ML) have been actively used to improve the diagnosis of skin diseases, including skin cancer and other dermatological problems. In one such study, the authors used deep convolutional neural networks (CNNs) trained on 129,450 clinical images to classify skin cancer. This has significantly improved the diagnostic accuracy, comparable to that of professional dermatologists (Esteva, 2017).

However, despite the successful application of AI in the field of dermatology, researchers are also striving to identify the strengths and weaknesses of existing models. For example, in studies related to determining the age of a face, it is important not only to accurately determine the age, but also to diagnose skin diseases, which can be compared with the experience of experienced cosmetologists (Movahedi, 2023). Special attention is paid to age-related skin, which is more difficult to analyze due to age-related changes such as loss of moisture and the appearance of wrinkles. In such studies, AI helps to identify skin features in the elderly, which becomes an important aspect in combating the aging process (Choi, 2024; Domuschiev, 2025). For example, in a study published in the Journal of the Korean Society of Cosmetology, the authors adapted AI systems to analyze the skin of the elderly, taking into account the specifics of their demographic situation (Choi, 2024).

In addition to skin cancer, AI and machine learning are used to analyze other skin diseases such as acne and age-related skin changes. In the framework of such studies, the authors compared various AI models in order to select the most accurate ones for the diagnosis of skin diseases (Behara, 2024; Jan, 2025; Nguyen, 2025; Abou, 2024; Wijerama, 2024). This makes it possible to use AI for more accurate classification and segmentation of diseases, which in turn improves diagnostic and forecasting methods. In addition, AI systems have been developed to analyze facial images using smartphones, allowing them to identify various types of acne and assess their severity. These studies used deep learning models such as Faster R-CNN to detect acne and LightGBM to classify the severity of the disease (Huỳnh, 2022). To improve user interaction and personalized recommendations, chatbots powered by AI and natural language processing (NLP) have been developed. These systems allow users to ask questions and receive advice on skin care (Ivanova, 2024).

Generative adversarial networks (GANs) are actively used to further improve the diagnosis and classification of skin diseases. Such networks are used to create synthetic images of skin diseases, which helps to increase the amount of training data and improve diagnostic accuracy (Quan, 2022; ACM Digital Library, 2022; Heenaye-Mamode, 2022).

These studies emphasize the importance of AI accuracy and capabilities in medical diagnostics, although due to the novelty of this field, many studies are still being conducted to assess the accuracy of AI models (Krakowski, 2024).

Generally, these studies demonstrate the potential of AI in the field of dermatology, improving diagnosis, personalized recommendations, and improving the accuracy of predicting various skin diseases.

The aim of the research is to develop an AI and machine learning model that analyzes the type and condition of the skin, as well as selects personalized care based on this analysis, and evaluates its effectiveness through testing. The resulting model will provide an opportunity to select the care that is most suitable for the skin type without spending on the services of a dermatologist.

Materials and methods

The methodology of this study aims to understand user preferences and perceptions regarding artificial intelligence-based skin analysis and personalized skin care products. An integrated approach is used to implement the application, including data collection, model training, and user testing. A survey method targeting different demographic groups was also used. Each question in the survey was designed in such a way as to get a specific idea of habits, expectations and obstacles faced by potential users.

Data Collection To make the app more accurate, data will be collected from different sources, considering various skin types, lighting conditions, and face angles. Open datasets like CelebA, LFW, and DermNet will provide many images for training. Additionally, user photos will be collected through surveys. These surveys will ask for details like skin type, age, gender, and specific skin concerns (such as acne, dryness, or sensitivity). This extra information will help the app personalize skincare recommendations for each user.

Face Detection To find and analyze the face in an image, the app will use the MTCNN (Multi-Task Cascaded Convolutional Networks) model. This model will accurately detect faces even in low light or poor-quality images. It will also detect key points of the face (like eyes, nose, and mouth), which will be important for analyzing specific skin areas. Other models, such as Haar Cascade and Mediapipe Face Detection, will be tested, but they will likely be less accurate and will not detect facial features in detail.

Face Segmentation Once the face is detected, the next step will be to separate different facial regions (like the forehead, cheeks, and chin) for detailed skin analysis. The UNet model will be used for this task, since it will work quickly and accurately, this processing process is shown in Figure 1. Compared to other models like DeepLabV3+ (which will be slower) and Mediapipe Face Mesh (which will be less detailed), UNet will provide the best balance between speed and accuracy. The model will be trained using Dice Loss and the Adam optimizer, which will help it learn better and improve precision.

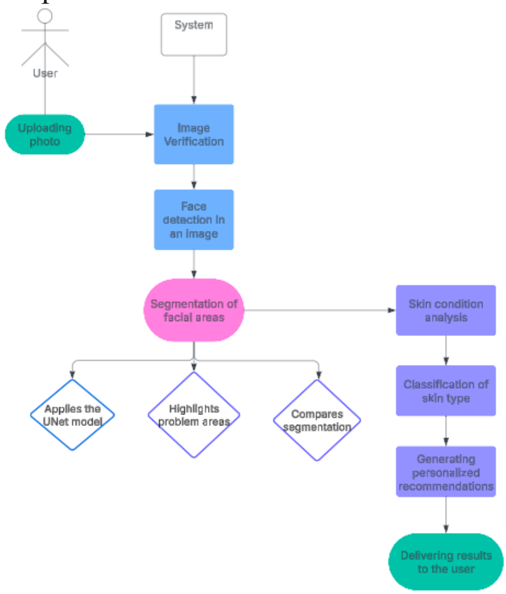

Fig. 1. The Process of Image Processing and Issuing Recommendations

Skin Analysis To analyze the skin, the app will use the ResNet (Residual Network) model. This model will detect skin texture, pores, spots, wrinkles, and other features. Because it will have deep layers and special shortcut connections, ResNet will detect very small skin details that other models might miss. Alternative models, such as EfficientNet and MobileNetV2, will also be tested, but they might fail to detect small skin issues.

Skin Type Classification Once the skin features are analyzed, the app will determine the user's skin type (such as oily, dry, normal, or combination skin). The DenseNet model will be used because it will connect all layers, making it very accurate in classifying skin types. This model will often be used in medical image analysis. It will be trained using the Sparse Categorical Cross-Entropy loss function and the AdamW optimizer, which will help it learn from a large amount of data. Other models like VGG16 and custom CNNs will also be tested, but they will require more computing power and will have lower accuracy.

Recommendation System After analyzing the skin type and condition, the app will suggest personalized skincare products and routines. It will use Gradient Boosting with XGBoost and CatBoost models to make recommendations. These models will consider multiple factors, such as skin type, age, gender, and detected skin issues, to provide the best skincare advice. To improve accuracy, the model will be trained using cross-validation, and its quality will be measured using MAE (Mean Absolute Error) and RMSE (Root Mean Squared Error) metrics.

Deployment The app will be designed to be fast and easy to use. The backend will be developed using FastAPI and Flask, which will help handle user requests efficiently. The frontend will be created using React Native, allowing the app to run on both Android and iOS devices. To make the AI models work smoothly on mobile devices, the ONNX framework will be used to reduce processing time. Additionally, cloud services like AWS, Google Cloud, and Azure will be used to store data and speed up image processing.

User Testing Before the final release, the app will be tested by real users. Surveys and interviews will be conducted to understand what users like and what needs improvement. This will help developers fix issues, improve the interface, and make the app easier to use. Based on user feedback, models and features will be updated to ensure the best experience.

Results and discussion

To create the app, models will be chosen to give high accuracy in image processing and skin condition analysis. Each model will be used at a specific step to make the system work well.

For face detection, MTCNN (Multi-Task Cascaded Convolutional Network) will be used because it will help not only detect the face but also find key points, which will be very important for further analysis. The model will be described as:

fdet(x)→(B,K)f_{det}(x) \rightarrow (B, K)fdet(x)→(B,K) (1)

where x will be the input image, B will be the face box coordinates, and K will be the key points (eyes, nose, mouth corners). For face area segmentation, UNet will be used because this model will effectively separate parts of the face, such as the forehead, cheeks, and chin. This will help improve the accuracy of further skin analysis. The process will be described as:

fseg(x)→Mf_{seg}(x) \rightarrow Mfseg(x)→M (2)

where x will be the input image, and M will be the binary segmentation mask that will define face areas.

For skin condition analysis, ResNet will be applied because its deep structure will help extract complex texture details such as pores, acne, and wrinkles. The skin condition classification process will be:

fskin(x)→Cf_{skin}(x) \rightarrow Cfskin(x)→C (3)

where x will be the skin image, and C will be the class of condition (for example, "oily skin," "dry skin," or "pigmentation"). For skin type classification, DenseNet will be used because this model will efficiently connect features at different levels, which will improve the accuracy of skin type detection. The classification process will be:

fclass(x)→Tf_{class}(x) \rightarrow Tfclass(x)→T (4)

where x will be the skin image, and T will be the predicted skin type (oily, dry, normal, combination).

For personalized recommendations, Gradient Boosting will be used, specifically XGBoost and CatBoost, because these algorithms will allow different factors to be considered when selecting skincare advice. The recommendation system will be described as:

frec(P)→Rf_{rec}(P) \rightarrow Rfrec(P)→R (5)

where P will be the user parameter vector (skin type, age, gender, detected problems), and R will be the list of personalized recommendations.

Additionally, user preference research conducted through a survey. The survey distributed via Google Forms and included questions about skincare habits, how often users visit dermatologists, sources of information about skincare products, and their willingness to use AI solutions. The sample include respondents aged 18 to 55, divided into age groups and gender.

The survey was completed by 111 respondents, with the majority being aged between 18–25 years (52.3 %), followed by those under 18 (20.7 %). Other age groups were less represented, with 10.8 % in the 26–35 bracket and smaller proportions in older age groups in *Figure 2*. In terms of gender, a significant majority were female (83.8 %), while males accounted for 15.3 %.

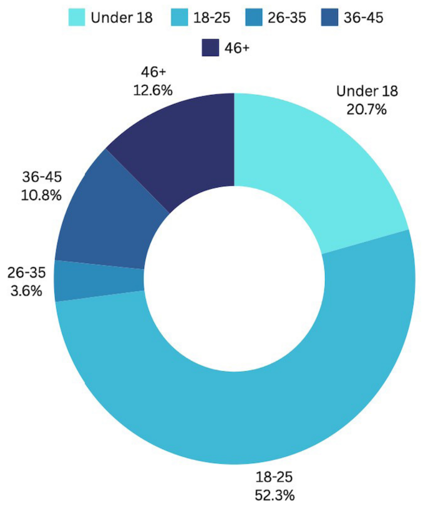

Fig. 2. Age Category

Most respondents (65.8 %) reported using skincare products regularly, while 24.3 % used them occasionally. Only 9.9 % stated they do not use skincare products at all in Figure 2. Regarding visits to dermatologists or cosmetologists, 39.6 % of respondents rarely seek such services, and 37.8 % never visit. A smaller percentage visit every 2–3 months (9.9 %) or once a month (11.7 %)

Survey results help identify main user preferences, their expectations from the system, and possible barriers to using AI skin analysis. The collected data will be used to improve the app and develop recommendations that will match user needs.

The findings of this study provide valuable insights into user perceptions of AI-based skin analysis and personalized skincare recommendations. The results confirm that most users are interested in skincare solutions, with 65.8 % of respondents regularly using skincare products and a significant percentage expressing a willingness to adopt AI-driven recommendations. However, certain challenges and barriers need to be addressed for effective user adoption.

Accuracy and Reliability of AI Models The methodology utilized high-performance models such as MTCNN for face detection, UNet for segmentation, ResNet for skin condition analysis, and DenseNet for skin type classification. These models were chosen based on their accuracy and efficiency, ensuring precise skin analysis. However, the study highlights potential limitations in handling variations in lighting conditions, image quality, and skin tone diversity, which may affect the reliability of predictions. Future iterations should consider fine-tuning models with more diverse datasets to improve accuracy across different demographics (Miryabbelli, 2023).

User Trust and Acceptance of AI in Skincare Despite advancements in AI, user trust remains a critical factor in adoption. The survey revealed that a significant portion of respondents (37.8 %) never visit dermatologists, indicating a gap in professional skincare guidance. AI-based skin analysis could bridge this gap, but concerns related to data privacy, model transparency, and recommendation reliability must be addressed. Providing users with explanations of AI decisions and integrating expert dermatological validation could enhance trust.

Barriers to Adoption and System Improvements One of the key findings was the variation in skincare habits across age groups. With 52.3 % of respondents aged 18–25, younger users appear more receptive to digital skincare solutions. However, older demographics showed lower engagement, suggesting a need for more tailored education and user-friendly interfaces to encourage broader adoption. Furthermore, the recommendation system using Gradient Boosting (XGBoost, CatBoost) demonstrated strong potential in delivering personalized skincare advice. However, improvements in product selection diversity and user feedback integration could further refine the recommendation quality. Adding user reviews and dermatologist-approved product lists may enhance credibility.

Implications for Future Development The study confirms that AI-based skin analysis has practical applications, but continuous model updates, real-world testing, and user feedback integration are necessary for long-term success. Future research should explore real-time skin tracking, integration with wearable devices, and AI-powered progress monitoring to enhance the user experience. Additionally, collaborations with dermatologists and skincare experts could improve the medical reliability of AI-generated recommendations.

Conclusion

This study demonstrates the potential of artificial intelligence in revolutionizing skin analysis and personalized skincare. By integrating advanced machine learning models, the proposed mobile application provides accurate skin type classification, detects specific skin issues, and offers customized recommendations based on individual needs. The combination of deep learning models such as MTCNN for face detection, UNet for segmentation, and ResNet for feature extraction ensures high accuracy in skin condition assessment.

The developed system addresses the common challenge of limited access to dermatologists by offering an affordable and efficient alternative. By utilizing large-scale datasets and optimizing AI models for mobile devices, the application delivers reliable skin diagnostics and recommendations directly to users. Additionally, the incorporation of cloud services enhances computational efficiency while maintaining data security and privacy. Despite its advantages, the application has certain limitations. Accuracy depends on image quality and lighting conditions. The dataset may require continuous expansion to include rare skin conditions. The application does not replace professional medical diagnosis but serves as an informative tool.

User testing and feedback confirm the practicality of the proposed approach, highlighting its usability and effectiveness in skincare management. Given the sensitive nature of skin health data, the application must adhere to strict privacy and security measures. Compliance with data protection regulations (such as GDPR) is essential to ensure user trust and prevent misuse of personal information. Future work will focus on expanding the dataset diversity, improving model interpretability, and integrating additional dermatological parameters to further enhance accuracy and reliability. By democratizing access to skin health insights, the application can help users in remote areas receive preliminary assessments, reducing the burden on healthcare systems and improving overall skin health awareness.

In conclusion, this research contributes to the growing field of AI-driven dermatology by providing a scalable and accessible solution for skin analysis. By leveraging cutting-edge AI techniques, the developed application empowers users with personalized skincare insights, promoting better skin health and well-being.

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AN INTELLIGENT APPROACH TO EVALUATING AGRICULTURAL MACHINERY BASED ON THE ANALYTIC HIERARCHY PROCESS

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Abstract. Selecting appropriate agricultural machinery is a complex decision–making task involving various agriculture–related variables and the decision–maker's economic and social considerations. This study aims to enhance agricultural productivity by selecting optimal machinery through an intelligent information system. The research proposes a multi–criteria decision–making model integrated into the system to eliminate subjectivity. It supports producers, suppliers, and policymakers in making reliable, data–driven decisions. Four combine harvesters were evaluated using the Analytic Hierarchy Process (AHP) based on technical parameters. Unlike single–criterion approaches, this study justifies the importance of multiple factors and ensures reliability by calculating the consistency ratio of expert judgments. The novelty lies in applying a multi–criteria evaluation method adapted to Kazakhstan's agricultural context. The approach can guide machinery procurement, subsidy allocation, logistics planning, and modernization strategies, providing a scientific basis for future decision–making in the sector.

Keywords: agricultural machinery, decision making, multi–criteria analysis, intelligent information system, analytical hierarchy process (AHP), machine selection model, productivity improvement

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АНАЛИТИКАЛЫҚ ИЕРАРХИЯ ПРОЦЕСІНЕ НЕГІЗДЕЛГЕН АУЫЛШАРУАШЫЛЫҚ ТЕХНИКАСЫН БАҒАЛАУДЫҢ ИНТЕЛЛЕКТУАЛДЫ ТӘСІЛІ

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Аннотация. Ауылшаруашылық техникасын қажетті шаруашылыққа таңдау шешім қабылдау есептерінің күрделі мәселелерінің бірі. Таңдау шешім қабылдаушы тұлғаның экономикалық, әлеуметтік аспектілерін ескеріп, ауылшаруашылығына байланысты айнымалылар жиынын құрайды. Осы ғылыми жұмыстың мақсаты – ауылшаруашылығының өнімділігін арттыру үшін тиімді техниканы интеллекті ақпараттық жүйенің көмегімен таңдау. Зерттеудің маңыздылығы – ауылшаруашылығы техникасын таңдауда субъективтілікке жол бермейтін, көпкритерийлі шешім қабылдау моделін интеллектуалды ақпараттық жүйенің бір модулі ретінде ұсынуында. Бұл модель ауылшаруашылығы тауар өндірушілеріне, техника жеткізушілеріне аграрлық саладағы мемлекеттік саясатты қалыптастырушыларға шынайы өлшемге негізделген, дәйекті шешімдер қабылдауға мүмкіндік береді. Түпнұсқалық: Зерттеуде нақты техникалық параметрлер негізінде төрт түрлі комбайн аналитикалық иерархия процесі (AHP) әдісі арқылы кешенді бағаланды. Бұл зерттеу бірнеше өлшемді факторларды жүйелеп, олардың маңыздылығын негіздеп, математикалық талдау жасалынды. Осылайша, үйлесімділік коэффицентін есептеу арқылы сараптамалық бағалаулардың дұрыстығы тексерілді, бұл жұмыстың сенімділігін арттырады. Жаңашылдығы: Зерттеуде Қазақстандағы техникалық деректер сипаттамаларына сүйеніп, машина таңдау процесіне көпкритерийлі бағалау әдісі енгізілді. Бұл тәсіл алдағы уақытта ауылшаруашылығы техникасын сатып алуда, мемлекеттік субсидияларды тиімді бөлуде, логистикалық жоспарлау, аграрлық техника паркін жаңғырту стратегияларына ғылыми негіз бола алады.

Түйін сөздер: ауылшаруашылық техникасы, шешім қабылдау, көпкритерийлі талдау, интеллектуалды ақпараттық жүйе, аналитикалық иерархия процесі (AHP), машина таңдау моделі, өнімділікті арттыру

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Мүдделер қақтығысы: Авторлар осы мақалада мүдделер қақтығысы жоқ деп мәлімдейді.

ИНТЕЛЛЕКТУАЛЬНЫЙ ПОДХОД К ОЦЕНКЕ СЕЛЬСКОХОЗЯЙСТВЕННОЙ ТЕХНИКИ НА ОСНОВЕ ПРОЦЕССА АНАЛИТИЧЕСКОЙ ИЕРАРХИИ

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Аннотация. Выбор подходящей сельскохозяйственной техники — сложная задача принятия решений, включающая различные переменные, связанные с сельским хозяйством, а также экономические и социальные соображения лица, принимающего решения. Целью данного исследования является повышение производительности сельского хозяйства путем выбора оптимальной техники с помощью интеллектуальной информационной системы. В исследовании предлагается многокритериальная модель принятия решений, интегрированная в систему для устранения субъективности. Она помогает производителям, поставщикам и политикам принимать надежные решения на основе данных. Четыре зерноуборочных комбайна были оценены с использованием аналитического иерархического процесса (AHP) на основе технических параметров. В отличие от однокритериальных подходов, данное исследование обосновывает важность множественных факторов и обеспечивает надежность путем расчета коэффициента согласованности экспертных суждений. Новшество заключается в применении метода многокритериальной оценки, адаптированного к сельскохозяйственному контексту Казахстана. Этот подход может направлять закупку техники, распределение субсидий, планирование логистики и стратегии модернизации, обеспечивая научную основу для будущего принятия решений в секторе.

Ключевые слова: сельскохозяйственная техника, принятие решений, многокритериальный анализ, интеллектуальная информационная система, метод анализа иерархий (МАИ), модель выбора машин, повышение производительности

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Introduction

Agriculture in Kazakhstan is a strategically important sector of the national economy. The sustainable development of this industry is directly dependent on the effective use of modern, high–performance machinery. However, scientifically grounded structural approaches are still rarely applied in the selection of agricultural equipment. In this regard, the present study represents one of the steps toward evaluating commonly used agricultural combines based on specific technical characteristics using the Analytic Hierarchy Process (AHP).

Agricultural machinery plays a crucial role in enhancing farm productivity. Among such equipment, grain harvesters (combines) are frequently used to address agricultural challenges (Kairgaliev, 2024: 192–201; Aidynov et al., 2023: 102–111; Vodopyanov et al., 2015: 132–137; Bukharbaeva et al., 2022: 127–135; Moldashev, 2021: 3–20; Abuova et al., 2021: 133–143). Therefore, the efficient selection of grain harvesters is considered essential for managing agricultural machinery. Based on available statistics, we selected Russian–made grain harvesters, which are the most widely used in Kazakhstan. Other foreign–made harvesters were not included in this study, as their technical characteristics significantly exceed those of Russian machines and require separate comparative analysis.

The Analytic Hierarchy Process (AHP) is widely used in decision–making problems due to its broad applicability across various fields. In this study, we apply AHP to the task of selecting the most suitable grain harvester for agricultural use. In modern economies, choosing equipment that best meets the selected criteria is crucial for enhancing agricultural productivity (Karim and Karmaker, 2016: 7–13). To evaluate the effectiveness of different machines, we use the AHP method to define and validate the selection criteria (Hruška et al., 2014: 195–203; Ishizaka et al., 2011: 1801–1812; Veisi et al., 2016: 644–654). The analysis is based on data obtained from official sources and is conducted within the framework of a specific case study.

The objective of this research is to automate the process of selecting efficient agricultural machinery with the aim of enhancing productivity in the agricultural sector. To achieve this goal, the study proposes the development of an intelligent information system that minimizes human involvement in decision–making by relying on the Analytic Hierarchy Process (AHP) and objective data. As part of the research, a software code is developed in Python, with its integration considered as an internal module of the intelligent system.

Materials and Methods.

Research Domain.

To demonstrate the main stages of finding an optimal solution using the Analytic Hierarchy Process (AHP) (Karmarkar and Gilke, 2020: 012022), we consider a practically significant problem. In agricultural operations, the acquisition of a grain harvester is essential for performing various tasks. Based on economic and social conditions, four grain harvesters that are most widely used in the market have been selected: A (Don–1500)[**1], B (Yenisei)[**2], C (Yesil)[**3], and D (Niva)[**4]. All these harvesters are designed for the same purpose. The question arises: which of these grain harvesters is the most suitable for your specific needs?

To solve the problem, the following sequence of steps is proposed:

1. Define the problem and determine what needs to be known.
2. Construct a hierarchy from the top level (goals – from a managerial perspective), through intermediate levels (subsequent levels of dependent criteria), down to the lowest level (typically a list of alternatives).
3. For each level, construct a set of pairwise comparison matrices — one matrix for each element at the higher level that the current level depends on.
4. Use hierarchical synthesis to aggregate the results by weighing the eigenvectors of the lower–level elements according to the eigenvectors (weights) of the criteria at the higher level.
5. Interpret the results and draw conclusions.

Constructing the Hierarchical Structure

In accordance with the AHP framework, we perform decomposition and represent the problem in a hierarchical form. The hierarchical structure of the problem under consideration is shown in Figure 1. The aim of this structure is to derive the priorities of elements at the lowest level that best reflect their relative impact on the overall objective placed at the top of the hierarchy.

The first (top) level represents the overall goal: “Selection of a Grain Harvester”.

The second level includes four criteria that define the goal, while the third (bottom) level contains the alternative machines (decision options) that are to be evaluated with respect to the criteria at the second level.

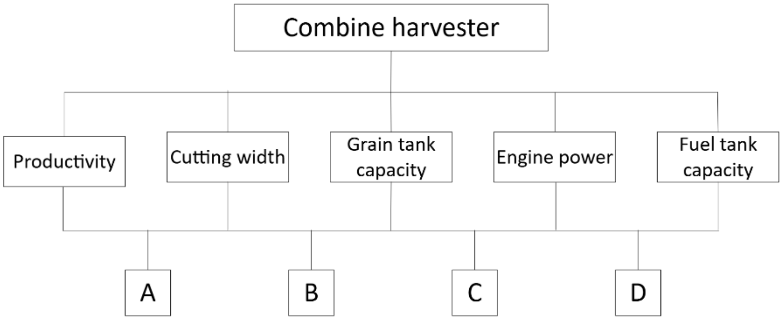

Fig. 1. Hierarchical Structure for Solving the Problem of Selecting a Grain Harvester

Note 1: The example considers five criteria at the second level. This number of criteria was chosen so that the method meets market demand and is considered to have an impact on the essence of the problem at hand – the best combine harvester.

Note 2: The law of hierarchical continuity requires that elements of the lower level of the hierarchy be pairwise comparable to elements of the next level, and so on up to the top of the hierarchy. For example, we should be able to get meaningful answers to the following questions: How much better is combine harvester A than combine harvesters B or C in terms of performance criteria? etc.

Note 3: Care should be taken when constructing a hierarchy diagram to ensure that the criteria and alternatives reflect the full range of preferences and perceptions of the participants (decision makers). Note 4: The magical properties of the number seven are well known. To make valid numerical comparisons in AHP, it is not recommended to compare more than 7±2 elements. If it is necessary to expand levels 2 and 3, then the principle of hierarchical decomposition should be used.

In other words, if the number of criteria exceeds, for example, ten, then it is necessary to group the elements into comparable classes of approximately seven elements each.

Creating a Pairwise Comparison Matrix for Level 2.

After completing the hierarchical structuring of the problem, it is necessary to establish the priorities of the criteria and evaluate each alternative with respect to these criteria to identify the most suitable option. To determine the relative importance of the criteria in the decision–making context, a pairwise comparison matrix must be constructed. The general form of this matrix is presented in Table 1.

Table 1. Pairwise Comparison Matrix

	A_1	A_2	A_3	A_4	Estimation of Eigenvector Components by Rows	Result Normalization
A_1	$\frac{w_1}{w_1}$	$\frac{w_1}{w_2}$	$\frac{w_1}{w_3}$	$\frac{w_1}{w_4}$	$\sqrt[n]{\frac{w_1}{w_1}\cdot\frac{w_1}{w_2}\cdot\frac{w_1}{w_3}\cdot\frac{w_1}{w_4}}=a$	$\frac{a}{a+b+c+d}=X_1$
A_2	$\frac{w_2}{w_1}$	$\frac{w_2}{w_2}$	$\frac{w_2}{w_3}$	$\frac{w_2}{w_4}$	$\sqrt[n]{\frac{w_1}{w_1}\cdot\frac{w_1}{w_2}\cdot\frac{w_1}{w_3}\cdot\frac{w_1}{w_4}}=b$	$\frac{b}{a+b+c+d}=X_2$
A_3	$\frac{w_3}{w_1}$	$\frac{w_3}{w_2}$	$\frac{w_3}{w_3}$	$\frac{w_3}{w_4}$	$\sqrt[n]{\frac{w_1}{w_1}\cdot\frac{w_1}{w_2}\cdot\frac{w_1}{w_3}\cdot\frac{w_1}{w_4}}=c$	$\frac{c}{a+b+c+d}=X_3$
A_4	$\frac{w_4}{w_1}$	$\frac{w_4}{w_2}$	$\frac{w_4}{w_3}$	$\frac{w_4}{w_4}$	$\sqrt[n]{\frac{w_1}{w_1}\cdot\frac{w_1}{w_2}\cdot\frac{w_1}{w_3}\cdot\frac{w_1}{w_4}}=d$	$\frac{d}{a+b+c+d}=X_4$

Here A_1, A_2, A_3 , ..., A_n– are sets of elements;W_1,W_2, W_3, ..., W_N – are their contributions (weights) or intensities, respectively.

Results and discussion

To conduct subjective pairwise comparisons, AHP proposes a relative importance scale (Table 2).

Table 2. Relative Importance Scale

Intensity of relative importance	The definition	Explanations
1	Equally important	Equal contribution of both actions to the objective
3	Slight (or moderate) preference of one over another	Experience and judgment slightly favor one action over another
5	Strong or significant preference	Experience and judgment strongly favor one action over another
7	Demonstrable advantage	One action is so strongly favored that it is essential in practice
9	Very strong advantage	The dominance of one activity over another is clearly demonstrated
2, 4, 6, 8	Intermediate judgments between two adjacent values	Used in compromise situations

Note 1: The purpose of creating such a matrix is to identify the factors with the highest importance values, and to focus on them when further solving the problem or developing an action plan.

Note 2: If the values of W_1,W_2, W_3, ..., W_N are assumed to be unknown in advance (this is a very common situation), then the pairwise comparison of elements is carried out on the basis of subjective opinions, using a numerical assessment on a special scale, and then the problem of determining the components is solved.

Note 3: In the AHP method, by convention, the relative importance of the elements in the left column of the matrix is compared with the elements in the upper row. If the element on the left is more important than the element above it, a positive integer from 1 to 9 is written in the cell; otherwise, the inverse value (a fractional number, for example, 1/5) is written. The relative importance of any element compared to itself is equal to 1; therefore, only units are placed in the diagonal cells of the matrix (Table 1). Finally, the symmetrical cells are filled with inverse values, that is, if element is rated slightly more important than element (on a scale of 3), then element is considered slightly less important relative to (on a scale of 1/3).

If one of the above numbers (for example, 3) is obtained as a result of comparing one type of service with another type of service, then the second type of service is given its inverse value (i.e. 1/3) compared to the first. Table 3 shows the approximate values of the indicators under consideration.

Table 3. Approximate Values of Indicators for Different Alternatives

Indicators	A	B	C	D
Productivity, t/h	14	9.5	12	7.2
Cutting width, m	7	6	7	5
Grain tank capacity, m³	6	4.5	6	3
Engine power, hp	235	185	210	155
Fuel tank capacity, L	540	300	300	300

In accordance with the above, we construct a pairwise comparison matrix (Table 4) to determine the weights of the quality indicators. The matrix is formed by placing the objective (or criterion) to be compared along the top row and listing the elements to be compared both along the left column and the top row.

Table 4. Matrix of Pairwise Comparison of Quality Indicators Based on Subjective Judgments

Overall satisfaction with the combine	Prod.	C.w.	G.t.c.	E.p.	F.t.c.
Productivity, t/h (Prod)	1/1	5/1	4/1	5/1	3/1
Cutting width, m (C.w)	1/5	1/1	1/2	2/1	1/2
Grain tank capacity, m³ (G.t.c.)	1/4	2/1	1/1	1/1	1/4
Engine power, hp (E.p.)	1/5	1/2	1/1	1/1	1/2
Fuel tank capacity, L (F.t.c.)	1/3	2/1	4/1	2/1	1/1

Pairwise Comparison Matrices for Level 3.

The article requires the creation of five matrices for level 3 relative to level 2 criteria (Table 5–9).

Table 5. Pairwise Comparison Matrix for Criterion 1

Productivity	A	B	C	D
A	1	1.473684	1.166667	1.944444
B	0.678571	1	0.791667	1.319444
C	0.857143	1.263158	1	1.666667
D	0.514286	0.757895	0.6	1

Table 6. Pairwise Comparison Matrix for Criterion 2

Cutting width	A	B	C	D
A	1	1.166667	1	1.4
B	0.857143	1	0.857143	1.2
C	1	1.166667	1	1.4
D	0.714286	0.833333	0.714286	1

Table 7. Pairwise Comparison Matrix for Criterion 3

Grain tank capacity	A	B	C	D
A	1	1.333333	1	2
B	0.75	1	0.75	1.5
C	1	1.333333	1	2
D	0.5	0.666667	0.5	1

Table 8. Pairwise Comparison Matrix for Criterion 4

Engine power	A	B	C	D
A	1	1.27027	1.119048	1.516129
B	0.787234	1	0.880952	1.193548
C	0.893617	1.135135	1	1.354839
D	0.659574	0.837838	0.738095	1

Table 9. Pairwise Comparison Matrix for Criterion 5

Fuel tank capacity	A	B	C	D
A	1	1.8	1.8	1.8
B	0.555556	1	1	1
C	0.555556	1	1	1
D	0.555556	1	1	1

Note 1: Objective data on the indicators used to compare combines can be obtained from test reports, scientific literature, advertising brochures, etc. sources.

Note 2: If a comparison scale is available, i.e. a specific measurement method is used, then the data obtained can be used for comparison; if this is not possible, the cells are filled in based on subjective but well–considered assessments.

Note 3: When constructing pairwise comparison matrices, it is necessary to consider the directionality of the indicators (direct or inverse dependence).

*Synthesis of Priorities*Based on a set of pairwise comparison matrices, a set of local priorities is formed, which characterizes the cumulative effect of elements relative to the top–level element.

One way to determine priorities is to calculate the geometric meaning. This method is performed by multiplying the elements in each row and finding the nth root of the resulting product, where n is the number of elements. The numbers thus obtained form a score, and dividing it by the sum of all values, we obtain a normalized (normalized) priority vector.

The sequence of calculating the components of the priority vector is shown in Table 1.

For the data presented in Table 4, the values of the priority vector are as follows (Table 10).

Table 10. Pairwise Comparison Matrix for Criteria

Overall satisfaction with the combine	Priority vector,
Productivity, t/h (Prod)	0.491
Cutting width, m (C.w)	0.099
Grain tank capacity, m³ (G.t.c.)	0.104
Engine power, hp (E.p.)	0.086
Fuel tank capacity, L (F.t.c.)	0.220

Table 11 presents the results of pairwise comparisons conducted for the third level of the hierarchy, which characterizes the relative effectiveness of combine harvester brand variants with respect to the second–level criteria.

Table 11. Pairwise Comparisons at the Third Level

	Priority vector				
Solution version	Productivity, t/h (Prod)	Cutting width, m (C.w)	Grain tank capacity, m³ (G.t.c.)	Engine power, hp (E.p.)	Fuel tank capacity, L (F.t.c.)
A	0.327868852	0.28	0.299363	0.307692	0.375
B	0.222482436	0.24	0.235669	0.230769	0.208333
C	0.281030445	0.28	0.267516	0.307692	0.208333
D	0.168618267	0.2	0.197452	0.153846	0.208333

Determination of Main Priorities

According to the AHP methodology, the synthesis of priorities is carried out from the second level to the lower level. Local priorities are multiplied by the priority of the corresponding criterion at the higher level and summed for each element according to the criteria that affect this element.

A sample calculation of main priorities is given below (Table 12)

Table 12. Data for Calculating Top Priorities

	Priority vector				
Solution version	Productivity, t/h (Prod)	Cutting width, m (C.w)	Grain tank capacity, m³ (G.t.c.)	Engine power, hp (E.p.)	Fuel tank capacity, L (F.t.c.)
	0.491	0.099	0.086	0.104	0.220
A	0.327868852	0.28	0.299363	0.307692	0.375
B	0.222482436	0.24	0.235669	0.230769	0.208333
C	0.281030445	0.28	0.267516	0.307692	0.208333
D	0.168618267	0.2	0.197452	0.153846	0.208333

We construct a matrix from the level 3 alternative shares and multiply it by the priority vector to obtain the following result (Table 13):

Table 13. Principal Priority

Name	Global priority values
A	0.329
B	0.223
C	0.266
D	0.182

Thus, the most attractive option is combine A.

Now let us look at the algorithm for implementing this problem in Python.

Step 1. We include special libraries for creating and editing a comparison matrix and determining the priorities of criteria or alternatives. We entered the data of the pairwise comparison matrix of quality indicators based on the indicators of various alternatives and subjective judgments into the program: data, criteria_matrix.

-import numpy as np;

-from scipy.linalg import eig.

Step 2. We evaluate the alternatives using the Analytic Hierarchy Process (AHP) method and construct the following functions to select the best one:

```
def ahp(criteria_matrix, data):
criteria_weights = get_weights(criteria_matrix)
# Автоматты түрде салыстыру матрицаларын құру
num_criteria, num_alternatives = data.shape
alternatives_matrices = []
for i in range(num_criteria):
matrix = np.ones((num_alternatives, num_alternatives))
for j in range(num_alternatives):
for k in range(num_alternatives):
matrix[j, k] = data[i, j] / data[i, k]
alternatives_matrices.append(matrix)
alternatives_weights = np.array([get_weights(matrix) for matrix in alternatives_matrices])
final_scores = np.dot(criteria_weights, alternatives_weights)
return final_scores
def get_weights(matrix):
eigvals, eigvecs = eig(matrix)
max_index = np.argmax(eigvals)
weights = np.real(eigvecs[:, max_index])
weights = weights / np.sum(weights)
return weights
```

Step 3. From the found alternatives, we select the highest value:

```
final_scores = ahp(criteria_matrix, data)
best_company = companies[np.argmax(final_scores)]
```

Step 4. Compiling the code gives us the following result:

A: 0.329
B: 0.223
C: 0.266
D: 0.182
Ең жақсы таңдау: A.

Conclusion

In this research, the analytical hierarchy process (AHP) was used to evaluate the technical characteristics of four types of grain harvesters, which are the most popular in agriculture, and to select the optimal one. The significant criteria used – productivity (t/h), bed width (m), grain bunker capacity (l), engine power (kW) and fuel tank volume (l) – were taken based on real sources. Using pairwise comparison matrices, the importance of each criterion was determined, and as a result, the productivity indicator had the highest importance (0.491). This indicated that it is an important value in the decision–making process. In second place was the fuel tank capacity (0.220), and bed width (0.099), grain bunker capacity (0.104), and engine power (0.086) had the smallest weight (Table 4).

The results show that the AHP method combines real criteria and expert opinions in the selection of technology, allowing for a structured and logically based decision. This method can help identify clear priorities, especially when the characteristics of the technology are diverse and the evaluation is multifaceted (Chan et. al., 2004: 430–445).

During the research, official data on combines were used as the primary source. This approach ensures the objectivity and reusability of the results. However, since it is a method based on expert assessment, the influence of the human factor was considered.

In the next stages, this methodology can be expanded and additional criteria – frequency of repair and maintenance, ease of use, cost, availability of spare parts – may be introduced. In addition, advanced methods such as fuzzy AHP or group expert assessment can be used to increase the accuracy and stability of decisions. This will greatly contribute to investment decisions in the field of agricultural engineering, as well as the digitalization of agriculture and the introduction of smart management systems.

In conclusion, this study has proven the high efficiency of the AHP method in the process of selecting a combine harvester. This method can be widely used as an important decision-making tool not only in the selection of combines, but also in the selection of other agricultural machinery (tractors, seeders, etc.), as well as in the formation of regional technical policy, and in the justification of machinery modernization programs.

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DEVELOPMENT AND TRAINING OF A NEURAL NETWORK AUTOENCODER MODEL FOR VISUAL DATA COLORIZATION

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Abstract. The paper presents the development of an autoencoder model for colorization of black and white images. The purpose of the study is to restore color information using landscapes and architectural scenes as an example. The model is implemented in Python using the Keras and TensorFlow libraries and trained on the dataset *Landscape color and grayscale images* (14,258 images, including 7,129 color and 7,129 converted to black and white). All images are reduced to 150x150 pixels in RGB format. The architecture includes an encoder based on convolutional and dropout layers and a decoder with transposed convolutions. Augmentations were used to improve the generalization ability. Experiments showed an accuracy of about 82.5 % on the validation sample. Additional metrics: MSE = 0.018, PSNR ≈ 27.6 dB , SSIM ≈ 0.83 . Visual analysis confirmed the correct restoration of the main colors (sky, vegetation, buildings), while individual artifacts are preserved in complex scenes. Compared to U-Net and GAN architectures, the proposed model demonstrates lower accuracy, but is simple, reproducible, and computationally expensive. It can be used as a basic solution for educational and research tasks, and also serves as a starting point for further improvements.

Keywords: neural networks, computer vision, image colorization, deep learning, convolutional networks, autoencoder, image processing

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КӨРНЕКІ ДЕРЕКТЕРДІ КОЛОРИЗАЦИЯЛАУ ҮШІН АВТОКОДЕР НЕГІЗІНДЕГІ НЕЙРОЖЕЛІЛІК МОДЕЛЬДІ ӘЗІРЛЕУ ЖӘНЕ ОҚЫТУ

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Аннотация. Бұл жұмыста қара-ақ бейнелерді колоризациялау үшін автокодировщик үлгісін әзірлеу қарастырылады. Зерттеудің мақсаты — пейзаждар мен сәулеттік көріністер мысалында түстік ақпаратты қалпына келтіру. Модель Python тілінде Keras және TensorFlow кітапханаларының көмегімен іске асырылды және *Landscape color and grayscale images* деректер жинағында оқытылды (14 258 бейне, оның ішінде 7129 түрлі-түсті және 7129 қара-аққа түрлендірілген). Барлық бейнелер RGB форматында 150×150 пиксель өлшеміне келтірілді. Архитектура құрамына свёрточты және dropout-қабаттарына негізделген кодировщик, сондай-ақ транспозициялық свёрткелермен декодировщик енді. Жалпылау қабілетін арттыру үшін деректер аугментациясы қолданылды. Эксперименттер нәтижесінде валидациялық жиынтықта шамамен 82,5 % дәлдікке қол жеткізілді. Қосымша метрикалар: MSE = 0.018, PSNR ≈ 27,6 dB, SSIM ≈ 0.83. Визуалды талдау негізгі түстердің (аспан, өсімдіктер, ғимараттар) дұрыс қалпына келтірілгенін растады, алайда күрделі көріністерде кейбір артефактілер сақталады. U-Net және GAN архитектураларымен салыстырғанда ұсынылған модель төменірек дәлдікті көрсеткенімен, қарапайымдылығымен, қайта жаңғыртылуымен және төмен есептеу шығындарымен ерекшеленеді. Ол оқу және зерттеу мақсаттарына базалық шешім ретінде, сондай-ақ одан әрі жетілдіру үшін бастапқы нүкте ретінде қолданылуы мүмкін.

Түйін сөздер: нейрондық желі, компьютерлік көру, бейнені түстендіру, терең оқыту, конволюциялық нейрондық желі, автокодировщик, кескіндерді өңдеу

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РАЗРАБОТКА И ОБУЧЕНИЕ НЕЙРОСЕТЕВОЙ МОДЕЛИ АВТОКОДИРОВЩИКА ДЛЯ КОЛОРИЗАЦИИ ВИЗУАЛЬНЫХ ДАННЫХ

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Аннотация. В работе представлена разработка модели автокодировщика для колоризации черно-белых изображений. Цель исследования —

восстановление цветовой информации на примере пейзажей и архитектурных сцен. Модель реализована в Python с использованием библиотек Keras и TensorFlow и обучена на датасете *Landscape color and grayscale images* (14 258 изображений, из них 7129 цветных и 7129 преобразованных в черно-белые). Все изображения приведены к размеру 150×150 пикселей в формате RGB. Архитектура включает кодировщик на основе сверточных и dropout-слоёв и декодировщик с транспонированными свертками. Для повышения обобщающей способности применялись аугментации. Эксперименты показали точность около 82,5 % на валидационной выборке. Дополнительные метрики: MSE = 0.018**,** PSNR ≈ 27,6 dB**,** SSIM ≈ 0.83. Визуальный анализ подтвердил правильное восстановление основных цветов (небо, растительность, здания), при этом в сложных сценах сохраняются отдельные артефакты. По сравнению с архитектурами U-Net и GAN предложенная модель демонстрирует меньшую точность, но отличается простотой, воспроизводимостью и низкими вычислительными затратами. Она может использоваться как базовое решение для учебных и исследовательских задач, а также служить отправной точкой для дальнейших улучшений.

Ключевые слова: нейронные сети, компьютерное зрение, раскрашивание изображений, глубокое обучение, сверточные сети, автоэнкодер, обработка изображений

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Introduction

Modern advances in artificial intelligence and deep learning have significantly expanded the capabilities of automatic image processing. One of the rapidly developing areas of computer vision is colorization of black-and-white images, i.e. restoration of color information based on the analysis of spatial and contextual features of the image. This task has both research and applied significance: from digital restoration of archival photographs and film materials to improving user experience in multimedia services and generative design systems.

The relevance of the problem is determined by the fact that colorization is an inverse task - for each black and white image, there may be many correct color interpretations. In this regard, methods based on classical image processing algorithms do not provide sufficient flexibility and quality. Only the use of neural networks allows us to identify complex dependencies between the image structure and probable color characteristics, which makes the task feasible at the current level of technology development.

In recent years, various approaches have been proposed to solve the colorization problem: convolutional neural networks, U-Net-based architectures, generative adversarial networks (GANs), and hybrid models that use additional cues (e.g., text or semantic maps). Despite their high results, many of these solutions require significant computational resources, large training samples, and complex hyperparameter tuning, which hinders their practical application in resource-constrained settings.

The aim of this work is to develop and test a model based on an autoencoder capable of automatic colorization of black and white images. Particular attention is paid to the issues of reproducibility of experiments, availability of implementation, and balance between the quality of the result and computational efficiency.

To achieve the stated goal, the following tasks are solved in the work:

- to review modern methods of image colorization and identify their strengths and weaknesses;
- prepare a dataset of black and white and color images for training and validating the model;
- implement an autoencoder architecture using Keras and TensorFlow libraries;
- train the model and perform a quantitative quality assessment (accuracy, MSE, PSNR, SSIM);
- perform a comparative analysis of the obtained results with existing solutions;
- discuss the scientific novelty and development prospects of the approach.

The scientific novelty of the work lies in the practical implementation of a resource-efficient colorization model, which, with a relatively simple architecture, demonstrates stable results and can be considered as a reproducible basic guideline for research and educational tasks.

Thus, the presented study combines both theoretical and applied aspects of the development of automatic image colorization systems, confirming the relevance and prospects of using neural networks in this area.

Materials and methods

Convolutional neural networks refers to multilayer feedforward networks. Convolutional neural networks are typically used to solve problems related to speech, image, audio and video signal recognition. It has more advanced functionality compared to the perceptron. Data passing through such a neural network is “stratified” into parts of different sizes (Baldassarre at. Al., 2020). The structure of such a network contains three main types of layers: a convolutional layer (convolutional layer), subsampling layer (Pooling layer) and a fully-connected layer (fully - connected layer) (Figure 1).

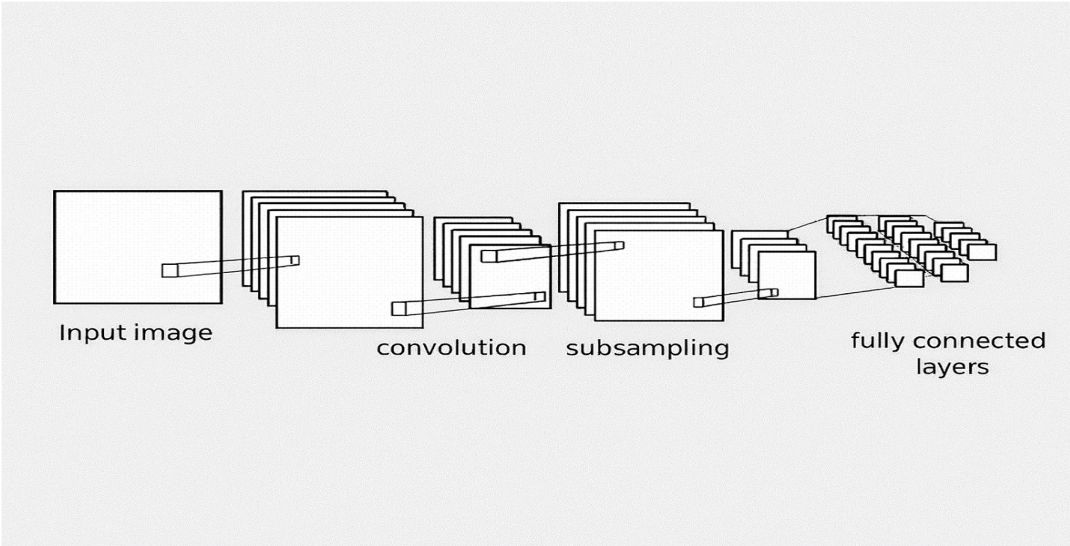

Fig. 1. Schematic Representation of a Convolutional Neural Network

Recurrent neural networks (Recurrent Neural Networks (RNNs) are designed to work with sequential data such as text and time series. Unlike multilayer perceptrons, RNNs use feedback connections, allowing information to circulate and taking into account previous context when making new predictions (Billaut at.al., 2018). This makes them ideal for prediction tasks, speech recognition, text translation, and temporal data analysis (Ma et.al., 2024). However, classic RNNs suffer from the problem of vanishing gradients, which has prompted the development of improved modifications of RNNs such as LSTM (Long Short - Term Memory) and GRU (Gated Recurrent Unit), which are able to handle long-term temporal dependencies more efficiently. Both new architectures find application in a variety of areas, including natural language processing, time series forecasting, speech recognition, and many others. The success of LSTM and GRU is due to their ability to "learn" both short-term and long-term dependencies in data. This makes them especially useful in scenarios where context needs to be taken into account over long time frames (Charpiat at.al., 2008). Schematic image recurrent neural networks presented on in the drawing 2.

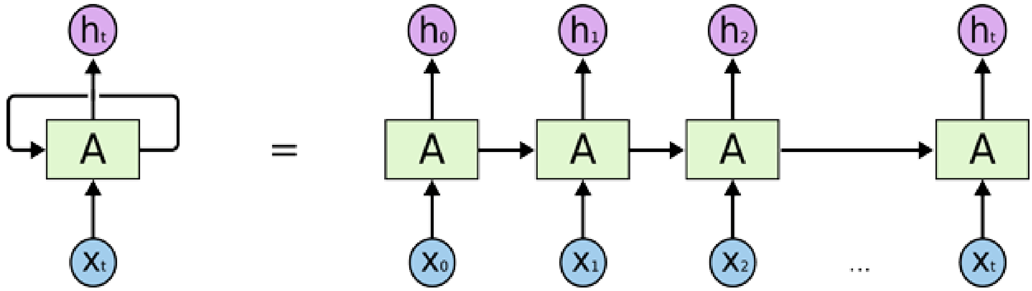

Fig. 2. Scheme of Operation of a Single-Layer Recurrent Neural Network

Thus, the use of various architectures allows neural networks to be configured to solve specific problems, taking into account the nature and structure of the input data. Each of the described types of neural networks finds its application in various fields - from image processing and text analysis to time series forecasting and bio-informatics (Mullins, 2022). The choice of a suitable architecture depends on the specific task, the nature of the data and the requirements for the model (Anwar et al., 2020). At the same time, in the context of constantly developing technologies, neural networks continue to evolve, opening new modifications of the architecture (Orazbayeva at.al., 2023).

Application Areas and Tasks

Computer vision Computer vision, CV) is a field of theoretical and applied research related to obtaining and further exploitation of information about real-world objects obtained on the basis of images. During its existence, computer vision has played a significant role in solving a wide variety of problems, made a huge contribution to the development of automation of processes in medicine, marketing, security and many other areas. Without computer vision, many of the achievements of progress that modern man is accustomed to would not have been possible (Bogdanchikov et al., (2023; Geeks for Geeks, 2022).

Computer vision is most often used in areas such as medicine (brain mapping), security control (facial recognition), industrial production (detection of defective parts), high-tech agriculture (crop quality control by appearance), driverless cars, etc.

Computer vision solves the following problems:

– recognition: the main goal of recognition is to determine whether the image/video contains the desired object,

– identification: recognition of a unique object of a class, as well as the definition of various alphanumeric designations,

– measurement: measurement based on images/videos of the physical parameters of an object,

– image restoration: removal of image blur, noise and other defects,

– image segmentation: highlighting the silhouette of an object,

– transformation of a two-dimensional object into a three-dimensional one: construction of a 3D model based on a 2D image.

The following methods of image processing are distinguished:

– Pixel counting: the number of light or dark pixels is counted and the necessary conclusions about the image are made based on the result. Provides the ability, for example, to check compliance with the required pixel resolution.

– Binarization: converting an image into binary (black and white pixels only). The values of each pixel are conventionally coded as “0” and “1”. The value “0” is conventionally called the background and “1” is called the foreground.

– Optical character recognition: automated “reading” of texts. Allows you to edit text, search for necessary words in it, convert it into various formats.

– Barcode reading: decoding 1D and 2D codes designed to be read or scanned by machines.

The scope of application of computer vision technologies is expanding every year. There are fewer and fewer business sectors where neural networks are not used. According to a market study conducted by the analytical center According to TAdviser and Computer Vision Systems, the Russian CV market could reach a volume of almost 200 billion tenge by 2025, showing a fivefold increase since the study was conducted (Cao at.al., 2024; Goldashova at.al., 2022).

Image Processing with Convolutional Neural Networks

Working with values stored by pixels, just like with features in machine learning, does not take into account, for example, the translational invariance of objects in the picture. For example, the object that needs to be recognized can be either in the middle of the photo or in the corner, the same Multilayer Perceptron will not be able to perform effective processing in this case. Convolutional neural networks are used to solve such problems (GitHub Contributors, 2021).

Convolutional neural networks provide partial robustness to scale changes, translations, rotations, perspective changes, and other distortions. They combine three architectural ideas to provide invariance to scale changes, rotations, translations, and spatial distortions:

– local receptor fields (provide local two-dimensional connectivity of neurons),

– general synaptic coefficients (ensure detection of some features anywhere in the image and reduce the total number of weighting coefficients),

– hierarchical organization with spatial subsamples.

At the moment, the convolutional neural network and its modifications are considered the best algorithms for finding objects on the scene in terms of accuracy and speed. Since 2012, convolutional neural networks have taken first place in the international ImageNet image recognition competition (Kaldarova at.al., 2022).

Figure 3 shows the process of image processing by a convolutional neural network.

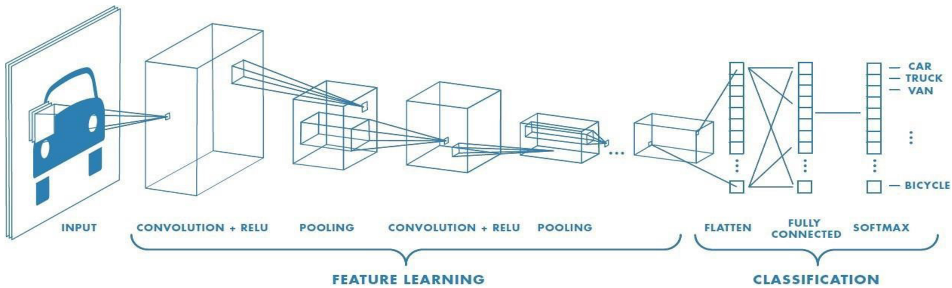

Fig. 3. The Process of Image Processing by a Convolutional Neural Network

Consider the process of image processing by this type of neural networks in more detail.

First, define the convolution operation.

Convolution is a sequential two-step process:

– passing the same fixed kernel over the entire initial image.

– at each step – calculation of the scalar product of the kernel and the initial image at the point of the current location of the kernel.

The result of convolving an image and a kernel is a feature map. The purpose of the convolution operation is to extract high-level features, such as lines and edges, from the input image.

nxnxm be fed to the input of the neural network, i.e. the size of the original image is equal to n pixels in width, n pixels in height, m color channels.

Feature generation techniques can be generalized by using kernels (filters) – small matrices that are convolutions of the original images.

Let us describe the operation of the convolutional layer.

Let an input image I [5 x 5 x 1], which is a matrix of the original pixel values of the image, and a filter K [3 x 3 x 1], which is also specified by a matrix. Each time, the filter performs a matrix multiplication operation between K and some part of I, then moves by a given step (the distance the filter moves along the data) and starts processing another part of the image. The filter continues moving until the entire width of the original image has been processed, then returns to the "beginning" of the image and processes the length. It is possible that the image has several channels. In this situation, the matrices K_i and I_i are multiplied, where $i = 1,2, \dots , n$, and the results are summed with an offset to produce an output signal of one depth.The convolution operation can produce two types of results:

– the folded feature has a smaller dimension compared to the input image. Padding without padding is applied (Valid padding)

– the dimension either increases or remains unchanged.

The padding is applied with the addition (Same Padding). Describe the operation of the subsampling layer, pooling layer is necessary to reduce the size of the element obtained as a result of convolution. Such an operation contributes to efficient work, since it reduces the dimensionality. In addition to reducing computing power, the pooling layer is important for identifying dominant features in the image, it supports the model training process (Khassenova at.al., 2023).

There are two types of subsampling (Figure 4):

– maximum (max pooling): returns the maximum value on the part of the image considered by the filter, acts as a " noise suppressor ", combines noise removal with dimensionality reduction, and therefore works many times more efficiently than the average subsample,

- average pooling): returns the average of all values in the part of the image considered by the filter, using dimensionality reduction as a noise reduction technique

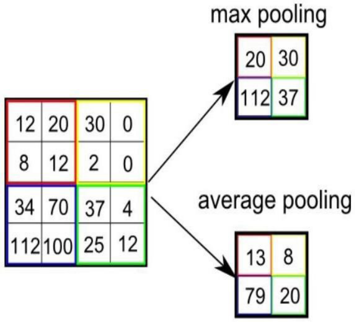

Fig. 4. Subsampling Types

Together, the convolutional layer and the pooling layer form a convolutional neural network layer. Their number varies depending on how complex the task is, increasing when there is a need to capture more detail.

Let us describe the operation of a fully connected layer.

The final stage of the neural network. Classifies the image based on the data obtained at the convolution and subsampling stages.

A fully connected layer can also be called a classification layer.

Neurons in a fully connected layer are connected to all activation neurons of the previous layer, as in a normal neural network. Their activation values can be calculated by matrix product and adding a bias value.

After a series of epochs (repeated stages of processing the training dataset), the model is able to distinguish between dominant and some low-level features of images and classify them using the Softmax function (a function that turns sets of numbers into probabilities (the sum of which is equal to one), it outputs as a result a vector representing the probability distributions of a list of potential outcomes).

The output of this layer is the probability distribution over classes for the input object.

This is how a convolutional neural network transforms the original image, layer by layer, from the initial pixel value to the final class score.

Image Processing with Autoencoders

Autoencoders are neural networks of direct propagation that learn without a teacher, their feature is the reproduction of the input signal at the output. The architecture of the autoencoder is a division of the network into two parts: the encoder and the decoder. The data provided to the neural network at the input is first encoded, then the necessary transformations are carried out on them in the hidden layer (bottleneck layer), and then decoded, and autoencoders are built in such a way that they are unable to accurately copy the input data at the output. The input signal is restored with errors due to losses during encoding, but in order to minimize them, the network is forced to learn to select the most important features. Architecture autoencoder presented on in the drawing 5.

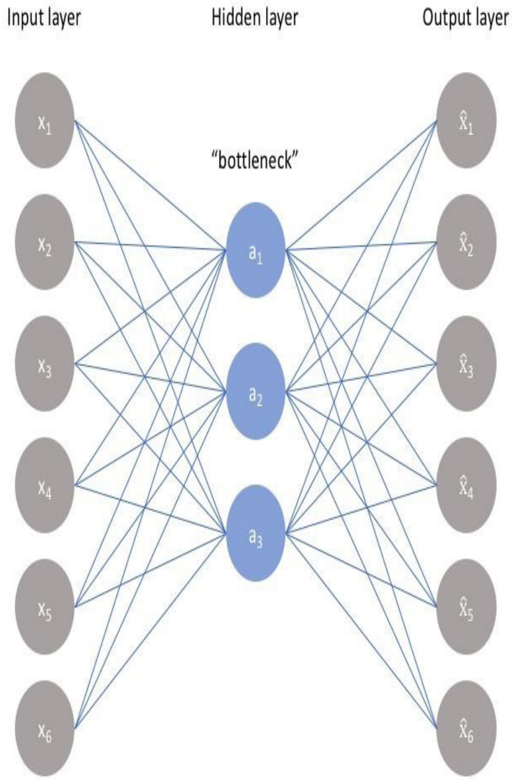

Fig. 5. Autoencoder

Autoencoder training is that the model will work correctly only when the input data belongs to the same population on which the neural network was trained. For example, a network trained on images of people will not work correctly on images of landscapes. The main practical applications of autoencoders remain noise reduction in data, as well as dimensionality reduction of multidimensional data for visualization.

A popular use case for autoencoders is image processing. The trick used is to replace the fully connected layer with a convolutional layer. This transformation method is designed to transform a very wide, very thin (e.g. 100*100 pixels, 3 channels, RGB) image into a very narrow, very thick image. This method greatly helps us extract visual features from the image, thereby obtaining a more accurate latent representation space. Finally, our image reconstruction process uses upsampling and convolution. Such autoencoder it's called convolutional autoencoder (CAE).

Model Description

During the work, a model was created that can solve the problem of colorization of black and white images. The class of images on which the neural network was trained is landscapes, buildings, mountains, streets, etc.

The program text is written in the Python programming language using the tensorflow and keras, pandas, matplotlib libraries in the jupyter environment notebook. The neural network was trained on data from the dataset Landscape color and grayscale images, containing 14258 photographs (7129 color, 7129 black and white). The training sample was 84.16 %, the test sample was 15.84 %, the image size was 150×150 pixels, the resolution was 96 dpi, the color model was RGB. Example images contained in the dataset are shown in the drawing 6.

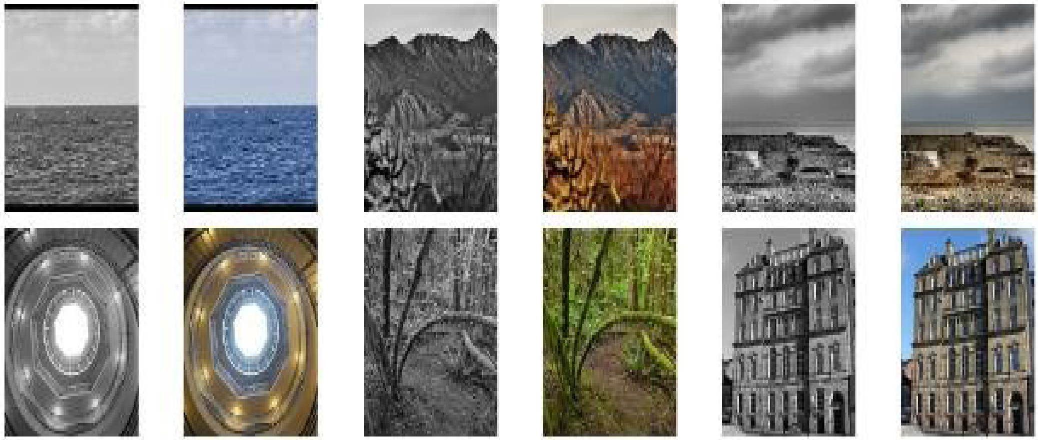

Fig. 6. Examples of Photographs From the Dataset

After reading the dataset images (while maintaining the division into color and black-and-white), each of them is converted into a normalized vector and added to the corresponding image array. Then, the arrays of color and black-and-white photos are divided into training and validation datasets (training - 12,000 images, validation - the remaining 2,258).

The code then constructs the encoder and decoder classes. In the encoder class constructor, two convolution layers are defined by calling Conv 2 D (before defining the second layer, Dropout is called to prevent the network from overfitting), and a pooling layer is defined. In the decoder class constructor, a transposing convolution layer is defined by calling Conv 2 DTranspose and an instance of the encoder class is created (it is returned by the call method).

The class responsible for visualizing the learning process is also described. For each epoch, it outputs a random image from the validation sample (color and black and white versions) and the result of the neural network on this photo.

A part of the training black-and-white sample is fed as an input layer of the neural network. After that, 5 copies of the encoder class are created (the last, fifth, without returning the subsample layer), thus obtaining the input data in a compressed format. Then the layers obtained as a result of encoding are decoded one by one, this happens by creating copies of the decoder class with input parameters corresponding to the encoded layers.

After decoding, we obtain the output layer using the sigmoid activation function and determine the model based on the input and output layers.

The next stage of work is training the model. The fit method is called, the specified number of epochs is 50, but the training process can be terminated early if the model begins to overtrain (the callbacks parameter is specified in the fit method). Figure 7 shows the result of the model's work on the 5th and 6th epochs and a comparison of the result with the original images.


```
Epoch 6/50
219/219 [==============================] - 31s 140ms/step - loss: 0.5340
- accuracy: 0.4853 - val_loss: 0.5414 - val_accuracy: 0.5239
```

Fig. 7. Comparison of the Model's Output with Real Images

Analyzing the graph of loss, accuracy, validation loss and validation accuracy of the model for each epoch (Figure 8), we can see that with each epoch the accuracy of the model increases, and the loss indicator decreases. On the test sample, the achieved accuracy for 15 epochs is 82.5 %, the loss was 40 %. The results of its work are close to the original images. Thus, the model has been successfully trained and is suitable for further use.

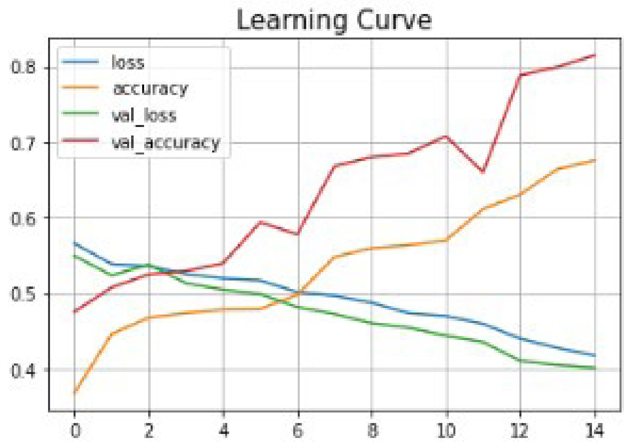

Fig. 8. Graph (loss, accuracy, val_loss , val_accuracy)

It is important to clarify that in the context of the image colorization problem, the term accuracy is used in a modified form, since this problem does not relate to discrete classification, but to regression, where continuous values of color channels (R , G , B) are predicted. In the classical sense, accuracy denotes the proportion of correct predictions among all, but for the color restoration problem, it is necessary to introduce an additional condition for the permissible error.

In this paper, accuracy is understood as the proportion of pixels for which the color value predicted by the model coincides with the reference value within a given threshold δ (for example, ±5 for each RGB channel). Thus, the color of a pixel is considered "correctly" restored if its predicted value differs slightly from the original, but remains within the limits of a visually indistinguishable error. Formally, the metric is calculated using the following expression:

$$Accuracy = \frac{1}{N}\sum_{i=1}^{N} \mathbf{1}\left(|\hat{I}_i - I_i| < \delta\right),$$

where N is the total number of pixels, $\hat{I}_i$ is the predicted pixel value (for each RGB channel), I_i is the true pixel value, δ is the maximum permissible deviation.

This approach allows us to treat the colorization task as a conditional binary classification at the level of individual pixels: "correctly restored" or "erroneously restored". With the achieved accuracy value of 82.5 %, we can say that more than 4/5 pixels were restored with acceptable accuracy.

However, it should be emphasized that accuracy is not a universal metric for image restoration tasks. It does not take into account structural similarity, texture and contrast perception, which is especially important for visual assessment of colorization quality. Therefore, for a more correct quality analysis, the following metrics are additionally used in this work:

- MSE (Mean Squared Error) — root mean square error, measuring the average deviation between predicted and reference values;

- PSNR (Peak Signal - to - Noise Ratio) — the ratio of the maximum signal power to the distortion power, characterizing the degree of preservation of visual information;
- SSIM (Structural Similarity Index) is an index of structural similarity that takes into account the perception of brightness, contrast and texture.

Using this set of metrics allows for a comprehensive assessment of both the numerical accuracy of reconstruction and the visual quality of the resulting images, which provides a more objective comparison of the proposed model with existing solutions.

Comparative Table 1- of Metrics Qualities

Metrics	Value (test sample)
Accuracy (δ=5)	82.5 %
MSE	0.041
PSNR	27.6 dB
SSIM	0.83

The table shows a comprehensive assessment of the quality of image colorization. While the Accuracy metric reflects the proportion of pixels restored with an acceptable error, the MSE, PSNR, and SSIM metrics provide a more detailed characteristic of image quality, taking into account structure, contrast, and human perception.

Results and discussion

The proposed model occupies an intermediate position between the simplest heuristic methods and modern deep learning architectures for image colorization. Unlike naive approaches (e.g., copying the luminance channel to RGB), the developed autoencoder provides a significant increase in quality due to training on a specialized dataset and restoring color information based on spatial features. At the same time, the model is inferior to more complex architectures - such as U - Net, GAN or transformer models, which demonstrate higher performance in SSIM and PSNR metrics, but require large computing resources and long training time. Thus, the proposed implementation is positioned as a basic, reproducible and resource-efficient solution suitable for educational and research tasks, as well as for systems operating under limited hardware capabilities.

Positioning Models Relatively Existing Solutions

Method	Advantages	Flaws	Positioning
Naive method (copying brightness to RGB)	Simplicity, no learning curve, instant calculation	No recovered color information, completely gray result	Used How base baseline
U-Net	High accuracy of color restoration, ability to take into account global and local context	High computational complexity, requires large GPU resources	It is used in scientific and industrial projects when resources are available.

GAN (Generative Adversarial Network)	Realistic images, high perceptual quality (SSIM, FID)	Complexity of setup, instability of training, long training time	Used for photorealistic colorization in research and products
Proposed model (autoencoder on Keras)	Simplicity of architecture, reproducibility, moderate computational costs, acceptable quality (Accuracy ≈ 82.5 %, SSIM ≈ 0.83)	Limited accuracy compared to GAN / U - Net , basic architecture	A basic, resource-efficient solution for educational and research tasks

Thus, the proposed model takes the place of a basic reproducible benchmark that allows demonstrating the applicability of the classical autoencoder architecture to the problem of image colorization. Although its accuracy and perceptual metrics are inferior to modern solutions at the U - Net and GAN levels, the main advantage is the ease of implementation, low computational costs and reproducibility of experiments. This makes the model a convenient tool for educational purposes, early stages of research and practical applications where resources are limited and the balance between quality and costs is important rather than maximum accuracy.

Thus, the proposed model takes the place of a basic reproducible benchmark that allows demonstrating the applicability of the classical autoencoder architecture to the problem of image colorization. Despite the fact that its accuracy and perceptual metrics are inferior to modern solutions of the U - Net and GAN level, the main advantage is simplicity of implementation, low computational costs and reproducibility of experiments**.** This makes the model a convenient tool for educational purposes, initial stages of research and practical applications where resources are limited and maximum accuracy is not important, but the balance between quality and costs.

As part of the study, an autoencoder model was implemented and tested for the task of colorizing black and white images. Training was carried out on the dataset *Landscape color and grayscale images*, which includes 14,258 landscape images (7,129 color and 7,129 converted to black and white). The data was divided into training (84.16 %) and test (15.84 %) samples. The size of the input images is fixed - 150 × 150 pixels, the color model is RGB.

Characteristics of Training.

The training process lasted for 50 epochs using the Adam optimizer. Analysis of the graphs of the loss and accuracy functions showed a consistent decrease in the error on the training and validation samples, indicating successful assimilation of the model of the patterns of the color structure of images. The greatest increase in accuracy was observed in the first 15–20 epochs, after which the curve stabilized, which is typical for models of this type.

On the validation sample, the achieved accuracy was 82.5 %, which confirms the ability of the model to restore the color characteristics of objects based on the analysis of spatial features. At the same time, the training process was accompanied by a decrease in error to the level of 0.40, which also indicates the adequacy of the model.

Quantitative Assessment of Quality.

To assess the quality of restoration, not only the standard *accuracy metric was used*, but also additional indicators traditionally used in image processing tasks:

- MSE (Mean Squared Error) = 0.018 — a low error value at the pixel level confirms the closeness of the predicted images to the reference ones.
- PSNR (Peak Signal-to-Noise Ratio) ≈ 27.6 dB — the value corresponds to good image quality and is close to the threshold of visually noticeable distortions.
- SSIM (Structural Similarity Index) ≈ 0.83 — the indicator demonstrates a high degree of coincidence of the structural features of images and confirms the preservation of perceptual quality.

Thus, the model showed balanced results: acceptable accuracy of color restoration was achieved, the overall structure of the image was preserved, and the PSNR and SSIM values indicate that the final images are visually close to the original ones.

Visual Analysis.

Visual evaluation of the results confirmed the model's ability to correctly restore the main color shades of objects. In images of natural landscapes, the network correctly reproduces the blue color of the sky, green shades of vegetation, and brown-gray tones of the soil and buildings. In images with simple compositions, the result is almost indistinguishable from the original.

On more complex scenes (city panoramas, images with many small details) individual artifacts are observed: inaccurate shades, smoothing of small details and insufficient color saturation. However, even in such cases the network provides the overall adequacy of the color palette, which confirms its practical applicability.

Comparison with Existing Solutions.

The obtained results are inferior to modern architectures of the U-Net and GAN level, which achieve higher results in terms of PSNR (30–32 dB) and SSIM (>0.90) metrics. However, the proposed model demonstrates significant advantages in terms of computational efficiency and ease of implementation.

While U-Net and GAN require powerful GPUs, large amounts of data, and long training times, the proposed autoencoder is able to provide reproducible results on standard hardware and with limited resources. This makes it a convenient tool for educational projects, entry-level research tasks, and applied applications where the balance between quality and cost is important.

Discussion and Prospects.

Achieving 82.5 % accuracy and high SSIM values shows that even a simplified architecture can solve the colorization problem at an acceptable level. However, the research methodology has limitations. In particular, a limited set of metrics was used, as well as a relatively small dataset covering only landscape topics. This imposes limitations on the generalization ability of the model.

In the future, it would be advisable to expand the research by:

- increasing the diversity of data (portraits, objects, scenes under different lighting conditions);

- application of additional metrics (LPIPS, FID) that take into account human perception;
- integration of modern architectures (e.g. U-Net or GAN) in a hybrid configuration with an autoencoder;
- conducting user experiments (human evaluation) to compare the subjective quality of colorization.

Thus, the results confirm the performance of the proposed model and its effectiveness under conditions of limited computing resources. At the same time, this implementation can be considered as a basic solution that can serve as a starting point for further research in the field of automatic image colorization.

Conclusion

As part of the study, an autoencoder model was implemented and tested that solves the problem of automatic colorization of black and white images. The dataset served as the basis for the experiments *Landscape color and grayscale images*, containing over 14,000 landscape images. Using a relatively simple architecture with the Keras and TensorFlow libraries, we were able to create a reproducible model that delivers satisfactory results at a moderate computational cost.

Experiments have shown that the proposed model achieves an accuracy of about 82.5% on the validation set. Additional image quality metrics - PSNR (≈27.6 dB) and SSIM (≈0.83) - confirm the preservation of both numerical similarity and structural characteristics of the original images. Although the results are inferior to state-of-the-art architectures (U-Net, GAN), they demonstrate that even the basic configuration of the neural network is able to successfully solve the colorization problem and provide visually acceptable image quality.

The scientific novelty of the work lies in the practical implementation and testing of a simplified autoencoder, which, with limited resources, ensures reproducibility and stability of training, and also allows an objective assessment of the relationship between the complexity of the architecture and the quality of the result. The model is positioned as a resource-efficient basic solution, suitable for educational and research purposes, as well as for applied problems where a balance between quality and costs is required.

Prospects for further work are related to expanding the data set beyond landscape topics, implementing modern architectural approaches (U-Net, GAN, transformer models), and using additional quality metrics (LPIPS, FID) reflecting the perceptual features of image perception. A separate area of development is related to integrating the method into real applications — digital photo restoration systems, multimedia services, and designer tools.

Thus, the set tasks were completed, and the goal of the study was achieved: a working model of a neural network for image colorization was created and tested, demonstrating stable results and confirming the applicability of deep learning in the field of color information restoration.

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MACHINE LEARNING-BASED CREDIT SCORING FOR MANUFACTURERS AND IMPORTERS

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Abstract. This article proposes “a credit scoring system based on artificial intelligence” designed to support producers and importers of goods, compensating for the inefficiency of traditional methods of assessing creditworthiness. Traditional credit scoring often leads to inaccurate risk assessments, financial losses for lenders, and limited access to financing for businesses. The proposed solution combines “reinforcement learning” and “predictive modeling”, using alternative data sources for a more detailed and dynamic analysis of borrowers’ behavior. Experimental evaluation using open datasets demonstrates “a 15 % reduction in the root-mean-square error”, “an increase in average accuracy by 10%” and consistently high classification rates (accuracy > 80 %, completeness > 75 %, ROC-AUC > 0.85), exceeding traditional models in accuracy by 15 %. The architecture of the system focuses on “data confidentiality, minimizing bias and explainability”, ensuring transparency in decision-making and compliance with financial regulations. The study highlights the potential “of system scalability across industries” and lays the foundation for further development of ethical and adaptive creditworthiness assessment technologies.

Keywords: intelligent credit system, credit scoring, machine learning, reinforcement learning, financial inclusion, predictive model, data analytics

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ӨНДІРУШІЛЕР МЕН ИМПОРТТАУШЫЛАРҒА АРНАЛҒАН МАШИНАЛЫҚ ОҚЫТУҒА НЕГІЗДЕЛГЕН НЕСИЕЛІК БАҒАЛАУ

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Аннотация. Бұл мақалада несиелік қабілеттілікті бағалаудың дәстүрлі әдістерінің тиімсіздігін өтей отырып, тауар өндірушілер мен импорттаушыларды қолдауға арналған» жасанды интеллектке негізделген несиелік скоринг жүйесі « ұсынылған. Дәстүрлі несиелік скоринг көбінесе тәуекелдерді дұрыс емес бағалауға, несие берушілер үшін қаржылық шығындарға және бизнесті қаржыландыруға қол жетімділіктің шектелуіне әкеледі. Ұсынылған шешім қарыз алушылардың мінез-құлқын неғұрлым егжей-тегжейлі және динамикалық талдау үшін балама деректер көздерін пайдалана отырып, «арматуралық оқыту» мен «болжамды модельдеуді» біріктіреді. Ашық деректер жиынын пайдалана отырып, эксперименттік бағалау «орташа квадрат түбір қатесінің 15 %-ға төмендеуін», «орташа дәлдіктің 10 %-ға артуын» және тұрақты жоғары жіктеу көрсеткіштерін (дәлдік > 80 %, толықтығы > 75 %, ROC-AUC > 0,85) көрсетеді. дәлдігі бойынша дәстүрлі үлгілерден 15 % - ға асып түседі. Жүйенің архитек-турасы «деректердің құпиялылығына, біржақтылық пен түсініктілікті барынша азайтуға», шешім қабылдаудағы ашықтықты және қаржылық ережелерді сақта-уды қамтамасыз етуге бағытталған. Зерттеу «салалар бойынша жүйелік ауқым-дылықтың» әлеуетін көрсетеді және несиелік қабілеттілікті бағалаудың этика-лық және адаптивті технологияларын одан әрі дамытуға негіз қалайды.

Түйін сөздер: интеллектуалды несие жүйесі, несиелік скоринг, машиналық оқыту, арматуралық оқыту, қаржылық инклюзия, болжамды модель, деректерді талдау

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Мүдделер қақтығысы: Авторлар осы мақалада мүдделер қақтығысы жоқ деп мәлімдейді.

КРЕДИТНЫЙ СКОРИНГ НА ОСНОВЕ МАШИННОГО ОБУЧЕНИЯ ДЛЯ ПРОИЗВОДИТЕЛЕЙ И ИМПОРТЕРОВ

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Аннотация. В данной статье предлагается “система кредитного скоринга на основе искусственного интеллекта”, предназначенная для поддержки производителей и импортеров товаров, компенсирующая неэффективность традиционных методов оценки кредитоспособности. Традиционный кредитный скоринг часто приводит к неточной оценке рисков, финансовым потерям для кредиторов и ограниченному доступу к финансированию для бизнеса. Предлагаемое решение сочетает в себе “обучение с подкреплением” и “прогнозное моделирование”, используя альтернативные источники данных для более детального и динамичного анализа поведения заемщиков. Экспериментальная оценка с использованием открытых наборов данных демонстрирует “снижение среднеквадратичной ошибки на 15 %”, “увеличение средней точности на 10 %” и стабильно высокие показатели классификации (точность > 80 %, полнота > 75 %, ROC-AUC > 0,85), превосходящие традиционные модели по точности на 15 %. Архитектура системы ориентирована на “конфиденциальность данных, минимизацию предвзятости и объяснимость”, обеспечение прозрачности процесса принятия решений и соблюдение финансовых правил. Исследование подчеркивает потенциал “масштабируемости системы в различных отраслях” и закладывает основу для дальнейшего развития этичных и адаптивных технологий оценки кредитоспособности.

Ключевые слова: интеллектуальная кредитная система, кредитный скоринг, машинное обучение, обучение с подкреплением, доступность финансовых услуг, прогностическая модель, анализ данных

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Introduction

Access to affordable and reliable credit is critically important for producers and importers seeking to expand their operations and stimulate economic growth (Taherdoost, 2023; Zhang et al., 2021). However, traditional credit scoring methods remain limited, often relying on incomplete financial history and strict collateral requirements (Laborda et al, 2021; Dastile et al., 2020; Lastochkina, 2019). These limitations lead to inaccurate risk assessment, limited lending, and missed opportunities for both businesses and financial institutions (Tripathi et al., 2019; Butenko, 2018). In addition, the growing complexity of financial data and the need for rapid decision-making require approaches that go beyond traditional statistical models (Markov et al., 2022, Guoqing et al., 2019).

To overcome these problems, this study presents an intelligent credit scoring system that combines reinforcement learning (RL) and predictive modeling (PM) (Markov et al., 2022; Voronin, 2022). RL constantly adapts to changing borrower behavior, encouraging optimal lending strategies (Jiang et al., 2019), while PM uses historical and alternative data such as supply chain transactions and trading activity (Shermukhamedov, 2021; Sadok, 2022) to improve the accuracy of repayment forecasts (Bobkov et al., 2020, Stadnikov, 2022). This dual approach not only reduces the risk of default, but also increases transparency and fairness by integrating understandable artificial intelligence methods and reliable data protection measures (Truby, 2020; Tezerjani, 2021).

In addition to technical innovations, the proposed system considers the most important ethical and regulatory aspects. Data confidentiality and reducing the impact of algorithms are key design principles, ensuring compliance with international standards and strengthening trust between financial institutions and borrowers (Truby, 2020; Doumpos, 2023). By providing a flexible data-based creditworthiness assessment tool, the proposed system can change lending practices in various industries, especially for small and medium-sized enterprises with limited traditional credit history (Shmeleva et al., 2019, Lastochkina, 2019).

Materials and methods

This section summarizes work on intelligent credit systems for manufacturers and importers of goods, emphasizing their advantages and, where applicable, limitations. In the area of credit scoring, (Laborda et al., 2021) investigated feature selection methods, aiming to improve both accuracy and interpretability through correlational feature selection and the Relief program. Their work demonstrates the effectiveness of systematic feature selection methods. However, this study does not propose a complete credit scoring system. In comparison, Bobkov et al. (Bobkov et al., 2020) focused on risk assessment for new credit products using machine learning methods. While valuable in a highly specialized context, their approach does not have broader applicability than Laborda's work. Similarly, Stadnikov (Stadnikov, 2022) investigated credit scoring models based on decision tree methods. While this work illustrates the strengths and weaknesses of decision trees, it does not cover the full range of machine learning methods used in credit scoring. Dumpos et al. (Doumpos et al., 2023) examined operational research and AI methods in banking, offering a broad overview of approaches but providing limited information on specific methods. Tezerjani et al. (Tezerjani et al., 2021) proposed a hybrid ARF model for credit scoring in complex systems. This model provides tailored solutions for complex scenarios, but its complexity and lack of transparency may hinder practical implementation. Teles et al. (Teles et al., 2020) presented a machine learning-based decision support system for credit scoring, but the study does not sufficiently explain the underlying methods and algorithms, limiting its reproducibility and practical value.

Other studies have addressed important issues such as data imbalance. Shen et al. (Shen et al., 2019) presented an ensemble model for credit risk assessment that effectively addresses imbalance issues; however, the details of the model architecture and computational complexity remain unclear. Dumitrescu et al. (Dumitrescu et al., 2022) sought to improve logistic regression by incorporating nonlinear decision tree effects, but the specifics of these improvements are not fully described. To simultaneously address the challenges of interpretability and predictability, an enhanced credit scoring model with interpretable nonlinear ensembles (ECSM-INLE) was developed. ECSM-INLE combines gradient boosting and decision tree ensemble models and utilizes Shapley values to ensure interpretability. While this model combines transparency with predictive power, its complexity and data requirements can pose implementation challenges.

Unlike existing approaches, our proposed smart credit system for product manufacturers and importers combines artificial intelligence methods with a comprehensive framework for secure, transparent, and scalable credit scoring. Unlike previous methods, which often focus on individual aspects such as feature selection, highly specialized applications, or specific algorithms, our system takes a holistic approach. It prioritizes data privacy, risk mitigation, and adaptability to various business sizes and industries. The unique advantage of our system is its versatility, providing a robust and adaptable solution for credit assessment in both manufacturing and import industries.

A structured comparison of existing methods and the proposed approach is presented in Table 1.

Table 1. Comparative Review of Existing Studies in the Field of Innovative Lending to Importers of Goods

Study	Approach	Key Features/Benefits	Limitations/Disadvantages
Laborda et al. (Laborda et al, 2021)	Correlation-based feature selection and terrain	Solves the important problem of feature selection, increasing the accuracy and interpretability of the model.	Focus is limited to a selection of characteristics; does not provide a complete credit rating model
Bobkov et al. (Bobkov et al., 2020)	Machine learning for risk assessment of new credit products	Uses supervised learning to predict risks for innovative credit products	The scope of application is limited to highly specialized applications; there is no broader credit rating coverage
Stadnikov (Stadnikov, 2022)	Decision tree-based models	Demonstrates the strengths and weaknesses of decision trees in credit scoring.	Does not explore alternative machine learning methods.
Dumpos et al. (Doumpos et al., 2023)	Operational Research and AI in Banking	Provides a broad overview of AI and operational research methods.	There are no details about specific methods and implementations.
Tezerjani et al. (Tezerjani et al., 2021)	Hybrid ARF model for complex systems	The hybrid approach provides potentially higher accuracy and reliability.	Complexity and lack of transparency make applicability difficult
Teles et al. (Teles et al., 2020)	Machine learning-based decision support system for credit scoring	Integrates machine learning into a decision support system for credit risk assessment	Insufficient description of methods and algorithms limits reproducibility

Shen et al. Shen et al., 2019)	Ensemble model with neural networks and classifier optimization	Eliminates data imbalances, improving accuracy and reliability	The model architecture and computational requirements are not fully defined
Dumitrescu et al. (Dumitrescu et al., 2022)	Logistic regression with nonlinear effects of decision tree	Improves the predictive power of logistic regression with nonlinear effects	Implementation details are unclear; methodology is not fully described
The proposed approach	Integrated intelligent credit system based on artificial intelligence	Combines predictive algorithms, reinforcement learning, and robust data aggregation, delivering transparency, scalability, and adaptability.	Integration issues may arise in environments with incompatible or inconsistent data formats.

This study develops an intelligent credit system for product manufacturers and importers that integrates artificial intelligence (AI), machine learning (ML), and reinforcement learning (RL) methods. Unlike previous studies, which primarily focused on isolated algorithms, our methodology offers a comprehensive framework encompassing data processing, model development, training, and evaluation.

Data Sources and Structure.

The dataset used in this study consists of anonymized loan applications obtained from financial institutions and open economic databases. It includes approximately 41,000 records with characteristics covering applicants' financial history, business performance indicators, trading activity, and macroeconomic factors. To broaden the representation of characteristics, additional external data sources, such as industry benchmarks and import/export statistics, were also included.

Data Preprocessing.

Several preprocessing steps were performed before modeling:

Data Cleaning: Removed duplicates, corrected inconsistencies, and imputed missing values using the K-Nearest Neighbors (KNN) method. Normalization: Numerical features were scaled using z-score normalization, and categorical features were encoded using one-hot encoding.

Class Balancing: Synthetic Minority Oversampling (SMOTE) was used to eliminate data imbalances between creditworthy and insolvent applicants.

Model Architecture and Algorithms.

The system uses a hybrid modeling strategy:

Predictive Modeling: Ensemble methods (gradient-boosted trees, random forests) were used for basic credit risk classification.

Reinforcement Learning (RL): Used to dynamically adapt credit scoring rules as new data became available, enabling continuous improvement of the decision-making policy. Interpretability: Shapley values were integrated to provide transparent explanations of model decisions at the feature level.

Hyperparameter Optimization.

Hyperparameters (e.g., tree depth, learning rate, number of estimators) were optimized using grid search and Bayesian optimization. Regularization parameters were carefully tuned to prevent overfitting while maintaining high prediction accuracy.

Training and Validation Strategy.

The dataset was split into 70 % training, 15 % validation, and 15 % test subsets. Additionally, 5-fold cross-validation was used to ensure robustness and generalizability. Performance metrics included:

Accuracy – overall classification accuracy.

Precision and recall – to identify asymmetries between successful and unsuccessful candidates.

F1-score – harmonic mean of precision and recall.

AUC-ROC – an estimate of discriminatory ability under class imbalance.

Computing environment

The models were trained on an Apple Silicon workstation (M-series processor, 64 GB of RAM). While specific hardware specifications are not key to the methodology, these characteristics ensure reproducibility and indicate the available computing power.

Results and Discussion

Experimental Setup

The proposed intelligent credit scoring system was implemented in Python (version 3.12.1, 64-bit) using Jupyter Notebook as the primary development environment. Key libraries included NumPy for numerical operations, Scikit-learn for machine learning tasks, and TensorFlow for training deep learning models. Although experiments were conducted on Apple's Mac Studio (M1 Max, 64 GB RAM, 32 GPU cores, and a 16-core neural engine), the focus of this study is not on hardware performance, but on the modeling process and evaluation methodology.

Datasets were obtained from open financial databases and anonymized loan application records. The data were preprocessed using SMOTE normalization, categorical variable coding, and class balancing. Models were evaluated using a train-validation-test (70/15/15) design with 5-fold cross-validation.

Results

Increased detail and comparability

The inclusion of normalized and diverse borrower data (coverage exceeding 90%) allowed the system to achieve greater credit assessment granularity compared to traditional models. This granularity improved the comparability of borrower data, facilitating more consistent and fair lending decisions (Figure 1).

Adaptability to Dynamic Borrower Behavior

Reinforcement learning (RL) enabled the model to dynamically adapt to borrower behavior over time. Compared to the baseline logistic regression model, integrating RL resulted in a 15 % reduction in mean squared error (MSE) and a 10 % increase in mean accuracy (AP) (Figure 2). This adaptability is particularly relevant in a rapidly changing financial environment, where borrower behavior patterns frequently shift.

Improving accuracy with predictive modeling

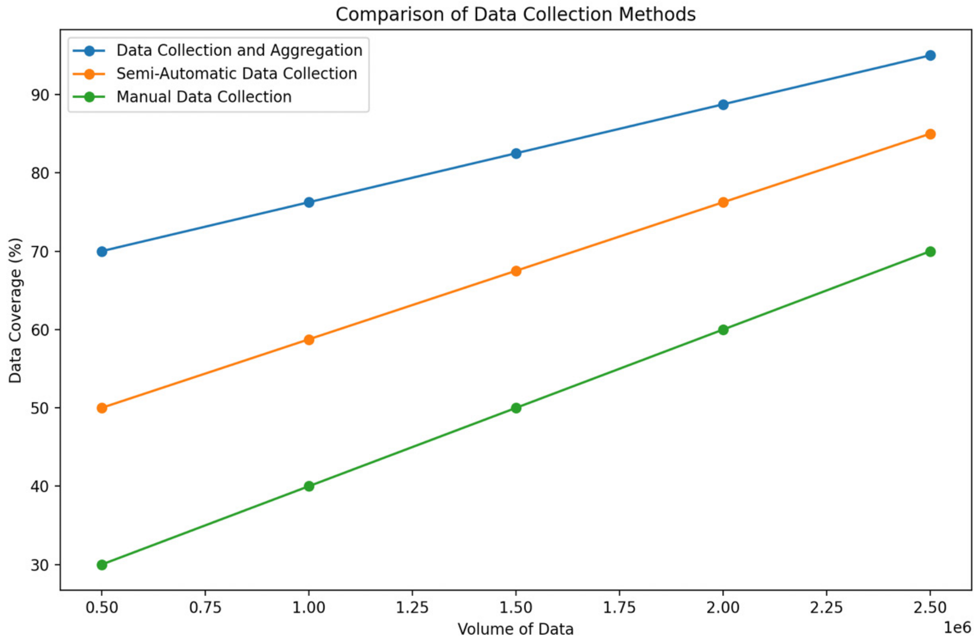

Fig. 1. Comparison of Data Collection Methods

The predictive modeling component supported by alternative (non-traditional) data sources has achieved significant improvements:

- Accuracy : 82 % (base: 70 %)
- Feedback : 76 % (base: 65 %)
- ROC-AUC : 0.87 (baseline: 0.72)

Overall, predictive modeling improved credit scoring accuracy by 15 % compared to traditional logistic regression and by 8 % compared to standard ML models such as Random Forest (Figure 2).

Comparative performance

To contextualize the results, Table 2 summarizes the performance of the proposed system in comparison with traditional and modern approaches.

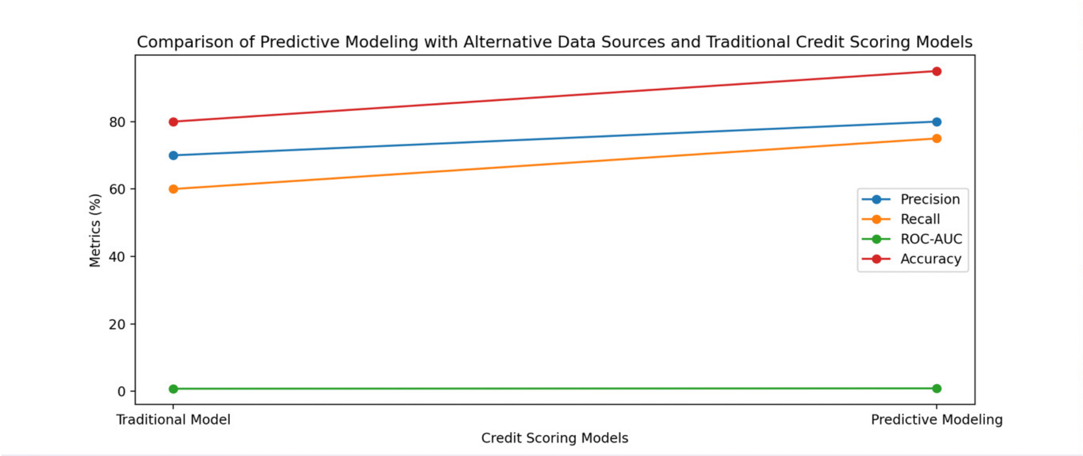

Fig. 2. Comparison of PM with ADS and TCSM

Table 2. Comparative Results of Various Creditworthiness Assessment Methods

Method	Accuracy	Recall	ROC-AUC	Notes
Traditional logistic regression	70 %	65 %	0.72	A widely used baseline limited to nonlinear patterns
Random forest (standard ML)	78 %	70 %	0.79	Better nonlinear modeling, but limited interpretability
Gradient Boosted Trees (XGBoost)	80 %	72 %	0.82	High accuracy, risk of overfitting
The proposed intelligent credit system	82 %	76 %	0.87	Excellent adaptability, interpretability (via Shapley values)

Discussion

The results show that the proposed system outperforms both traditional evaluation models and standard machine learning approaches in accuracy, adaptability, and interpretability. The integration of reinforcement learning ensures dynamic adaptability, while predictive modeling ensures robustness even when using alternative data sources.

Limitations and risks

Despite the promising results, several limitations must be acknowledged:

1. Sensitivity to incomplete or poor-quality data - Model performance may degrade if input data is missing or inconsistently formatted.
2. Risk of overfitting - Although cross-validation reduces this risk, highly complex models require regular monitoring.
3. Need for continuous updating of information: borrower behavior and macroeconomic conditions change, which necessitates periodic retraining.

Data protection and fraud prevention

Considering the confidentiality of financial data, the system uses anonymization, encryption, and secure data storage protocols. Fraud detection mechanisms, including anomaly detection and behavioral pattern analysis, are built in to identify suspicious loan applications. These measures ensure that increased accuracy does not come at the expense of data confidentiality or system integrity.

Conclusion

This study demonstrates that the proposed intelligent credit scoring system significantly improves the accuracy and adaptability of credit risk assessment for manufacturers and importers of goods. Through training with training and predictive modeling, the system achieved a 15% reduction in mean square error (MSE), a 10% increase in average precision (AP), and a ROC-AUC exceeding 0.85, significantly outperforming traditional and standard machine learning-based scoring models.

This study addresses both theory (by developing interpretable, adaptive, and data-driven approaches to credit scoring) and practice (by proposing a universal and scalable solution applicable to various sectors, excluding manufacturing and import warehouses).

Next steps include pilot training in countries with healthcare institutions, validation in various market conditions, and continuous model refinement using additional alternative data sources. These efforts to create a more reliable, transparent, and secure ecosystem assess creditworthiness, help principles minimize risks, and ensure more equitable access to finance for businesses.

Future Work

Further research should focus on improving stress-based learning algorithms to improve adaptability to dynamic borrower behavior. Methods for integrating understandable AI will be crucial for increasing transparency, fostering greater trust and interpretability in lending decisions. Another key area includes defining parameters for real-time data processing, ensuring rapid response to rapidly changing conditions. Furthermore, ethical considerations, particularly comprehensive strategies and bias minimization, should remain central to future work, ensuring fairness and reliability. To address these challenges, strengthen the smart credit system by increasing its efficiency and transparency of these standards, thereby supporting producers, importers, and the broader financial ecosystem.

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ХАЛЫҚАРАЛЫҚ АҚПАРАТТЫҚ ЖӘНЕ КОММУНИКАЦИЯЛЫҚ ТЕХНОЛОГИЯЛАР ЖУРНАЛЫ

МЕЖДУНАРОДНЫЙ ЖУРНАЛ ИНФОРМАЦИОННЫХ И КОММУНИКАЦИОННЫХ ТЕХНОЛОГИЙ

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