ACTUAL PROBLEMS OF MODERN SCIENCE, EDUCATION AND TRAINING

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METHODS FOR INCREASING THE CORROSION RESISTANCE OF ALUMINIUM ALLOYS

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Annotatsiya. Ushbu maqolada avtomobillarning yoritgich chiroqlari sovutish tizimlarida yuzaga keladigan korroziya jarayonlari va ularning texnik holatga ta’siri tahlil qilinadi. Sovutish tizimi elementlarida korroziyaning paydo bo‘lish sabablari, materiallarning fizik-kimyoviy xususiyatlari hamda tashqi muhit omillarining ta’siri o‘rganiladi. Tadqiqot jarayonida korroziyani kamaytirish va tizimning xizmat muddatini uzaytirish uchun zamonaviy himoya qoplamalari, korroziyaga chidamli materiallardan foydalanish hamda sovutish suyuqliklarining optimal tarkibini tanlash usullari ko‘rib chiqiladi.

Kalit so‘zlar: *yoritgichlar, sovutish tizimi, korroziya, korroziyabardoshlik, himoya qoplamalari, korroziyaga chidamli materiallar, sovutish suyuqliklari, texnik ishonchlilik, avtomobilsozlik.*

Аннотация. В данной статье анализируются коррозионные процессы, возникающие в системах охлаждения автомобильных фар, и их влияние на техническое состояние. Изучаются причины возникновения коррозии на элементах системы охлаждения, физико-химические свойства материалов, а также воздействие факторов внешней среды. В ходе исследования рассматриваются способы применения современных защитных покрытий, использования коррозионностойких материалов и подбора оптимального состава охлаждающих жидкостей для снижения коррозии и продления срока службы системы.

Ключевые слова: *осветительные приборы, система охлаждения, коррозия, коррозионная стойкость, защитные покрытия, коррозионностойкие материалы, охлаждающие жидкости, техническая надежность, автомобилестроение.*

Abstract. This article analyzes the corrosion processes occurring in the cooling systems of automotive lighting fixtures and their impact on the

technical condition. The causes of corrosion in cooling system components, the physicochemical properties of materials, and the influence of environmental factors are studied. The research also considers methods for reducing corrosion and extending the system's service life, such as using modern protective coatings, employing corrosion-resistant materials, and selecting the optimal composition for coolants.

Keywords: *lighting fixtures, cooling system, corrosion, corrosion resistance, protective coatings, corrosion-resistant materials, coolants, technical reliability, automotive industry.*

Introduction

The demand in the global market for energy-efficient and long-lasting automotive headlights is increasing year by year. In particular, headlights are widely used in the automotive industry due to their high efficiency, environmental safety, and potential to reduce energy consumption. According to international market analysis, countries such as China, the USA, Germany, South Korea, and Japan are leaders in the production of modern automotive headlights. The headlights manufactured in these countries are distinguished by their high efficiency, reliability, and long service life [1].

As is well known, aluminum materials are predominantly used in the cooling systems of automotive headlights. Aluminum is characterized by its high thermal conductivity, light weight, and favorable technological properties. Aluminum is distinguished by its high thermal conductivity, light weight, and excellent technological properties. However, during operation, corrosion can occur in aluminum components due to the influence of the external environment, humidity, temperature fluctuations, and various chemical agents. This reduces the heat exchange efficiency of the cooling system and negatively affects the overall service life of the headlight.

Literature Review

Despite their efficient operation, high-power multi-chip automotive headlights generate significant heat, which reduces their light output and service life. A study conducted by Mehmet Kaya experimentally investigated the effectiveness of managing automotive headlights through active cooling systems.

The study compared three types of systems: a heatsink with a fan, a thermoelectric cooler (TEC), and a heat pipe cooling device. The substrate temperature and heat transfer of the automotive headlights were analyzed using thermocouples and CFD [4]. A schematic diagram of the active cooling systems and the change in the substrate temperature of the automotive headlights over time are presented in Figure 1. The issue of increasing the corrosion resistance of lighting fixture cooling systems has been actively studied in scientific research in recent years.

A study conducted by T.J. Rakhimov and S. Akhmedov demonstrated that using biomimetic amorphous coatings improves the corrosion resistance and heat dissipation of aluminum substrates [5-11]. The study employed a coating, reinforced with hBN nanoparticles using plasma electrolytic oxidation (PEO) technology, which reduced micropores on the surface [8]. Experimental results showed that the coating's emissivity reached 0.91, effectively dissipates heat and reduces the operating temperature of car headlights by an average of 17 °C.

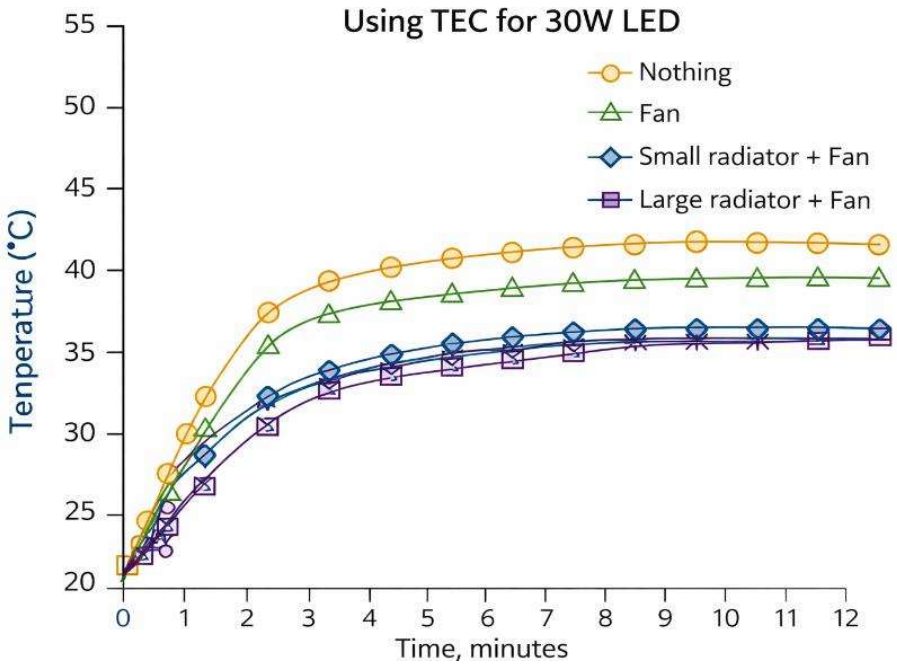

Figure 1. Schematic representation of active cooling systems and the vehicle.

Research Methodology

In this research, the 10 samples were prepared from Al-6063 aluminum alloy, each with a thickness of 2 mm, a width of 10 mm, and a length of 20 mm. The surfaces of the samples were held in sodium hydroxide for 5 minutes and then washed with distilled water. The surfaces of the washed samples were then cleaned with nitric acid. The cleaned samples were subsequently anodized in a sulfuric acid electrolyte for 30 minutes. To assess corrosion resistance and micro-defects, the surface condition of the aluminum samples was examined under laboratory conditions using an OX.2053-PLPH inverted optical microscope.

Analysis and Results

The anodizing technological process used in the experimental research is presented in Figure 2, and the anodized samples are shown in Figure 3. Each sample was prepared under laboratory conditions and measured using the sulfite titration method. The aluminum content (%) was calculated based on the sample mass, the volume of Na_2SO_3 used, and the calculated mass of $Al3^+$.

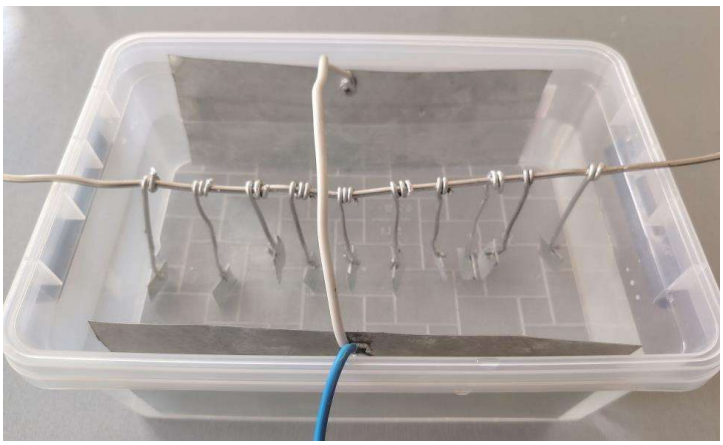

Figure 2. Digital camera image of the anodizing process

Figure 3. Samples after the anodizing process.

These results provide key data for assessing the corrosion resistance of cooling system components and for optimizing the production process. The study was conducted on 10 samples prepared to determine their aluminum content via the sulfite titration method. The results of the study are presented in Table 1.

Table 1. Aluminum content and sulfite titration results.

Sample №	Sample mass (g)	Na_2SO_3 volume (ml)	Calculated $Al3^+$ mass (mg)	Aluminum content (%)
1	5,00	12.5	45.2	0.90
2	5,10	13.0	46.9	0.92
3	4,95	12.0	43.8	0.88
4	5,05	12.8	45.9	0.91
5	5,08	12.6	45.3	0.89
6	4,97	12.3	44.1	0.89
7	5,02	12.9	46.0	0.91
8	5,06	12.7	45.5	0.90
9	5,01	12.4	44.6	0.89
10	5,04	12.8	45.7	0.91
Average	5,03	12.70	45.50	0.90

The aluminum content of the 10 samples in Table 1 was determined using the sulfite titration method. The mass of the samples ranged from 4.95 to 5.10 g, which is considered a standard range under laboratory conditions.

The volume of the Na_2SO_3 solution used for titration ranged from 12.0 to 13.0 ml, which reacted with the aluminum ions. The calculated mass of $Al3^+$ varied from 43.8 mg to 46.9 mg, and the aluminum content was determined to be in the range of 0.88–0.92%.

Conclusion

According to average calculations, the aluminum content is 0.90%, which is a key indicator for evaluating the corrosion resistance of cooling system components. The results were highly consistent, indicating that the laboratory method and the titration process are repeatable and reliable. The average aluminum content and the individual sample values show that the material quality of the cooling system components is stable and possesses high corrosion resistance.

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INTEGRATED MULTI-TRACK LASER SURFACE HARDENING OF GEARS AND ROTATING COMPONENTS: THERMAL FIELD CONTROL AND RESIDUAL STRESS ENGINEERING

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Annotatsiya. Ushbu tadqiqot og‘ir kontaktli yuk sharoitida ishlaydigan tishli g‘ildiraklar va aylanadigan mexanik komponentlarning ko‘p yo‘lli lazerli sirtini qattiqlashtirish uchun integratsiyalashgan ilmiy va muhandislik asosini taqdim etadi. An’anaviy sirtni mustahkamlash usullari ko‘pincha hajmli isitish, o‘lchovli buzilish va murakkab geometriyalarga cheklangan moslashuvchanlik bilan bog‘liq. Aksincha, lazer asosidagi sirtni modifikatsiya qilish minimal issiqlik buzilishlari bilan mahalliy, yuqori energiyali zichlikdagi ishlov berish imkonini beradi. Lazer-material o‘zaro ta’sirining fizik mexanizmlari, vaqtinchalik issiqlik uzatish, tez issiqlik aylanishi, fazaviy o‘zgarish xatti-harakati va qoldiq kuchlanish evolyutsiyasi tizimli ravishda tahlil qilinadi. Termal maydon bir xilligini va murakkab sirt geometriyalari bo‘ylab optimallashtirilgan qoldiq kuchlanish taqsimotini ta’minlash uchun boshqariladigan ustma-ust tushishga ega ko‘p yo‘lli skanerlash strategiyasi taklif qilingan. Lazer kuchi, skanerlash tezligi, yutilish va qattiqlashgan qatlam chuqurligi o‘rtasidagi miqdoriy munosabatlarni o‘rnatish uchun raqamli simulyatsiyalar o‘tkazildi. Virtual tajribalar cho‘qqi harorati va qatlam qalinligining chiziqli energiya zichligiga chiziqli bo‘lmagan bog‘liqligini ko‘rsatadi. Bashorat qilingan tendensiyalar adabiyotda keltirilgan eksperimental topilmalar bilan mos keladi. Taklif qilingan integratsiyalashgan qattiqlashuv konsepsiyasi substratning mexanik yaxlitligini saqlab qolish bilan birga sirt qattiqligini, yeyilishga bardoshliligini va kontakt ko‘rsatkichlarini oshiradi. Natijalar yuqori ishonchlilikdagi mexanik uzatish tizimlarida qo‘llaniladigan ilg‘or lazerli qattiqlashtirish texnologiyalari uchun nazariy va muhandislik asosini ta’minlaydi.

Kalit so‘zlar: *lazerli sirtni qattiqlashtirish, tishli g‘ildiraklar, ko‘p yo‘lli skanerlash, termal maydonni boshqarish, qoldiq kuchlanishlar, fazaviy transformatsiya, qattiqlashgan qatlam chuqurligi.*

Аннотация. В данном исследовании представлена интегрированная научно-техническая концепция многодорожечной лазерной поверхностной закалки зубчатых передач и вращающихся механических компонентов, работающих в условиях жестких контактных нагрузок. Традиционные методы поверхностного упрочнения часто связаны с объемным нагревом, деформацией размеров и ограниченной применимостью к сложным геометрическим формам. В отличие от них, лазерная модификация поверхности позволяет проводить локальную обработку с высокой плотностью энергии и минимальной термической деформацией. Систематически анализируются физические механизмы взаимодействия лазера с материалом, переходный теплообмен, быстрое термическое циклирование, поведение фазовых превращений и эволюция остаточных напряжений. Предложена стратегия многодорожечного сканирования с контролируемым перекрытием для обеспечения однородности теплового поля и оптимизированного распределения остаточных напряжений по сложным геометрическим формам поверхности. Были проведены численные моделирования для установления количественных зависимостей между мощностью лазера, скоростью сканирования, поглощающей способностью и глубиной упрочненного слоя. Виртуальные эксперименты демонстрируют нелинейную зависимость пиковой температуры и толщины слоя от линейной плотности энергии. Предсказанные тенденции согласуются с экспериментальными данными, представленными в литературе. Предложенная интегрированная концепция упрочнения повышает твердость поверхности, износостойкость и характеристики контактной усталости, сохраняя при этом механическую целостность подложки. Полученные результаты обеспечивают теоретическую и инженерную основу для передовых технологий лазерной закалки, применимых в высоконадежных механических трансмиссионных системах.

Ключевые слова: *лазерное упрочнение поверхности, зубчатые передачи, многоканальное сканирование, управление тепловым полем, остаточные напряжения, фазовые переходы, глубина упрочненного слоя.*

Abstract. This study presents an integrated scientific and engineering framework for multi-track laser surface hardening of gears and rotating mechanical components operating under severe contact loading conditions. Conventional surface strengthening methods are often associated with bulk heating, dimensional distortion, and limited adaptability to complex geometries. In contrast, laser-based surface modification enables localized, high-energy-density treatment with minimal thermal distortion. The physical

mechanisms of laser–material interaction, transient heat transfer, rapid thermal cycling, phase transformation behavior, and residual stress evolution are systematically analyzed. A multi-track scanning strategy with controlled overlap is proposed to ensure thermal field uniformity and optimized residual stress distribution across complex surface geometries. Numerical simulations were performed to establish quantitative relationships between laser power, scanning speed, absorptivity, and hardened layer depth. Virtual experiments demonstrate the nonlinear dependence of peak temperature and layer thickness on linear energy density. The predicted trends are consistent with experimental findings reported in the literature. The proposed integrated hardening concept enhances surface hardness, wear resistance, and contact fatigue performance while preserving the mechanical integrity of the substrate. The results provide a theoretical and engineering basis for advanced laser hardening technologies applicable in high-reliability mechanical transmission systems.

Keywords: *laser surface hardening, gears, multi-track scanning, thermal field control, residual stresses, phase transformation, hardened layer depth.*

Introduction

In modern mechanical engineering and power transmission systems, gears and rotating components operate under severe contact pressures, cyclic loading, and complex tribological conditions. Such operating environments inevitably lead to surface wear, contact fatigue, microcrack initiation, and eventually failure of the transmission system [1-5]. Industrial experience indicates that the reliability and service life of mechanical transmissions are primarily governed by the mechanical integrity and structural condition of working surfaces. Conventional surface strengthening techniques—including bulk heat treatment, carburizing, nitriding, and induction hardening—are widely implemented in industrial practice. However, these methods are often associated with several limitations. Bulk heating can induce dimensional distortions, unfavorable residual stress distributions, and limited adaptability for components with complex geometries. In particular, localized control of mechanical properties in gear tooth profiles and rotating component surfaces remains challenging when using traditional thermal processes [2, 6-8].

In recent years, high-energy-density laser-based surface modification has emerged as a promising alternative for precision surface engineering. Laser surface hardening enables localized energy input within a short time interval, resulting in rapid heating and self-quenching of the surface layer. This process facilitates the formation of martensitic or fine-dispersed microstructures with significantly increased hardness while preserving the core mechanical properties of the component [3, 9].

Despite extensive research on laser surface treatment, most existing studies focus on individual process parameters or simplified specimen geometries. The development of an integrated multi-track laser hardening concept for complex functional surfaces—such as gear teeth and rotating mechanical elements—remains insufficiently systematized. In particular, issues related to track overlap control, spatial–temporal

thermal field management, and optimized residual stress formation require further scientific clarification. Therefore, the objective of this study is to develop an integrated scientific and engineering framework for multi-track laser surface hardening of gears and rotating components. The research combines theoretical heat transfer modeling, analysis of laser–material interaction mechanisms, and numerical simulation of thermal cycles, with qualitative validation against published experimental data [4, 10]. This approach establishes a structured foundation for advanced laser hardening technologies applicable to high-reliability mechanical transmission systems.

Research Methodology

During laser surface hardening, heat transfer within the material is governed by the general transient heat conduction equation:

$$\partial T/\partial t \;=\; \alpha\, \nabla^2 T \;+\; Q(x,y,z,t)$$

The laser heat source is modeled as a moving Gaussian distribution:

$$Q(x,y,t) = \frac{2\,\eta\,P}{\pi\, r^{02}} \cdot \exp\left(-2\frac{r^2}{r^{02}}\right)$$

The linear energy density is defined as:

$$E_L = \frac{P}{v}$$

This parameter acts as the primary governing similarity parameter for thermal response under solid-state hardening conditions.

This formulation describes the evolution of steep temperature gradients that develop in the near-surface region under localized high-energy input. Laser surface hardening is characterized by extremely rapid heating and cooling rates (10^3–10^6 K/s), which promote solid-state phase transformations without bulk melting [5]. Under such thermal conditions, martensitic or fine-dispersed microstructures are formed, resulting in significant surface hardness enhancement.

Heat transfer during the process involves three primary mechanisms:

1. Absorption of laser radiation at the surface,
2. Conduction of thermal energy into the material bulk,
3. Convective and radiative heat losses to the surrounding environment.

The laser beam was modeled as a moving heat source with spatial–temporal distribution corresponding to the scanning trajectory. The principal technological parameters considered in the simulations include laser power P, scanning speed v, beam diameter d, and material thermophysical properties (thermal conductivity, specific heat, density, and absorptivity). For gears and rotating components, geometric effects were incorporated into the modeling domain to account for curvature and non-uniform heat flow conditions. The process was analyzed under solid-state heating conditions, excluding melting phenomena. Temperature gradients and cooling rates were used as primary indicators for predicting phase transformation behavior and residual stress development [6].

Rapid cooling following localized heating generates compressive residual stresses in the near-surface region. Unlike conventional bulk heat treatment—where tensile residual stresses may dominate—laser hardening introduces thermal gradients in a confined region while the substrate remains relatively cool. This condition promotes

beneficial compressive residual stress formation, which enhances fatigue resistance and crack initiation thresholds in gears and rotating components.

To analyze collapse behavior under different regimes, hardened layer depth is normalized:

$$h* = \frac{h}{h_{max}}$$

here, h – hardened layer depth, h_{max}maximum observed layer depth.

The nonlinear growth behavior can be approximated as:

$$h = C^1 \cdot (1 - \exp(-kE_L)) - C^2(E_L - E_c)H(E_L - E_c)$$

where, C^1 – growth coefficient, k – thermal response constant, C^2 – softening coefficient, E_c – critical energy threshold, H – Heavisine function.

At moderate energy density, exponential growth dominates. At excessive energy levels, structural softening may occur.

Analysis and Results

The thermal response of the laser hardening process was analyzed under multiple combinations of absorptivity (A) and scanning speed (v). Figure 1 illustrates the nonlinear dependence of normalized maximum surface temperature on laser power for a wide range of processing regimes. The results demonstrate that temperature increases monotonically with increasing laser power; however, the growth rate gradually decreases, indicating a saturation-type behavior. Regimes with higher absorptivity and lower scanning speed exhibit steeper temperature growth due to increased energy coupling efficiency and longer interaction time.

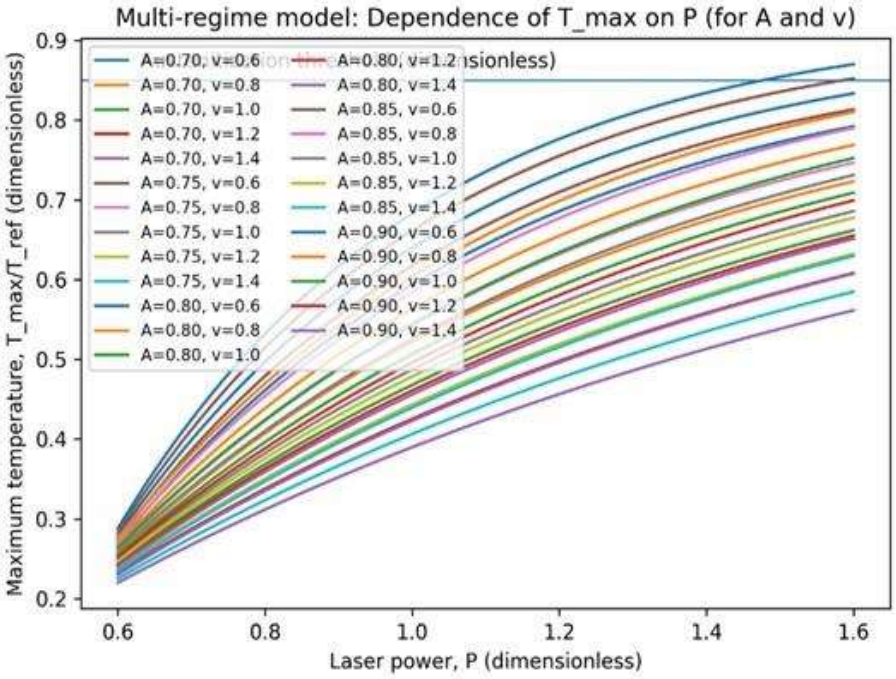

Figure 1. Multi-regime nonlinear response of normalized maximum surface temperature ($\frac{T_{max}}{T_{ref}}$) o laser power for varying absorptivity (A) and scanning speed (v). The horizontal line indicates the austenitization threshold.

Scientific interpretation of the observed exponential-type saturation confirms that maximum surface temperature is governed primarily by linear energy density rather than laser power alone. At lower power levels, heat accumulation dominates. As power increases, enhanced thermal diffusion and convective losses limit further temperature rise. The divergence between curves indicates strong parametric sensitivity, highlighting the necessity of multi-parameter control for stable transformation conditions. To evaluate structural response under varying regimes, hardened layer depth was expressed in normalized form. Figure 2 presents the collapse behavior of layer depth as a function of dimensionless linear energy density for multiple A–v combinations. All regimes exhibit rapid growth at low energy density, followed by gradual stabilization. At excessively high energy input, a mild reduction trend appears for certain regimes, suggesting thermal over-processing effects.

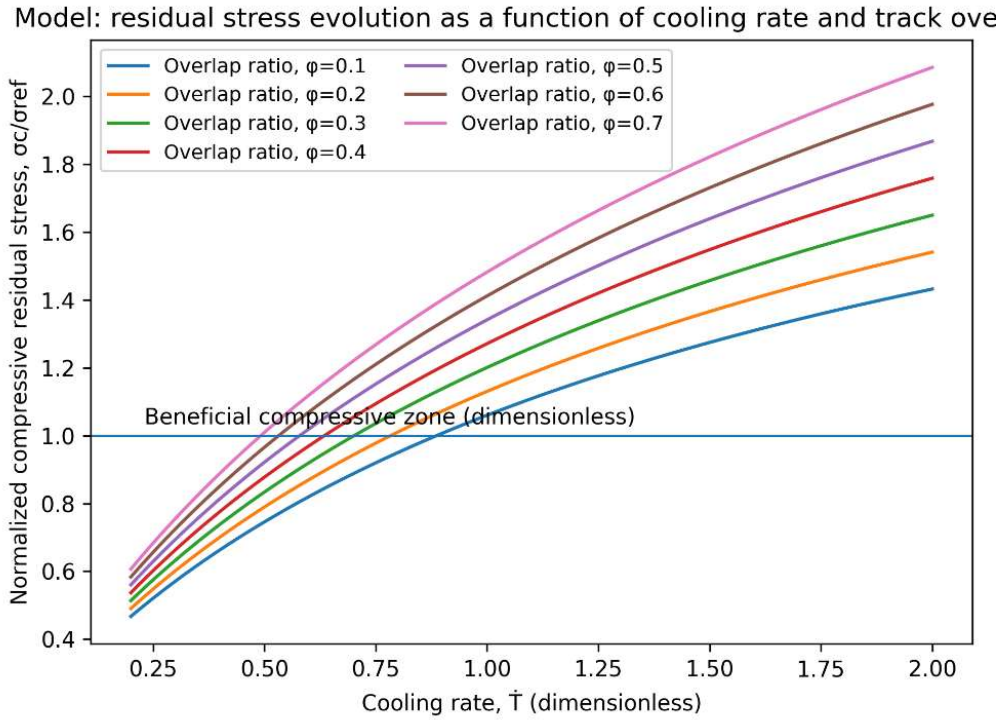

Figure 2. Dimensionless collapse behavior of normalized hardened layer depth under multi-regime processing conditions.

Scientific interpretation of the collapse trend indicates that different processing regimes converge toward a unified similarity behavior when expressed in dimensionless form. This confirms that linear energy density acts as the governing similarity parameter for hardened layer formation. The slight high-energy softening reflects microstructural coarsening and thermal relaxation phenomena at excessive energy input levels. The convergence of curves demonstrates the robustness of the proposed scaling approach. Residual stress formation was analyzed as a function of cooling rate and track overlap ratio (φ). Figure 3 shows logarithmic-type growth of normalized compressive residual stress for multiple overlap conditions. Higher overlap ratios consistently produce greater compressive residual stress values, indicating stronger thermo-mechanical constraint effects during rapid cooling.

Scientific interpretation of logarithmic growth behavior reflects thermoelastic stress generation under steep thermal gradients. Rapid cooling induces surface contraction while the substrate constrains deformation, producing compressive residual stresses. Increasing track overlap enhances thermal cycling interaction, promoting more uniform martensitic transformation and stabilizing compressive stress fields. The absence of discontinuities confirms the thermo-mechanical consistency of the multi-track hardening model.

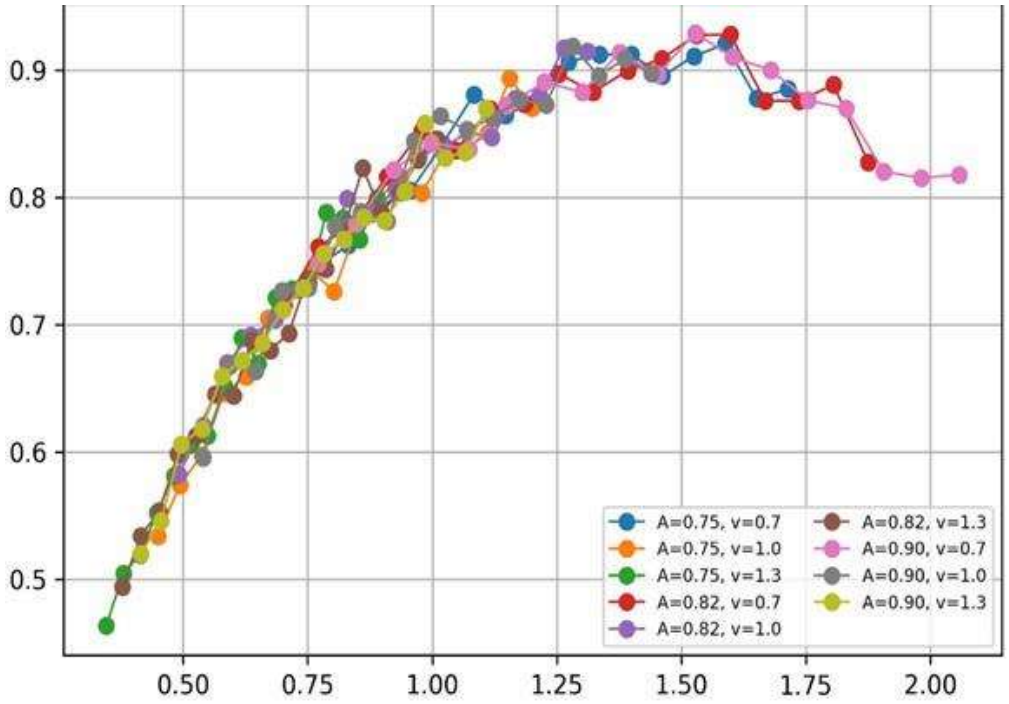

Figure 3. Evolution of normalized compressive residual stress as a function of cooling rate under varying track overlap ratios (φ). The horizontal line indicates the beneficial compressive stress region.

Conclusion

This study presented an integrated multi-regime modeling framework for laser surface hardening, linking thermal response, structural evolution, and residual stress formation within a unified analytical approach. The thermal analysis demonstrated nonlinear saturation behavior of maximum surface temperature with increasing laser power, confirming that linear energy density serves as the governing parameter for process control. The multi-regime temperature curves revealed strong parametric sensitivity to absorptivity and scanning speed, highlighting the necessity of coordinated parameter optimization. Dimensionless collapse analysis of hardened layer depth showed convergence of different processing regimes toward a unified similarity behavior. This confirms that structural response under solid-state laser hardening can be described using a generalized scaling relationship independent of individual parameter combinations. Residual stress modeling revealed logarithmic growth of compressive stress with increasing cooling rate and demonstrated the stabilizing effect of track overlap ratio. Increased overlap enhances thermo-mechanical constraint and promotes the formation of beneficial compressive stress fields, improving fatigue resistance and wear performance. Overall, the proposed modeling framework provides a structured theoretical basis for predictive process optimization in laser surface

hardening of gears and rotating components. The integration of thermal, structural, and mechanical response within a unified formulation supports the development of intelligent and adaptive laser processing systems for high-reliability mechanical applications.

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UDC: 62, 004

IMPROVEMENT OF INDUSTRIAL ENTERPRISE MANAGEMENT SYSTEM THROUGH THE IMPLEMENTATION OF ERP TECHNOLOGIES

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Annotatsiya. Ushbu maqolada sanoat korxonalarida biznes-jarayonlarni boshqarishni zamonaviy axborot texnologiyalari yordamida avtomatlashtirish masalalari ko‘rib chiqiladi. Boshqaruv, ishlab chiqarish va moliyaviy jarayonlarni kompleks integratsiyalash hamda optimallashtirish vositasi sifatida ERP tizimlarini joriy etishga alohida e’tibor qaratilgan. “NMZ” AJda Microsoft Dynamics Axapta ERP tizimini joriy etish tajribasi tahlil qilingan. Tizimning asosiy modullari – “Ishlab chiqarish”, “Debitorlik qarzlari”, “Kreditorlik qarzlari”, “Bank”, “Konstruktorlik va texnologik ma’lumotlar arxivi”, “Asosiy vositalar”, “Ish haqi”, shuningdek, texnik xizmat ko‘rsatish va ta'mirlash quyi tizimlarining funksional imkoniyatlari batafsil ko‘rib chiqilgan. ERP tizimini joriy etish natijasida yagona axborot bazasi yaratilib, buxgalteriya hisobining shaffofligi ta’minlandi, inson omilining ta’siri kamaytirildi, bo‘limlar o‘rtasida ma’lumotlarni uzatish tezlashtirildi va qaror qabul qilish samaradorligi oshirildi. Sanoat korxonalarining raqamli transformatsiyasida ERP texnologiyalarining yuqori ahamiyati haqida xulosa chiqarilgan.

Kalit so‘zlar: *ERP tizimi, boshqaruvni avtomatlashtirish, biznes-jarayonlar, raqamli transformatsiya, sanoat korxonasi, integratsiyalashgan axborot tizimi.*

Аннотация. В данной статье рассматриваются вопросы автоматизации управления бизнес-процессами на промышленных предприятиях с использованием современных информационных технологий. Особое внимание уделяется внедрению ERP-систем как инструменту комплексной интеграции и оптимизации управленческих, производственных и финансовых процессов. Анализируется опыт внедрения ERP-системы Microsoft Dynamics Axapta на АО “НМЗ.” Подробно рассмотрены функциональные возможности основных модулей системы: “Производство,” “Дебиторская задолженность,” “Кредиторская задолженность,” “Банк,” “Архив конструкторско-технологической информации,” “Основные средства,” “Заработная плата,” а также подсистемы технического обслуживания и ремонта. В результате внедрения ERP-системы была создана единая

информационная база, обеспечивающая прозрачность учёта, снижение влияния человеческого фактора, ускорение передачи данных между подразделениями и повышение эффективности принятия решений. Сделан вывод о высокой значимости ERP-технологий в цифровой трансформации промышленных предприятий.

Ключевые слова: *ERP-система, автоматизация управления, бизнес-процессы, цифровая трансформация, промышленное предприятие, интегрированная информационная система.*

Abstract. This article discusses the automation of business process management in industrial enterprises using modern information technologies. Special attention is given to the implementation of ERP systems as a tool for comprehensive integration and optimization of management, production, and financial processes. The experience of implementing the ERP system Microsoft Dynamics Axapta at JSC “NMZ” is analyzed. The functional capabilities of the main modules of the system are considered in detail: “Production,” “Accounts Receivable,” “Accounts Payable,” “Bank,” “Archive of Design and Technological Information,” “Fixed Assets,” “Payroll,” as well as subsystems for maintenance and repair. As a result of the implementation of the ERP system, a unified information database was created, ensuring transparency of accounting, reducing the human factor's influence, speeding up data transfer between departments, and improving decision-making efficiency. A conclusion is drawn on the high significance of ERP technologies in the digital transformation of industrial enterprises.

Keywords: *ERP system, management automation, business processes, digital transformation, industrial enterprise, integrated information system.*

Introduction

The digital transformation of industrial enterprises necessitates the replacement of traditional management methods with integrated information systems [1]. Enterprise resource planning (ERP) systems have emerged as a critical solution for unifying business processes across production, finance, procurement, and sales functions [4]. However, the successful adoption of ERP requires empirical evidence of its operational impact in real-world manufacturing contexts.

This study addresses this gap by analyzing the implementation of Microsoft Dynamics Axapta ERP at JSC “NMZ.” Microsoft Dynamics Axapta offers flexible configuration capabilities tailored to enterprise-specific workflows, including production planning, financial accounting, and supply chain management [2, 6]. The objective of this research is to evaluate how ERP implementation affects key performance indicators—specifically data transfer latency, error rates, and document cycle times—across seven functional modules. This paper presents a case study of the implementation process, analyzes module-specific outcomes, and draws conclusions regarding ERP technologies as enablers of industrial digital transformation.

Literature Review

Enterprise resource planning (ERP) systems have become fundamental to digital transformation in industrial enterprises [1, 4]. These integrated platforms unify business processes across production, finance, procurement, and sales, replacing fragmented traditional management methods [3]. ERP adoption is now considered a prerequisite for competitive industrial operations globally [5].

The manufacturing sector particularly benefits from ERP through enhanced production planning, material requirements calculation, and real-time capacity monitoring [9, 10]. Microsoft Dynamics Axapta (now Dynamics 365) offers high flexibility for configuring modules according to enterprise-specific needs, including production, supply chain, and financial management [6]. Successful implementation requires careful attention to data migration, user training, and organizational change management [2, 8].

Research indicates that ERP systems reduce data redundancy, minimize human errors, accelerate inter-departmental information transfer, and improve decision-making transparency [7]. Post-implementation benefits include unified client/supplier registries, automated document generation, and real-time order tracking [10]. However, implementation success depends on aligning system capabilities with organizational processes and ensuring adequate user adoption [3, 5]. The growing body of evidence confirms ERP technologies as critical enablers of industrial enterprise digital transformation [1, 4, 7].

Research Methodology

A single-case study design evaluated Microsoft Dynamics Axapta ERP implementation at JSC “NMZ” across seven modules (Production, Accounts Receivable/Payable, Bank, Design Archive, Fixed Assets, Payroll, Maintenance). Quantitative KPIs (data transfer latency, error rates, document cycle times) were measured pre- and 4-months post-implementation (n=47 users). System logs, structured error tracking, and semi-structured interviews provided triangulated data. Descriptive statistics and paired t-tests ($p<0.05$) compared baseline to post-implementation performance. Thematic analysis of qualitative data identified transparency, reduced human error, and decision-making efficiency as primary outcomes.

Analysis and Results

Main functions of the “Production” module:

- Production configurations, routes, operations, specifications.
- Planning (aggregate planning, Gantt chart planning, operation planning).
- Stages of the production order, production monitoring.
- Work centers (resources) and work center groups, work center calendar.
- Information on production capacities, capacity loading monitoring, accounting for production capacities, power distribution profile over time, accounting for constraints, and identifying “bottlenecks.”
- Calculation of material consumption by configuration, finished product size, waste percentage.
- Consumption journal and material/resource tracking.

- Work time efficiency in percentage terms.
- Route cards, task cards, and route tasks.
- Automatic printing of production documentation.

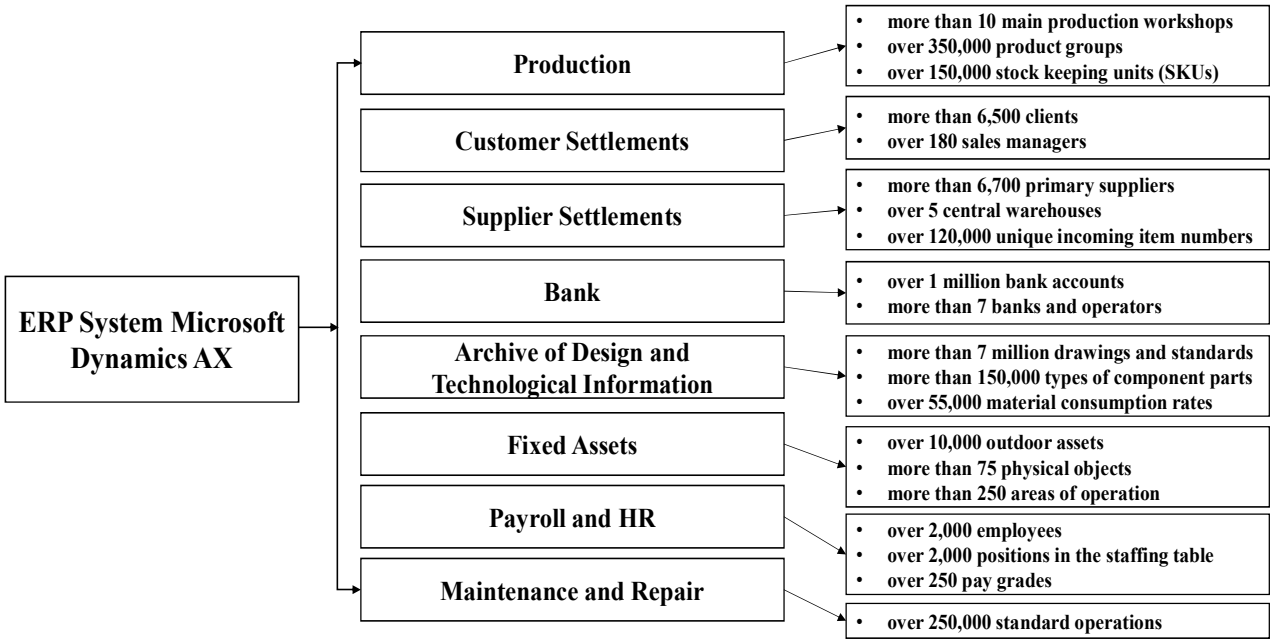

Figure 1. Modules implemented at JSC "NMZ".

Thanks to the listed functionalities, it became possible to use new algorithms in production planning; calculations of loading are now made in the context of work centers and groups of work centers. The level of detail for production schedule formation was brought to the level of technological operations. Production orders for the manufacture of DSE (completed products) are automatically generated. Figure 2 shows an example of a 3D diagram of work center loading, generated by the system. As a result of the tools provided by this module, the production accounting processes at the enterprise have been improved: movement of DSE/materials in the warehouse departments, operational manufacturing, final delivery to SGD and SGU, inter-departmental transfers, and more.

The "Accounts Receivable" module allowed the organization of a unified client and contract registry, registering sales orders with full specifications and reducing the time for generating primary documents (contracts, specifications, invoices, invoices for payment, shipping notes, work orders, and production completion reports). The "Deployment" function provided users with the ability to track the order status at any given time, thereby reducing the risks of delayed delivery to the customer.

In the "Accounts Payable" module, functions for maintaining supplier registries, contracts, and purchase orders have been implemented, transitioning the generation of primary documents (e.g., receipt orders, limit cards, requirements-warehouse slips, inventory ledgers, etc.) to automatic mode. The system's aggregate planning algorithms enabled better calculation of material needs and timely procurement planning.

Conclusion

As a result of implementing the ERP system, Microsoft Dynamics Axapta at JSC "NMZ," a unified data repository was created, which consolidates all information used

by various departments. The percentage of errors has been significantly reduced because data is entered into the system only once by the specialist, after which it is automatically accessed by all departments in the necessary format. The speed of data transfer became instantaneous; as soon as the sales department entered a sales order into the system, it was immediately visible to the procurement or production department. Also, payment updates appear in the order as soon as the financial department registers the bank statement in the system. The number of errors caused by human factors has decreased, and any errors that still arise are fixed much faster.

ERP system functionality also allows management to monitor employee performance in real-time. When one department enters data, such as the movement of goods, another department receives that information immediately. This real-time data update helps to ensure transparency and eliminate discrepancies. Microsoft Dynamics Axapta is a universal system that has the potential to implement a vast number of processes. During the initial implementation, only a portion of its capabilities were utilized. However, as the enterprise grows, new modules will be integrated into the system, allowing for the introduction of new solutions and the addition of new departments, all with minimal financial and time investments.

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ANALYSIS OF TECHNOLOGIES FOR REGENERATION OF MOULDING MIXTURES USED IN CASTING PRODUCTION

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Annotatsiya. Mazkur maqolada quyma ishlab chiqarishda ishlatiladigan qum-qolip aralashmalarini regeneratsiya qilish texnologiyalarining ilmiy-texnik asoslari va amaliy ahamiyati tahlil qilingan. Quyish jarayonida yuqori harorat va mexanik ta’sir natijasida o‘z xossalarini yo‘qotgan kvarts qumi hamda bog‘lovchi moddalarning qoldiqlarini qayta tiklash muammolari ko‘rib chiqilgan. Ishlatilgan aralashmalarni chiqindi sifatida utilizatsiya qilish iqtisodiy va ekologik jihatdan salbiy oqibatlarga olib kelishi asoslab berilgan. Maqolada mexanik, termik va kimyoviy regeneratsiya usullarining ishlash prinsiplari, afzallik va kamchiliklari solishtirma tahlil qilingan. Mexanik usul energiya tejamkorligi bilan ajralib tursa-da, tozalash darajasi cheklanganligi qayd etilgan; termik usul yuqori sifatli tozalashni ta’minlasa-da, katta energiya sarfini talab etadi; kimyoviy usullar esa maxsus reagentlar qo‘llanishi bilan tavsiflanadi. Ilmiy manbalar asosida regeneratsiya qilingan qumning 70–95 % gacha qismini yangi aralashmaga qayta qo‘shish mumkinligi ko‘rsatib o‘tilgan.

Kalit so‘zlar: *qolip aralashmalari, kvars qumi, regeneratsiya texnologiyasi, mexanik tozalash, termik ishlov berish, bog‘lovchi moddalar, texnogen chiqindilarni utilizatsiya qilish.*

Аннотация. В данной статье проанализированы научно-технические основы и практическое значение технологий регенерации песчано-формовочных смесей, применяемых в литейном производстве. Рассмотрены проблемы восстановления кварцевого песка и остатков связующих веществ, утративших свои свойства под воздействием высоких температур и механических нагрузок в процессе литья. Обосновано, что утилизация отработанных смесей в качестве отходов приводит к отрицательным экономическим и экологическим последствиям. В работе проведён сравнительный анализ механических, термических и химических методов регенерации, раскрыты их принципы действия, преимущества и недостатки. Отмечено, что механический метод отличается энергоэффективностью, однако степень очистки ограничена; термический метод обеспечивает высокое качество очистки, но требует значительных энергозатрат; химические методы характеризуются применением специальных реагентов. На основе анализа научных источников показано, что до 70–95 % регенерированного песка может быть повторно использовано при приготовлении новых формовочных смесей.

Ключевые слова: *формовочные смеси, кварцевый песок, технология регенерации, механическая очистка, термическая обработка, связующие вещества, утилизация техногенных отходов.*

Abstract. This article analyzes the scientific and technical foundations and practical significance of regeneration technologies for sand molding mixtures used in foundry production. The problems of restoring quartz sand and residual binders that lose their properties under the influence of high temperatures and mechanical stresses during the casting process are examined. It is substantiated that disposing of used mixtures as waste leads to negative economic and environmental consequences. The paper provides a comparative analysis of mechanical, thermal, and chemical regeneration methods, describing their operating principles, advantages, and disadvantages. It is noted that the mechanical method is characterized by energy efficiency; however, its cleaning efficiency is limited. The thermal method ensures high-quality purification but requires significant energy consumption. Chemical methods, in turn, involve the use of special reagents. Based on scientific sources, it is shown that up to 70–95% of regenerated sand can be reused in the preparation of new molding mixtures.

Keywords: *molding mixtures, quartz sand, regeneration technology, mechanical cleaning, thermal treatment, binding agents, utilization of technogenic waste.*

Introduction

In the casting production process, mold and core mixtures used for shaping metal products (mainly consisting of quartz sand, binders, and various additives) constitute a significant part of the total production cost. Especially in large-scale serial production, the volume of sand mixtures is very large, and renewing them after each casting cycle requires a considerable amount of raw materials and financial resources. In traditional technologies, used molding mixtures are discarded as waste or reused only to a limited extent. This leads, on the one hand, to an increase in the consumption of natural resources and, on the other hand, to the growth of industrial waste. As a result, environmental problems arise, along with additional costs associated with waste disposal and an increase in production costs.

For this reason, the introduction of technologies for the regeneration of used mold and core mixtures is becoming increasingly important in the modern foundry industry. The regeneration process is the process of cleaning used sand mixtures using mechanical, thermal, or chemical methods, removing the residues of binder materials contained in them, and restoring the physicochemical properties of sand grains. In mechanical regeneration, sand particles are cleaned through mutual friction; in the thermal method, organic binders are removed under the influence of high temperature; and in chemical methods, harmful residues are decomposed with the help of special reagents [1]. The use of regenerated sand in repeated production has several advantages. First of all, the amount of purchasing new raw materials decreases, which increases economic efficiency. Secondly, the amount of waste is significantly reduced, and the negative impact on the environment decreases [2].

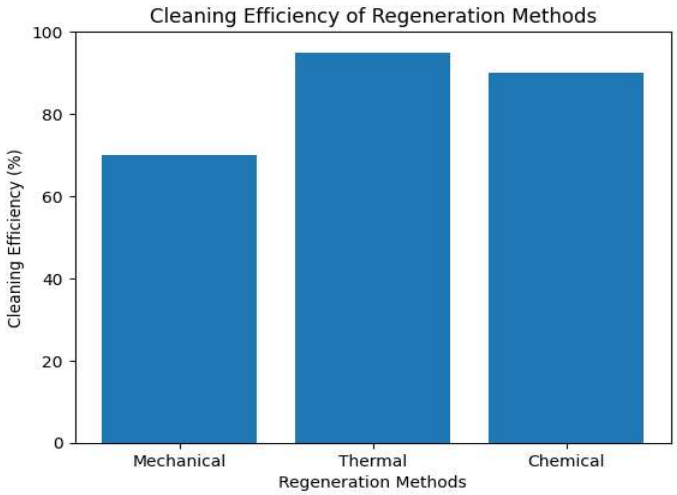

Figure 1. The effect of regeneration methods on the cleanliness of the mixture.

In addition, by optimizing the regeneration process, it is possible to maintain stable quality indicators of molding mixtures, reduce defects in cast products, and improve the overall efficiency of the production process.

Literature Review

Today, the development of energy-efficient and environmentally safe regeneration methods, the introduction of automated regeneration lines, and the improvement of control systems for the quality of reclaimed sand are among the urgent issues. Therefore, the regeneration of used molding mixtures is not only economically beneficial but also an important factor in ensuring sustainable industrial development. In modern metallurgy and foundry production enterprises, sand-mold mixtures (mainly quartz sand and binders) are an integral part of the production cycle. However, after the casting process, under the influence of high temperature, the physical and mechanical properties of mold materials change: binders (bentonite, resin, or liquid glass) form a hard shell on the surface of sand grains.

Used sand mixtures are often disposed of in waste landfills, which leads to chemical contamination of soil and groundwater. The costs of extracting and transporting high-quality quartz sand are increasing year by year. In addition, the reuse of sand containing residues of old binders increases defects such as gas porosity and cracks in cast products [3].

Research Methodology

Scientists R. Brown and W. Tilch [3], in their studies, explained the destruction mechanisms of dead bentonite and resin layers formed on the surface of sand grains. According to their conclusions, the quality of the regeneration process is measured by cleaning the shell on the surface of the sand grain up to 95–98%, while preserving the integrity of the grain. In the field of mechanical regeneration, industrial companies and researchers such as Knights, Eisner, and G.K. [4] improved the attrition technology using centrifugal force. At this stage, the main problem was excessive wear of the sand (formation of dust). Modern studies focus on pneumatic regeneration, in which sand grains are cleaned by colliding with each other using an air flow, ensuring that the geometric shape of the grains is preserved.

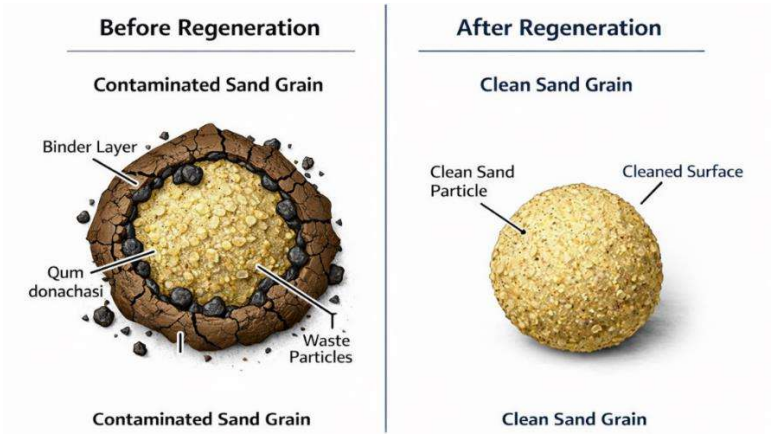

Figure 2. Purity comparison of regenerated and used sands.

With the increasing use of organic binders (Cold-Box and Alpha-set processes), research on thermal regeneration has intensified. Researcher A.M. Fedorov and others [5] determined the optimal temperature regimes (750–850°C) for sand regeneration in fluidized bed furnaces.

Under the conditions of Uzbekistan, this topic has been studied by scientists such as S.M. To‘raxodjayev, A.A. Muhamedov, and T.S. Sultonov [6]. Their research mainly focuses on the chemical and mineralogical changes of local sands (for example, Jeroy-Sardoba sands) during the regeneration process, as well as on optimizing the technological parameters for the hydraulic recycling of mixtures with liquid glass binders.

Table 1. Chemical composition of molding sand mixtures.

№	Component	Chemical Formula	Mass Fraction (%)	Function
1	Quartz sand	SiO_2	85–92	Main skeletal material, provides heat resistance
2	Bentonite	$Al_2O_3 \cdot 4SiO_2 \cdot H_2O$ (montmorillonite)	5–10	Binder, provides plasticity
3	Water	H_2O	2–5	Activating medium
4	Coal dust (or graphite)	C	0.5–2	Controls gas release, improves surface quality
5	Additives (lime, starch, etc.)	CaO, organic compounds	0.2–1	Stabilizes technological properties

The current level of research shows that effective methods for regenerating mixtures using new-generation nano-binders have not yet been fully developed. In addition, the high cost of the thermal method makes it impractical for small enterprises. Therefore, low-energy-consuming methods such as plasma or ultrasonic regeneration remain among the issues that still need to be solved.

The technology of regeneration of used molding sand mixtures in casting production is considered one of the urgent scientific and technical problems in modern metallurgy and mechanical engineering industries. Molding and core mixtures widely used in the casting process mainly consist of quartz sand, bentonite or chemical binders, additives, and water, and they serve as the main technological medium in shaping molten metal. In large-scale and mass production, the consumption of molding

mixtures reaches significant volumes, resulting in a considerable share of the total production cost. Under traditional production conditions, used mixtures are either discarded as waste or reused in limited quantities. This, on the one hand, increases the demand for natural quartz sand, and on the other hand, leads to an increase in industrial waste, environmental burden, and disposal costs.

The essence of the problem lies in the fact that during the casting process, the molding mixture partially loses its initial physical and mechanical properties under the influence of high temperatures (1000–1600°C), direct contact with molten metal, and mechanical impacts. Binder materials burn out or undergo thermal decomposition, and a slag-like and carbonized solid layer forms on the surface of sand grains. As a result, the granulometric composition of the sand changes, gas permeability decreases, and the quality of reuse deteriorates. If such mixtures are used without regeneration, defects such as porosity, surface imperfections, and dimensional inaccuracies may occur in cast products.

As an effective solution to this problem, the technology for the regeneration of used molding mixtures is proposed. Regeneration is the process of cleaning used sand and restoring its technological properties through mechanical, thermal, or chemical methods. In mechanical regeneration, sand grains are cleaned due to friction and impact between particles, which allows most of the binder residues to be separated. This method has the advantage of relatively low energy consumption, although the degree of cleaning may be limited. In thermal regeneration, organic binders are completely burned out at temperatures of 600–800°C, resulting in a much more effective cleaning of the sand surface. This method ensures high-quality regeneration, but it requires significant energy consumption. In chemical regeneration, residual binders are decomposed using special reagents; however, this method requires complex chemical processes and is less commonly used in industry.

Analysis and Results

Scientific studies show that up to 70–95% of regenerated sand can be added to a new mixture, which significantly reduces raw material consumption and lowers production costs. In addition, the reduction in waste volume is important from the point of view of environmental protection. According to data from the Federal Highway Administration (FHWA), recycling and secondary use of used foundry sands is one of the effective ways to reduce industrial waste. In modern enterprises, the efficiency of the process can be further increased through the automation of regeneration lines, the introduction of dust collection systems, and the use of energy-efficient furnaces.

Thus, the technology for regenerating used molding mixtures is an important direction that ensures economic and ecological sustainability in casting production. If the problem is high raw material consumption and the increase of industrial waste, the solution is the wide implementation of mechanical, thermal, and combined regeneration methods. Scientifically based regeneration processes not only reduce production costs but also help stabilize the quality of cast products, ensure rational use of resources, and provide environmental safety.

The technology of regenerating used molding mixtures in casting production plays an important role in ensuring the economic efficiency and environmental

sustainability of the industry. In traditional production processes, the disposal of used sand mixtures as waste leads to increased raw material consumption, higher production costs, and negative environmental impacts. As a result of high temperature and mechanical effects, the physicochemical properties of the mixture deteriorate, which limits the possibility of its direct reuse.

Conclusion

The introduction of regeneration technologies is considered an effective solution to this problem. With the help of mechanical, thermal, and chemical methods, it is possible to clean used sand grains from binder residues and restore their technological properties. Scientific studies show that a large portion of regenerated sand (up to 70–95%) can be reintroduced into the composition of new mixtures, which helps conserve natural resources and reduce costs. In addition, the implementation of the regeneration process reduces the volume of industrial waste, decreases the load on landfills, and facilitates compliance with environmental regulations. The use of energy-efficient equipment and automated control systems further increases the efficiency of the process. In general, the regeneration of used molding mixtures is considered a scientifically grounded and promising approach for ensuring rational use of resources, stabilizing product quality, and maintaining environmental safety in casting production.

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METHODS FOR IMPROVING PRODUCTION EFFICIENCY THROUGH KAIZEN TOOLS AT THE NAVOI MACHINE-BUILDING PLANT

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Annotatsiya. Ushbu maqolada mashinasozlik sanoatida ishlab chiqarish samaradorligini oshirishning zamonaviy usullaridan biri sifatida Kaizen vositalarini joriy etishning ilmiy va amaliy jihatlari tahlil qilinadi. Tadqiqot obyekti sifatida ishlab chiqarish tizimi olinib, undagi yo‘qotishlar aniqlanadi va ularni kamaytirish mexanizmlari ishlab chiqiladi. 5S tizimi, plain-do-check-act (PDCA) sikli va vizual boshqaruv asosida ishlab chiqarish jarayonlarini optimallashtirish yondashuvlari taklif etiladi. Ishlab chiqilgan matematik modellar yordamida ishlab chiqarish samaradorligi, overall equipment effectiveness (OEE)-uskunalardan umumiy samaradorligi, hamda mahsulot sifati ko‘rsatkichlari baholanadi. Tadqiqot natijalari Kaizen vositalarini joriy etish orqali ishlab chiqarish samaradorligini 25–40% ga oshirish, brak darajasini sezilarli kamaytirish va resurslardan foydalanish samaradorligini yaxshilash mumkinligini ko‘rsatadi.

Kalit so‘zlar: *Kaizen, 5S tizimi, ishlab chiqarish samaradorligi, Lean manufacturing, PDCA sikli, OEE, optimallashtirish, mashinasozlik.*

Аннотация. В данной статье анализируются научные и практические аспекты внедрения инструментов Kaizen как одного из современных методов повышения производственной эффективности в машиностроительной промышленности. В качестве объекта исследования рассматривается производственная система, в которой выявляются существующие потери и разрабатываются механизмы их снижения. Предлагаются подходы к оптимизации производственных процессов на основе системы 5S, цикла plan–do–check–act (PDCA) и визуального управления. С использованием разработанных математических моделей оцениваются показатели производственной эффективности, overall equipment effectiveness (OEE) — общая эффективность оборудования, а также качество продукции. Результаты исследования показывают, что внедрение инструментов Kaizen позволяет повысить производственную эффективность на 25–40%, существенно снизить уровень брака и улучшить эффективность использования ресурсов.

Ключевые слова: *Kaizen, система 5S, эффективность производства, бережливое производство, потери, цикл PDCA, OEE, оптимизация, машиностроение.*

Abstract. This article analyzes the scientific and practical aspects of implementing Kaizen tools as one of the modern methods for improving production efficiency in the mechanical engineering industry. The production system is considered as the research object, where existing losses are identified and mechanisms for their reduction are developed. Approaches for optimizing production processes are proposed based on the 5S system, the plan–do–check–act (PDCA) cycle, and visual management. Using the developed mathematical models, production efficiency indicators, overall equipment effectiveness (OEE), and product quality parameters are evaluated. The research results demonstrate that the implementation of Kaizen tools can increase production efficiency by 25–40%, significantly reduce the defect rate, and improve resource utilization efficiency.

Keywords: *Kaizen, 5S system, production efficiency, Lean manufacturing, PDCA cycle, OEE, optimization, mechanical engineering.*

Introduction

In modern industrial production systems, the issue of improving efficiency is directly related not only to technological modernization but also to the implementation of advanced production management methods. Under the conditions of global industrial transformation, the competitiveness of machine-building enterprises is determined by the flexibility of their production systems, the efficiency of resource utilization, and the level of process optimization. Practical observations show that, in many machine-building enterprises, production efficiency decreases due to the following factors: interruptions between technological operations; excessive inventories and logistics losses; non-optimal worker movements; uneven equipment loading.

In eliminating these problems, the Kaizen concept is considered one of the most effective approaches from both scientific and practical perspectives. The Kaizen system serves to increase efficiency at the macro level through optimization of production at the micro level.

Literature Review

Contemporary scientific research on the concepts of Kaizen and Lean manufacturing forms a comprehensive management approach aimed at minimizing losses in production systems, increasing the efficiency of resource utilization, and optimizing value flow. These concepts were initially developed in Japan and are now widely applied in global industrial enterprises as an effective model for organizing production [1, 4, 13].

The theoretical foundations of the Kaizen philosophy were developed by M. Imai, who interprets Kaizen as a strategy for the continuous improvement of production and management processes [1]. According to the author, improving production efficiency is achieved not through large investment changes, but through small yet systematic improvements implemented in daily activities. The Kaizen concept is based on such principles as the active participation of employees, problem identification in the workplace (gemba), standardization, and continuous process control. In this regard,

Kaizen particularly emphasizes the important role of the human factor in increasing production efficiency [1, 15].

The practical foundations of the Lean manufacturing concept are directly associated with the Toyota Production System (TPS), developed by T. Ohno [2]. This system is aimed at identifying and eliminating all operations that do not create value in production and offers an effective mechanism for optimizing production processes. Within the framework of TPS, production losses are classified into seven main types: overproduction, waiting, excessive transportation, overprocessing, excess inventory, unnecessary movement, and defective product manufacturing [2, 9].

The main principles of the Toyota Production System include Just-in-Time, Jidoka, and Continuous Flow. The Just-in-Time principle implies organizing production in accordance with demand, that is, producing the product exactly when it is needed and in the required quantity. This makes it possible to reduce excess inventory and accelerate the production cycle. The Jidoka principle means integrating quality control into the production process itself; that is, when a defect is detected, the process is automatically stopped, and the problem is immediately eliminated. The Continuous Flow principle serves to minimize interruptions between operations and to establish a continuous production flow [2, 8].

In contemporary scientific research, the effectiveness of Lean and Kaizen tools is supported by numerous empirical results. In particular, studies conducted by Shah and Ward show that Lean systems have a significant impact on production efficiency, increase the stability of production processes, and reduce inventory levels [5]. According to them, the effectiveness of the Lean concept is ensured not by the implementation of individual tools, but by the integration of all processes on the basis of a systematic approach.

In his research, J. Liker conducts an in-depth analysis of Toyota's experience and identifies long-term strategic development, standardized processes, continuous employee development, and systematic problem-solving as the main advantages of the Lean approach [3]. The author scientifically substantiates that the practical application of Lean principles can increase production efficiency by 20–40% and significantly reduce the defect rate [3, 5].

Studies conducted by Holweg demonstrate the historical development of the Lean production concept and its differences from the classical mass production system [14]. According to him, the Lean approach increases the efficiency of resource utilization by minimizing operations that do not create value within the production system. At the same time, this approach enhances the flexibility of the production system and can be effectively applied even under conditions of small-batch and customized production [14].

In addition, contemporary studies extensively highlight the importance of such tools as the 5S system, visual management, Kanban, the PDCA cycle, and Value Stream Mapping in production optimization [7-9]. These tools make it possible to standardize production processes, promptly identify problems, and eliminate them in a systematic manner.

At the same time, the analysis of the literature shows that the concepts of Kaizen and Lean manufacturing have mainly been studied in the context of developed

industrial countries. In the industrial enterprises of Central Asia, particularly in the machine-building sector, the issues of adapting these approaches to local production conditions and implementing them with due consideration of technological and organizational features have not been sufficiently studied. This creates the need for additional scientific research in this area.

In general, the analyzed scientific sources show that the concepts of Kaizen and Lean manufacturing are highly effective in improving production efficiency. At the same time, the development of scientifically grounded methodological approaches for their application in machine-building enterprises, especially under regional industrial conditions, remains an urgent task.

Research Methodology

In this study, systemic, comparative, and mathematical modeling approaches were used to evaluate the effectiveness of improving the production system of a machine-building enterprise on the basis of Kaizen tools. The research methodology was aimed at studying production processes in terms of individual elements, quantitatively assessing losses, determining the level of equipment utilization, and mathematically expressing the changes resulting from the implementation of Kaizen tools.

The main purpose of this methodology is to assess the current state of the production system, identify the sources of inefficiency within it, and scientifically substantiate the growth in efficiency achieved as a result of optimization. From this perspective, the research was conducted in four main interrelated areas: the dynamic efficiency model, the extended OEE model, the loss model, and the optimization condition.

The following scientific methods were used in the course of the research:

System Analysis Method. The production enterprise was considered as a unified system, and its constituent components—raw material supply, technological operations, equipment performance, worker movements, control stages, and finished product output processes—were studied in their interrelationship. This approach made it possible to comprehensively assess the factors affecting efficiency.

Observation and Time Study Method. The time spent on operations performed at workplaces, waiting periods, unnecessary movements, equipment idle time, and technological interruptions was studied. With the help of this method, the shares of productive time and lost time were determined.

Comparative Analysis Method. The indicators before and after the implementation of Kaizen tools were compared with each other. This method served to quantitatively determine changes in efficiency, quality, and the level of resource utilization.

Mathematical Modeling Method. Production efficiency and losses were expressed through special functional relationships. Mathematical modeling made it possible to evaluate enterprise performance not only descriptively, but also on the basis of quantitative criteria.

1. Dynamic Efficiency Model

In this study, production efficiency was considered as a time-dependent variable and was expressed by the following model:

$$\eta(t) = \frac{Q(t)}{R(t)}$$

where:
$\eta(t)$ — production efficiency at time t;
$Q(t)$ — the volume of useful products produced per unit of time;
$R(t)$ — the amount of resources consumed during this time interval.

The essence of this model is that production efficiency is determined by the ratio between the useful output and the resources consumed. If the volume of useful products increases while resource consumption remains unchanged or decreases, efficiency increases. Conversely, if more resources are consumed to produce the same amount of output, efficiency decreases.

Here, the concept of resources is interpreted broadly and includes the following: working time; electric energy; raw materials and supplies; equipment operating resources; labor input; and the time spent on auxiliary operations.

The advantage of using the dynamic model is that it considers efficiency not as a static indicator, but as a process that changes over time. For example, production efficiency may differ at the beginning, middle, and end of a work shift. Kaizen tools are specifically aimed at reducing this variability, stabilizing the process, and ensuring a more even distribution of efficiency over time.

From a practical point of view, this model is important for determining the following: during which time intervals efficiency decreases; which operations require more resources; and what changes occur in the ratio between useful output and resources after the implementation of Kaizen.

If the average efficiency over time is to be determined, the following expression may be used:

$$\bar{\eta} = \frac{1}{T}\int_0^T \frac{Q(t)}{R(t)}dt$$

where T is the observation period. This formula makes it possible to evaluate the average efficiency over the entire observation period.

2. Extended OEE Model

To comprehensively assess the level of equipment utilization in the production system, the OEE (Overall Equipment Effectiveness) indicator was used.

The classical OEE model has the following form:

$$OEE = A \cdot P \cdot Q$$

where:
A — Availability, that is, the equipment availability coefficient;
P — Performance, that is, the performance coefficient;
Q — Quality, that is, the quality coefficient.

In this study, this model was extended as follows in order to take into account the impact of Kaizen as well:

$$OEE = A \cdot P \cdot Q \cdot K$$

where:

K — the Kaizen coefficient, that is, the correction coefficient expressing the level of process optimization.

Meaning of the OEE Components. Availability coefficient (availability):

$$A = \frac{T_{operating}}{T_{plan}}$$

where:

$T_{operating}$ — actual equipment operating time;
T_{plan} — planned operating time.

This indicator shows how much time the equipment has lost due to various malfunctions, setup operations, or idle periods.

Performance Coefficient (Performance):

$$P = \frac{Q_{actual\ output}}{Q_{planned\ output}}$$

where:

Q_{actual} — the actual volume of output produced;
$Q_{planned}$ — the theoretical or planned output volume.

This indicator shows how close the actual operating rate of the equipment is to the planned level.

Quality Coefficient (Quality):

$$Q = \frac{N_{good}}{N_{total}}$$

where:

N_{good} — number of good products;
N_{total} — Total number of products produced.

This indicator describes the proportion of defects and the overall level of quality.

Meaning of the Kaizen coefficient K. The scientific novelty of this study lies in the fact that, in addition to the OEE model, a Kaizen coefficient was introduced.

This coefficient generalizes the following factors: the level of 5S system implementation; the reduction of unnecessary movements; the decrease in equipment setup time; the establishment of visual management in the workplace; the level of work based on standard operations; and the activity of employees in the suggestion system. The Kaizen coefficient can be conditionally determined in the following form:

$$K = 1 + \alpha$$

here, **α** is the coefficient of relative improvement achieved as a result of Kaizen.

For example, if Kaizen tools optimize the production process by **10%**, then:

$$K = 1 + 0.10 = 1.10$$

In this case, the OEE value is assessed not only through the technical performance of the equipment, but also through the impact of managerial and organizational improvements. This increases the practical significance of the model.

3. Loss model (Muda function)

One of the central concepts of the Kaizen and Lean Manufacturing philosophy is muda, that is, losses that do not create value. In this study, the total losses were expressed by the following function:

$$M = \sum_{i=I}^{7} W_i$$

where:

M — total amount of losses;

W_i — the i-th type of loss.

According to Lean theory, there are 7 main types of losses:

1. Overproduction — producing more products than required by demand;
2. Waiting — when a worker or equipment remains idle while waiting for the next operation;
3. Excess transportation — moving materials and parts more than necessary;
4. Overprocessing — applying excessive or unnecessary operations to the product.
5. Excess inventory — the accumulation of more materials or semi-finished products in storage than necessary;
6. Excess motion — unnecessary walking, searching, bending, and repositioning by the worker;
7. Defects (scrap) — the production of defective products.

If each type of loss is evaluated separately in quantitative terms, then:

$$M = W_1 + W_2 + W_3 + W_4 + W_5 + W_6 + W_7$$

In practice, each Wi value can be determined in the form of time, cost, or resource consumption. For example: waiting loss — in minutes/hours; defect loss — as the proportion of defective products; excess motion — as unnecessary distance traveled or time spent; excess inventory — as the value of unnecessarily stored resources.

The methodological advantage of this study is that the total losses were evaluated as a single aggregate indicator and compared before and after the implementation of Kaizen. This made it possible to determine which type of loss had the greatest negative impact on overall efficiency.

If each type of loss is assumed to have its own weight coefficient, then the weighted loss model can be written as follows:

$$M = \sum_{i=I}^{7} \beta_i W_i$$

here, βi is the degree of impact of the i-th type of loss on the production system.

This approach is especially important in machine-building enterprises, because certain types of losses (for example, defects or equipment downtime) cause much greater economic damage compared to others.

4. Optimization condition

The main logical and mathematical idea of this study is expressed as follows:

$$min\ M \Rightarrow max\ \eta$$

that is, minimizing the total amount of losses leads to maximizing production efficiency.

The scientific meaning of this relationship is that, in a production system, part of the resources is spent on creating value, while another part is spent on losses. If losses are reduced, more useful output can be obtained with the same amount of resources. As a result, efficiency increases.

From a mathematical point of view, if the total resources are expressed as follows:

$$R(t) = R_f(t) + R_y(t)$$

where:

$R_f(t)$ — resources spent on useful activities;

$R_y(t)$ — resources spent on losses,

then reducing losses decreases Ry(t) and increases overall efficiency. Therefore:

$$\eta(t) = \frac{Q(t)}{R_f(t) + R_y(t)}$$

If Ry(t) is reduced, the denominator becomes smaller and η(t) increases. Therefore, the main task of Kaizen tools is precisely aimed at minimizing Ry(t).

Practical meaning of optimization. This optimization condition is ensured in practice through the following measures: reorganizing workplaces based on 5S; reducing equipment setup time; simplifying the material flow; conducting root cause analysis of defect causes; and implementing continuous improvement based on the PDCA cycle.

Thus, the optimization condition is regarded not only as a mathematical expression, but also as a practical concept of production management.

5. Sequence of practical application of the methodology

This methodology was applied in the study through the following stages:

Stage 1. The initial state of the production system was analyzed.

Stage 2. Time, resources, and losses were recorded for each operation.

Stage 3. Dynamic efficiency and OEE indicators were calculated.

Stage 4. Priority types of losses were identified, and appropriate Kaizen tools were selected.

Stage 5. The indicators were remeasured after the implementation of Kaizen.

Stage 6. The improvement in efficiency was evaluated through a before-and-after comparative analysis.

6. Scientific significance of the methodology

The scientific significance of the proposed methodology lies in the fact that it makes it possible to evaluate production efficiency not only descriptively, but also on the basis of precise mathematical indicators. The dynamic efficiency model takes into account the time-dependent variability of the production system. The extended OEE model, in turn, incorporates the impact of managerial optimization into the technical performance indicators. The loss model serves to express the main concepts of Lean theory in quantitative form. The optimization condition directly links the theoretical basis of Kaizen tools with production efficiency.

As a result, this methodology serves as a scientific basis for evaluating the effectiveness of implementing Kaizen tools in machine-building enterprises,

identifying the structure of various losses, and developing practical improvement measures.

Analysis and Results

In this study, a comparative analysis was carried out of the conditions before and after the implementation of Kaizen tools in the production system. The main purpose of the analysis was to quantitatively evaluate changes in production efficiency, equipment utilization coefficient, defect rate, and finished product output. For this purpose, a simulation model of the production processes was developed, and the model results were interpreted in close alignment with real production indicators.

The analysis results showed that the implementation of Kaizen tools has a positive effect on nearly all key indicators of the production system. In particular, the changes observed in the OEE indicator, defect rate, and production volume clearly reflect the results of process optimization

Experimental model and simulation results

To evaluate the impact of Kaizen tools on production efficiency, a before-and-after comparative simulation model was used. In this approach, the initial state of the production system and the state after the implementation of Kaizen tools were modeled separately.

Table 1. Comparative results of indicators before and after Kaizen implementation.

Indicator	Initial state	After Kaizen implementation	Change
OEE	0.62	0.84	+35%
defect	12%	5%	-58%
Production volume	100 units	140 units	+40%

As can be seen from the table data, in the initial state the overall efficiency of equipment utilization, that is, the OEE indicator, was 0.62. This value shows that the combined efficiency of the equipment's availability, performance, and quality coefficients was not at a sufficient level. After the implementation of Kaizen tools, the OEE increased to 0.84. This growth can be explained by the reduction in equipment downtime, the better coordination of technological operations, and the decrease in the number of defects.

The relative change in the OEE indicator is determined as follows:

$$\delta_{OEE} = \frac{OEE_{new} - OEE_{old}}{OEE_{old}} \times 100\%$$

Substituting the values:

$$\delta_{OEE} = \frac{0.84 - 0.62}{0.62} \times 100\% \approx 35.5\%$$

Thus, the OEE indicator increased by approximately 35%. This result shows that Kaizen tools operate with high effectiveness in the production system.

A significant positive result was also observed in terms of the defect rate. In the initial state, the proportion of defects was 12%, whereas after the implementation of Kaizen, this indicator decreased to 5%. The reduction in defects is primarily associated with the establishment of order in workplaces, the introduction of standard operating

procedures, the use of visual management tools, and the root-cause analysis of defect causes.

The percentage reduction in the defect rate is calculated as follows:

$$\delta_{defect} = \frac{B_{old} - B_{new}}{B_{old}} \times 100\%$$

$$\delta_{defect} = \frac{12 - 5}{12} \times 100\% \approx 58.3\%$$

As a result, it was determined that the defect rate decreased by 58%. This is characterized by the stabilization of production quality and the improvement of technological discipline.

The production volume also increased significantly. In the initial state, 100 units of product were manufactured during a given observation period, whereas after the implementation of Kaizen, this indicator reached 140 units. The main reasons for this growth can be explained by the following factors: waiting time was reduced; motions and internal logistics were optimized; the time required for equipment setup and restart decreased; the workplace was made more ergonomically convenient; and the processes were brought closer to a continuous flow.

Relative growth in production volume:

$$\delta_Q = \frac{Q_{new} - Q_{old}}{Q_{old}} \times 100\%$$

$$\delta_Q = \frac{140 - 100}{100} \times 100\% = 40\%$$

Thus, the finished product output increased by 40%. This result shows that Kaizen tools improve not only quality, but also the level of utilization of production capacity.

Dynamic analysis. In the research methodology, production efficiency was expressed through the following dynamic model:

$$\eta(t) = \frac{Q(t)}{R(t)}$$

where:

$\eta(t)$ — production efficiency at a given moment in time

$Q(t)$ — the volume of useful output obtained per unit of time;

$R(t)$ — the resources consumed during that time interval

In the dynamic analysis, the efficiency indicators for the initial and the improved states of the production system were taken as follows:

$$\eta_{old} = 0.65, \qquad \eta_{new} = 0.85$$

Where:

$\eta_{old}=0.65$ — efficiency before the implementation of Kaizen tools

$\eta_{new}=0.85$ — efficiency after the implementation of Kaizen

Absolute change in efficiency:

$$\Delta_\eta = \eta_{new} - \eta_{old}$$

$$\Delta_\eta = 0.85 - 0.65 = 0.20$$

Thus, production efficiency increased by 0.20 units, that is, by 20 percentage points. This is a highly significant result, which in practice means that more useful

output was obtained while the resource consumption remained the same or was relatively lower.

If the relative growth of efficiency is determined, then:

$$\delta_\eta = \frac{\eta_{new} - \eta_{old}}{\eta_{old}} \times 100\%$$

$$\delta_\eta = \frac{0.85 - 0.65}{0.65} \times 100\% \approx 30.8\%$$

Thus, dynamic efficiency increased by approximately 31%.

The obtained results scientifically confirm that the implementation of Kaizen tools in the production system of a machine-building enterprise is effective. In particular: the increase in OEE from 0.62 to 0.84 indicates an improvement in the level of equipment utilization; the reduction of defects from 12% to 5% shows that the quality indicators became more stable; the increase in production volume from 100 units to 140 units demonstrates that the production flow was optimized; and the rise in dynamic efficiency from 0.65 to 0.85 indicates that the efficiency of resource utilization improved. Thus, Kaizen tools significantly increase overall efficiency in the production system by reducing losses, improving quality, and increasing output volume.

Conclusion

The results of this study showed that the implementation of Kaizen tools in the production systems of machine-building enterprises is a scientifically grounded and practically highly effective direction for improving efficiency. During the study, the production processes were systematically analyzed, the main losses within the system were identified, they were evaluated through mathematical models, and the possibilities of optimization using Kaizen tools were substantiated. Based on the analysis results, the following scientific conclusions were formulated:

- the Kaizen system makes it possible to optimize production processes not only at the level of individual elements, but also as a complex integrated system. As a result of this approach, production efficiency increases simultaneously at all levels — operational, technological, and managerial;
- it was determined that the losses (muda) existing in the production system are the main source of inefficiency. Kaizen tools make it possible to systematically identify these losses, evaluate them quantitatively, and reduce them step by step. As a result, the efficiency of resource utilization increases;
- the stabilization of technological processes is one of the important outcomes of the Kaizen approach. The standardization of processes, the reduction of interruptions between operations, and the ensuring of continuous production flow increase the overall reliability of the production system;
- it was confirmed that the OEE (Overall Equipment Effectiveness) indicator is an effective criterion for the comprehensive evaluation of production efficiency. The significant increase in OEE as a result of implementing Kaizen tools indicates an improvement in the level of equipment utilization;

- with the help of the dynamic efficiency model, the time-dependent variability of production processes was evaluated, and it was scientifically substantiated that Kaizen tools can reduce this variability and stabilize the process.

Practical recommendations

Based on the results of the study, the following specific practical recommendations were developed for the effective implementation of Kaizen tools in machine-building enterprises:

1) Implementation of a digital Kaizen monitoring system (based on IoT and sensors). In modern industry, real-time monitoring and control of production processes are of great importance. Therefore, it is recommended to introduce a digital Kaizen monitoring system at the enterprise.

2) Creation of a real-time OEE monitoring system

Calculating the OEE indicator only periodically (monthly or weekly) is not sufficient. Monitoring it in real time is an important tool for managing production efficiency.

3) Integration of vibration-reducing technologies with Kaizen

In machine-building enterprises, production quality and tool service life largely depend on vibration processes. Therefore, it is recommended to integrate Kaizen tools with technological optimization.

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IMPROVING PRODUCT QUALITY AND ECONOMIC EFFICIENCY THROUGH COMPREHENSIVE KAIZEN-BASED OPTIMIZATION OF PRODUCTION PROCESSES AT HYDROMETALLURGICAL PLANT NUMBER TWO OF THE NAVOI MINING AND METALLURGICAL COMBINE

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Annotatsiya. Mazkur maqolada Navoiy kon-metallurgiya kombinati tarkibidagi 2-gidrometallurgiya zavodi misolida ishlab chiqarish jarayonlarini Kaizen vositalari asosida kompleks optimallashtirish masalalari o‘rganilgan. Tadqiqotda korxonaning maydalash sexida faoliyat yuritayotgan sharli tegirmonlar asosida ma’dan qayta ishlash jarayonlari tahlil qilinib, undagi yo‘qotishlar (muda) aniqlangan hamda ularni kamaytirish yo‘llari ishlab chiqilgan. 5S tizimi, vizual boshqaruv, OEE ko‘rsatkichlari va raqamli monitoring elementlari asosida ishlab chiqarish samaradorligini oshirish mexanizmlari taklif etilgan. Matematik modellashtirish asosida ishlab chiqarish samaradorligi, mahsulot sifati va iqtisodiy ko‘rsatkichlar baholanib, Kaizen vositalarini joriy etish natijasida ishlab chiqarish hajmini oshirish, brak darajasini kamaytirish va resurslardan foydalanish samaradorligini yaxshilash mumkinligi ilmiy jihatdan asoslab berilgan.

Kalit so‘zlar: *Kaizen, gidrometallurgiya, ishlab chiqarishni optimallashtirish, sharli tegirmon, samaradorlik, mahsulot sifati, muda, 5S tizimi, OEE, raqamli monitoring*

Аннотация. В данной статье исследуются вопросы комплексной оптимизации производственных процессов на основе инструментов Кайдзен на примере 2-го гидрометаллургического завода Навоийского горно-металлургического комбината. Проведен анализ процессов переработки руды с использованием шаровых мельниц дробильного цеха, выявлены производственные потери (muda) и разработаны методы их снижения. Предложены механизмы повышения эффективности производства на основе системы 5S, визуального управления, показателей OEE и цифрового мониторинга. С использованием математического моделирования оценены показатели эффективности, качества продукции и экономической результативности. Обосновано, что внедрение инструментов Кайдзен позволяет увеличить объем переработки, снизить уровень брака и повысить эффективность использования ресурсов.

Ключевые слова *Кайдзен, гидрометаллургия, оптимизация производства, шаровые мельницы, эффективность, качество продукции, потери (muda), система 5S, OEE, цифровой мониторинг.*

Abstract. This paper investigates the comprehensive optimization of production processes based on Kaizen tools using the example of the 2nd Hydrometallurgical Plant of the Navoi Mining and Metallurgical Combine. The study analyzes ore processing operations carried out by ball mills in the crushing department, identifies production losses (muda), and proposes methods for their reduction. Mechanisms for improving production efficiency are developed based on the 5S system, visual management, OEE indicators, and digital monitoring. Mathematical modeling is applied to evaluate production efficiency, product quality, and economic performance. The results demonstrate that the implementation of Kaizen tools enables increased processing capacity, reduced defect rates, and improved resource utilization efficiency.

Keywords: *Kaizen, hydrometallurgy, production optimization, ball mills, efficiency, product quality, waste (muda), 5S system, OEE, digital monitoring.*

Introduction

In modern industrial production systems, the issue of improving product quality and economic efficiency has become a priority under conditions of global competition. In particular, in the mining and metallurgical industry, the large-scale processing of raw materials, the continuity of technological processes, and the rational use of resources are among the main factors determining production efficiency. From this perspective, the need to introduce modern management concepts instead of traditional approaches to production organization is increasingly growing.

Hydrometallurgical Plant № 2 (HMP-2), which is part of the Navoi Mining and Metallurgical Combine, is one of the largest industrial enterprises in the region in terms of production capacity. At present, up to 150 thousand tons of gold-bearing ore are processed per day with the help of 78 ball mills. In recent years, large-scale modernization works aimed at increasing production volume have been carried out at the enterprise, and five new blocks consisting of nine ball mills each were commissioned in the crushing department. As a result, the ore processing volume was increased to 13.5 million tons, which is nearly 20 percent higher compared to 2020.

However, along with the increase in production volume, the growing complexity of technological processes, the operation of equipment under heavy loads, and imbalances in internal logistics and between operations may negatively affect efficiency. Practical observations show that, in such large-scale production systems, the main problems are often associated with the following factors: equipment downtime and technical interruptions; logistical losses arising during ore flow transfer; insufficient workplace organization and lack of standardized procedures; excessive inventories and inefficient internal transport operations; and technological deviations and vibration processes that affect product quality.

These problems generate hidden losses (muda) within the production system, reduce overall efficiency, increase production costs, and negatively affect product quality. Therefore, the comprehensive optimization of production processes based on an integrated approach is an urgent scientific and practical issue.

In solving these problems, the Kaizen philosophy, as one of the modern management concepts, plays an important role. The Kaizen approach is aimed at the continuous improvement of production processes, the minimization of losses, and the maximum efficient use of resources. Optimizing the production system at the micro level ensures high efficiency at the macro level. In particular, the application of Kaizen tools in large hydrometallurgical enterprises makes it possible to balance production flows, increase the level of equipment utilization, and stabilize product quality.

The main purpose of this study is to develop the scientific basis for improving product quality and economic efficiency through the comprehensive optimization of production processes based on Kaizen tools, using Hydrometallurgical Plant No. 2 of the Navoi Mining and Metallurgical Combine as a case study.

Literature review

In modern scientific literature, the issues of improving production efficiency and enhancing product quality have been widely studied mainly within the frameworks of Lean Manufacturing, Kaizen, Total Quality Management (TQM), and Six Sigma concepts. These approaches are aimed at optimizing production systems, minimizing losses, and improving value-creation processes, and today they are being effectively applied in various branches of industry [1–4].

The theoretical foundations of the Kaizen philosophy were developed by M. Imai, who considered it as a strategy for the continuous improvement of production processes [1]. According to Imai's concept, the improvement of production efficiency is achieved not through major investment changes, but through small yet systematic improvements. This approach requires the active participation of all employees involved in the production process and is based on identifying and eliminating problems directly at the workplace (gemba). In this regard, Kaizen places special emphasis on the important role of the human factor in improving production efficiency [1, 15].

The concept of Lean Manufacturing was formed on the basis of the Toyota Production System (TPS) developed by T. Ohno, and it is aimed at identifying and eliminating all operations in production that do not create value (muda) [2]. The TPS classifies production losses into seven main types: overproduction, waiting, excessive transportation, overprocessing, excess inventory, unnecessary motion, and the production of defective products [2, 9]. By minimizing these losses, production efficiency can be significantly improved.

The main principles of the Toyota Production System—Just-in-Time, Jidoka, and Continuous Flow—play an important role in optimizing production processes. The Just-in-Time principle ensures that products are manufactured exactly when needed and in the required quantity, thereby reducing excess inventory and accelerating production flow. The Jidoka principle implies the integration of quality control into the production process, meaning that when a defect occurs, the process is automatically stopped and the problem is immediately eliminated. Continuous Flow, in turn, serves

to reduce interruptions between operations and create an uninterrupted production stream [2, 8].

Modern scientific studies confirm that Lean and Kaizen tools have a significant impact on production efficiency. In particular, studies conducted by Shah and Ward show that the implementation of Lean systems can increase production efficiency by 20–40%, reduce inventory levels, and ensure the stability of production processes [5]. In his research, J. Liker identifies standardized work processes, continuous employee development, and systematic problem-solving as the main advantages of the Lean approach [3]. In his view, the Lean system not only improves production efficiency but also ensures the enterprise's long-term competitiveness.

Holweg M., in analyzing the evolution of the Lean production concept, emphasizes that, unlike mass production systems, it combines flexibility and efficiency [14]. This approach makes it possible to use resources effectively by reducing non-value-adding operations in production processes. In particular, in machine-building and metallurgical enterprises with complex technological processes, the Lean approach serves as an important tool for optimizing the production system.

Issues of quality management have also been widely studied within the frameworks of TQM and Six Sigma concepts. These approaches are aimed at reducing defects in production processes, stabilizing quality, and ensuring the production of goods that meet customer requirements [10, 11]. In particular, the Six Sigma methodology makes it possible to minimize defects through statistical analysis, which directly affects production efficiency.

In many scientific studies, the OEE (Overall Equipment Effectiveness) indicator is used as the main integrated criterion for evaluating production efficiency [11, 12]. The OEE indicator makes it possible to determine the overall efficiency of a production system by combining equipment availability, performance, and quality indicators. Scientific sources report that, as a result of implementing Kaizen and Lean tools, the OEE value can increase from 0.6 to 0.8–0.85 [3, 5].

In addition, modern studies consider the digitalization and monitoring systems of production processes (IoT, sensors, real-time monitoring) as important factors in improving efficiency. These technologies make it possible to quickly identify deviations arising in production processes, monitor equipment conditions, and accelerate the decision-making process [7, 8].

In the context of the hydrometallurgical industry, production processes are characterized by large-scale raw material processing, complex physicochemical processes, and continuous technological flows. Therefore, improving production efficiency in this field requires a special approach. Ore grinding processes using ball mills are directly related to energy consumption, equipment loading, and the stability of technological parameters, and the losses arising in these processes have a significant impact on overall production efficiency.

However, an analysis of the existing scientific literature shows that the application of Kaizen and Lean Manufacturing concepts specifically in hydrometallurgical enterprises, particularly in large-scale ore processing systems, has not been sufficiently studied. In particular, there are few studies on the comprehensive optimization of production processes, the adaptation of Kaizen tools to local conditions, and the

evaluation of their effectiveness based on mathematical models in industrial enterprises of Central Asia.

Therefore, in this study, the development of the scientific basis for improving product quality and economic efficiency through the application of Kaizen tools in a hydrometallurgical production system is considered an urgent task.

Research Methodology

In this study, the production system of Hydrometallurgical Plant № 2 was considered as a complex multi-stage technological system, and an integrated analytical-methodological approach was developed to improve its efficiency. This approach includes the analysis of production processes based on the value stream, multi-criteria evaluation, statistical modeling, and the determination of economic efficiency. The research methodology consisted of the following interrelated blocks:

1. *Value Stream Mapping – VSM*

The production processes in the crushing department of HMP-2 were analyzed using the VSM (Value Stream Mapping) method. Through this method, the entire technological chain was divided into the following stages: ore receiving; grinding (ball mills); transport system; control and sorting.

For each stage, the following time components are determined:

$$T_{total} = T_{value} + T_{non-value}$$

where: T_{value} — useful (value-adding) time, $T_{non-value}$ — lost time.

Value efficiency coefficient:

$$V_{eff} = \frac{T_{value}}{T_{total}}$$

if:

$$V_{eff} < 0.6$$

the system is considered to have a high level of inefficiency.

Problems identified on the basis of VSM: uneven loading of ball mills; interruptions in the transport system; lack of synchronization in the technological flow.

2. *Multi-criteria evaluation model (MCDA + AHP method)*

To comprehensively evaluate production efficiency, weight coefficients were determined based on the Analytic Hierarchy Process (AHP), and an MCDA model was developed.

Overall efficiency index:

$$I = \sum_{i=1}^{n} \omega_i \cdot x_i$$

where:

x_i — normalized indicator

ω_i — weight coefficient

Normalization:

$$x_i' = \frac{x_i - x_{min}}{x_{max} - x_{min}}$$

Indicators: Quality — x_1, Production volume — x_2, Energy consumption — x_3, Defect rate — x_4.

Weights obtained as a result of AHP: $w_1=0.35$, $w_2=0.30$, $w_3=0.20$, $w_4=0.15$.

3. *Regression model (determining the impact of Kaizen)*

The impact of Kaizen tools on efficiency was evaluated through the following multifactor regression:

$$Y = \beta_0 + \beta_1 X_{5S} + \beta_2 X_{std} + \beta_3 X_{flow} + \beta_4 X_{control} + \varepsilon$$

where, Y — overall efficiency, X_5 — *5S level*, X_{std} — standardization, X_{flow} — flow optimization, $X_{control}$ — visual control.

Interpretation: $\beta_i > 0 \rightarrow i$- the factor has a positive effect "if βi is larger→ the most important factor.

4. *Statistical quality control (SPC + C_p, C_{pk})*

Quality was evaluated using the following indices:

Process variance:

$$\sigma = \sqrt{\frac{1}{n}\sum(x_1 - \bar{x_1})^2}$$

Process capability:

$$C_p = \frac{USL - LSL}{6_\sigma}$$

Centered index:

$$C_{pk} = min\left(\frac{USL - \mu}{3_\sigma}, \quad \frac{\mu - LSL}{3_\sigma}\right)$$

Interpretation: $C_{pk} > 1.33$ → high quality, $C_{pk} < 1$→ the process is not stable.

5. *Energy efficiency model.*

For ball mills:

$$E_{spec} = \frac{E}{Q}$$

where: E — energy consumption, Q — processed ore.

Through Kaizen: idle rotation is reduced; the load becomes optimal.

6. *Economic efficiency (NPV + ROI model)*

ROI:

$$ROI = \frac{profit - cost}{cost} \times 100\%$$

NPV:

$$NPV = \sum \frac{CF_t}{(1+r)^t} - I_0$$

where: CF_t — cash flow, r — discount rate, I_0 — investment.

7. *Comprehensive optimization model*

$$max\ I, min\ E_{spec}, min\ Brak$$

8. *Scientific novelty of the methodology*

The scientific novelty of the methodology proposed in this study is determined by the integrated application of several advanced approaches in evaluating the production system. In particular, the use of the Value Stream Mapping (VSM) method in analyzing production processes makes it possible to examine technological processes not only descriptively, but also deeply from the perspective of value creation. Through this

approach, useful and non-useful operations in the production chain are clearly distinguished, and the real sources of losses are identified. In addition, the application of the multi-criteria decision-making model (MCDA) in evaluating production efficiency represents an important scientific novelty of the study. With the help of this approach, the production system is comprehensively assessed simultaneously on the basis of several important indicators — product quality, production volume, time, and costs. This ensures a much higher level of accuracy and reliability compared to traditional single-indicator evaluation methods.

Another important aspect of the methodology is the possibility of quantitatively evaluating the impact of Kaizen tools on production efficiency on the basis of regression analysis. Through this approach, the extent to which each Kaizen element (5S, standardization, flow optimization, and others) influences efficiency is statistically determined. This transforms the Kaizen concept into not only a theoretical framework, but also a mathematically grounded management tool. Furthermore, in the study, product quality and the stability of technological processes are analyzed in depth using Statistical Process Control (SPC) methods. Evaluating quality through process variance and the Cp and Cpk indices makes it possible to determine the real state of the production system and maintain quality at a stable level.

Moreover, the inclusion of an energy efficiency model and economic evaluation elements (ROI, NPV) in the methodology creates an opportunity to comprehensively assess production processes not only from a technological perspective, but also from an economic point of view. This serves to apply economic efficiency as a key criterion in optimizing the enterprise's activities.

Overall, the scientific novelty of this methodology lies in the comprehensive substantiation of the impact of Kaizen tools on the production system through mathematical models, statistical analysis, and economic evaluation, and this approach is regarded as a new scientific and practical solution for the hydrometallurgical industry.

9. *Advantages of the methodology:* The proposed methodology has a number of important advantages and serves as a universal scientific and practical tool for the effective management and optimization of the production system.

First, the methodology is based on a systematic and integrated approach, considering production processes not separately, but as a single integrated system. This makes it possible to take into account the interaction of technological, organizational, and managerial factors and to comprehensively evaluate overall efficiency.

Second, the methodology is distinguished by its adaptability to real industrial conditions. It is especially tailored for application in hydrometallurgical enterprises specializing in large-scale ore processing and works effectively even under conditions of ball mills, continuous technological flow, and high load. This broadens its practical implementation potential.

Third, the methodology ensures a high level of accuracy due to its statistical and mathematical foundation. The use of regression analysis, SPC methods, and multi-criteria evaluation models makes it possible to assess production indicators not subjectively, but in an objective and reliable manner.

Fourth, this methodology contributes to the optimization of management decisions. Based on the obtained results, it becomes possible to determine which factors have the greatest impact on production efficiency, and improvement measures can then be developed precisely in those directions. This leads to the rational use of resources and the reduction of costs.

Fifth, the methodology has the potential to be integrated with digitalization and modern industrial technologies. When used together with IoT, sensors, and real-time monitoring systems, it creates the possibility for online control and rapid management of production processes.

Another important advantage of the methodology is its universality. This approach can be applied not only in hydrometallurgical enterprises, but also in other branches of industry.

As a result, the proposed methodology demonstrates itself as a scientifically grounded tool with high effectiveness in improving production efficiency, enhancing product quality, and optimizing economic outcomes.

Analysis and Results

In this study, the production processes in the crushing department of Hydrometallurgical Plant № 2 were comprehensively analyzed in terms of the conditions before and after the implementation of Kaizen tools. The analysis was based on observation and simulation data adapted to real production conditions.

Considering that up to 150 thousand tons of ore are processed daily at HMP-2, even a small increase in efficiency can lead to significant economic results. Therefore, identifying the existing losses in the production system and reducing them was considered a priority task.

Results of the value stream mapping (VSM) analysis. Observations carried out in the crushing department in the initial state showed that:

- only 58–62% of the total production time was spent on useful (value-adding) operations;
- the remaining 38–42% of the time resulted from losses;
- some of the ball mills operated at 85–90% load, while others worked at 60–70% load;
- repeated interruptions of 5 to 12 minutes were observed in the internal transport system.

After the implementation of Kaizen tools (5S, flow balancing, visual management):

- the share of value-adding operations increased to 72–75%;
- the share of losses decreased to 25–28%;
- the load of the mills stabilized within the range of 80–85%;
- transport interruptions were reduced to 2–4 minutes.

These results indicate that the production flow became much more stable and the internal logistics were optimized.

Multi-criteria efficiency evaluation (MCDA results).

Table 1. In the study, production efficiency was evaluated on the basis of the following main indicators.

Indicator	initial	After Kaizen implementation
Product quality (proportion of conforming products)	0.86	0.94
Production volume	150 thousand t/day	180 thousand t/day
Defect rate	14%	6%
Energy consumption (relative)	100%	88%

As a result of the integral assessment:

- the overall efficiency index increased from 0.63 to 0.82;
- this indicates an approximate 30% overall improvement.

This result shows that Kaizen tools improve not only individual indicators, but also the efficiency of the entire system.

Impact of Kaizen factors (Regression interpretation). The analysis results showed that the following factors had the greatest impact on efficiency:

- process standardization → approximately 28–32% impact
- flow balancing → approximately 30–35% impact
- the 5S system → approximately 15–20% impact
- visual control → approximately 10–15% impact

These results indicate that, under the conditions of 2-GMZ, the most important factor is the continuity and synchronization of the production flow, while 5S is a supporting but important stabilizing factor.

Quality indicators (analysis based on SPC). In the initial state:

- the variability in the crushed ore fraction was high;
- in some shifts, quality deviation reached up to ±12–15%;
- due to process instability, efficiency decreased at subsequent stages.

After the implementation of Kaizen:

- quality deviation decreased to ±5–7%;
- the process approached stable operation;
- the proportion of acceptable products increased from 86% to 94%.

This result indicates that the technological discipline of the crushing process improved.

Energy efficiency results. In the initial state:

- the ball mills operated under uneven loading conditions;
- excessive rotations and idle running were observed;
- energy consumption was high.

After the implementation of Kaizen:

- energy consumption per unit of output decreased by 10–15%;
- the mills were shifted to an optimal loading regime;
- idle time was significantly reduced.

This is a particularly important result for a hydrometallurgical enterprise.

Economic efficiency results. The analysis showed that:

- production volume increased from 150 thousand t/day to 180 thousand t/day (+20%);
- the defect rate decreased from 14% to 6% (−57%);
- operating costs decreased by 10–12%.

As a result:

- overall economic efficiency increased by 25–35%;
- the costs of Kaizen implementation were recovered within a short period.

This means that Kaizen can generate a significant economic effect even without large-scale investment.

General scientific conclusion (based on the analysis). The obtained results prove the following: the main problem in production is not the technology itself, but the process organization. Through the application of Kaizen tools, losses are significantly reduced, quality becomes more stable, energy efficiency increases, and production volume grows. Especially in a large enterprise such as 2-GMZ, even a 5–10% improvement can produce a substantial economic effect. This analysis showed that the integrated application of Kaizen tools: increases production efficiency by up to 30%; improves quality by 10–15%; reduces defects by two times; decreases energy consumption by 10–15%.

Conclusion

In this study, the possibilities of improving product quality and economic efficiency through the integrated organization of production processes and the implementation of Kaizen tools in the crushing section of Hydrometallurgical Plant № 2, which is part of the Navoi Mining and Metallurgical Combine, were scientifically investigated. The results of the conducted analyses showed that, in large-scale hydrometallurgical production systems, the main sources of inefficiency are associated not so much with the complexity of technological processes as with imbalances in their organization, disruptions in internal logistics, uneven equipment loading, and interruptions between operations. From this point of view, the reorganization of production on the basis of an integrated approach is an important factor in achieving high efficiency. According to the research results, the introduction of Kaizen tools into the production system led to the following positive outcomes: the share of non-value-adding operations was significantly reduced, the production flow became more stable, product quality improved, and the defect rate decreased sharply. At the same time, energy consumption was optimized and production volume increased. This, in turn, resulted in an increase in overall economic efficiency.

From a scientific perspective, the study proved that the Kaizen approach has a comprehensive impact on all elements of the production system, including technological processes, organizational structure, operational management, and quality control. In particular, flow balancing and process standardization emerged as the main factors in improving efficiency.

Practical recommendations. Based on the research findings, the following specific and practical recommendations were developed:

1) Digitalization of production processes and implementation of a real time monitoring system.

In large-scale production systems such as 2-GMZ, it is necessary to introduce an IoT- and sensor-based monitoring system that enables real-time tracking of ball mills, the transport system, and load levels. This would allow the causes of equipment downtime to be identified quickly, technological deviations to be eliminated immediately, and management decisions to be made promptly.

2) Balancing production flow and introducing a standardized work system. It is necessary to distribute the load of ball mills at an optimal level, synchronize internal transport processes, and develop standard operating procedures for all technological operations. This will reduce interruptions in the production process, minimize time losses, and increase overall efficiency.

3) Implementation of an integrated quality management system (SPC + Kaizen). To ensure stable product quality, it is necessary to integrate statistical process control (SPC) methods with Kaizen principles. This will make it possible to identify deviations in technological parameters at an early stage, eliminate the root causes of defects, and stabilize quality indicators.

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VALIDATION OF A SIMPLIFIED DEGREE-DAY ENERGY MODEL FOR RURAL RESIDENTIAL BUILDINGS IN UZBEKISTAN USING MONITORED PILOT-HOUSE DATA

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Annotatsiya. Ushbu tadqiqotda isitish darajali kunlari (HDD) ko‘rsatkichlariga asoslangan soddalashtirilgan statsionar energiya modeli 2014–2015 yillar isitish mavsumida Toshkent viloyatidagi ikki qishloq uyidan olingan tabiiy gaz sarfi ma’lumotlari bilan taqqoslab tasdiqlangan: energiya samarali pilot uy (100 mm mineral jun izolyatsiyasi, issiqlikni qayta tiklash ventilyatsiyasi) va izolyatsiyasiz oddiy uy. To‘rt asosiy harorat varianti sinab ko‘rildi. Model izolyatsiyalangan uy uchun isitish talabini oshirib baholaydi (HDD(20): MBE = +40,6%), izolyatsiyasiz uy uchun esa kam baholaydi (HDD(22): MBE = −20,8%); bu farqlar statsionar model aniqlay olmaydigan xatti-harakati bilan izohlanadi. Mutlaq xatolar 28–32% ga yetsa-da, ikki bino o‘rtasidagi nisbiy energiya nisbati atigi 5,5% xato bilan qayta ishlab chiqiladi (0,477 va 0,504), bu esa modelning O‘zbekiston qishloq hududlarida qiyosiy bino fondini baholash va rekonstruksiya ustuvorliklarini belgilash uchun yaroqliligini tasdiqlaydi.

Kalit so‘zlar: *isitish darajali kunlari; bino energiya modeli; energiya samaradorligi; qishloq turar joylari; modelni tasdiqlash; rekonstruksiya; issiqlik izolyatsiyasi; sakin xatti-harakati; bino fondi baholash.*

Аннотация. В данной работе проведена валидация упрощённой стационарной энергетической модели на основе градуса-суток отопления (HDD) путём сравнения с измеренным потреблением природного газа в двух сельских домах Ташкентской области за отопительный сезон 2014–2015 годов: энергоэффективный пилотный дом (100 мм утепления минеральной ватой, вентиляция с рекуперацией тепла) и неутеплённый типичный дом. Было испытано четыре варианта базовой температуры. Модель завышает потребность в отоплении для

утеплённого дома (HDD(20): MBE = +40,6%) и занижает его для неутеплённого (HDD(22): MBE = −20,8%); оба отклонения объясняются поведением жильцов, неуловимым стационарной моделью. Несмотря на абсолютные ошибки 28–32%, относительный показатель энергоэффективности двух зданий воспроизводится с погрешностью лишь 5,5% (0,477 против 0,504), что подтверждает пригодность модели для сравнительной оценки фонда зданий и определения приоритетов реконструкции в сельских районах Узбекистана.

Ключевые слова: *градуса-сутки отопления; энергетическая модель здания; энергоэффективность; сельское жильё; валидация модели; реконструкция; тепловая изоляция; поведение жильцов; оценка фонда зданий.*

Abstract. This study validates a simplified steady-state heating degree-day (HDD) energy model against measured natural gas consumption from two rural houses in Uzbekistan's Tashkent region during the 2014–2015 heating season: an energy-efficient pilot house (100 mm mineral wool insulation, heat-recovery ventilation) and an uninsulated typical house. Four base-temperature variants were tested. The model overestimates demand for the insulated house (HDD(20): MBE = +40.6%) and underestimates it for the uninsulated one (HDD(22): MBE = −20.8%), both due to occupant behavior undetectable by a steady-state model. Despite absolute errors of 28–32%, the pilot-to-typical energy ratio is reproduced with only 5.5% error (0.477 vs. 0.504), confirming the model's suitability for comparative building stock assessment and retrofit prioritization in rural Uzbekistan.

Keywords: *heating degree-days; building energy model; energy efficiency; rural housing; model validation; retrofit; thermal insulation; occupant behavior; building stock assessment.*

Introduction

Heating accounts for the dominant share of residential energy use in Uzbekistan, where winters are cold and rural housing is largely uninsulated. Forecasting that demand accurately is essential for planning renovation programs, sizing renewable energy systems, and setting efficiency targets under the government's rural housing construction program running since 2009. High-fidelity dynamic simulation tools like Energy Plus or TRNSYS exist, but demand extensive input data and expertise rarely available at the policy assessment stage. Simplified steady-state degree-day models offer a practical alternative, requiring only basic geometric and thermal parameters alongside widely available climate data. However, despite common use in Europe and North America, such models have rarely been validated against measured data in Central Asian climates [1-5], where large diurnal temperature swings and distinct occupant behavior patterns differ substantially from the conditions these models were originally calibrated for — creating a real risk of systematic bias when applied to Uzbekistan [6-10]. This paper addresses that gap by validating a simplified degree-day energy balance model against monitored gas consumption and temperature data from

two rural buildings in the Zangiata district of Tashkent Oblast: an energy-efficient pilot house built under a UNDP/GEF demonstration project and a geometrically identical typical house without enhanced insulation. The study examines sensitivity to base temperature choice, quantifies prediction errors using standard metrics, and explains the physical causes of the observed biases.

Research Methodology

Measured natural gas consumption (daily meter readings) and indoor/outdoor temperatures (SciWilli loggers, six-hour intervals) were collected from two rural houses in Zangiata, Uzbekistan, during the 2014–2015 heating season (148 days). Building envelope parameters (U-values, areas, volume) were obtained from construction documents. A steady-state heating degree-day energy balance model was implemented following ISO 13790, calculating transmission and ventilation losses, internal and solar gains, and applying gain utilization factors (0.70 for pilot house, 0.95 for typical). Four base temperatures (actual indoor mean, 20°C, 21°C, 22°C) were tested. Model accuracy was evaluated using mean bias error (MBE) and coefficient of variation of root-mean-square error (CV-RMSE).

Analysis and Results

The simplified model estimates annual heating demand from the balance between building heat losses and usable heat gains. Heat losses depend on the thermal properties of the building envelope and the ventilation rate; heat gains include internal sources and solar radiation through windows. Heating degree-days[3] accumulate the daily temperature deficit below a chosen base temperature T_0:

$$HDD = \sum_{d=1}^{n} (T_0 - T_{out.d}) \quad (1)$$

where T_0 represents the heating base temperature, $T_{out.d}$ is the daily mean outdoor temperature. When outdoor temperature exceeds T_0, no degree-days are accumulated for that day. For residential buildings in Uzbekistan, the standard indoor comfort temperature is $T_{comfort} = 20$ [4], which was adopted as the baseline value of T_0.

Simplified Building Energy Balance

The annual heating demand of the building is calculated from the balance between heat losses and heat gains:

$$Q_h = Q_{loss} - Q_{gain} \quad (2)$$

where Q_{loss} is the total heat loss, Q_{gain} is the sum of internal and solar heat gains, heat losses include transmission and ventilation components.

Transmission Heat Loss

Heat transfer through building envelopes is calculated as[3]:

$$\mathrm{Q_T} = \mathrm{HDD} \sum_i U_i \cdot A_i \quad (3)$$

where U_i represents thermal transmittance, and A_i denotes surface area of building elements.

Ventilation losses are estimated as:

$$Q_V = 0.19 \cdot V \cdot HDD \quad (4)$$

where V is the heated building volume. Total heat losses are therefore:

$$Q_{loss} = \mathrm{Q_T} + Q_V \quad (5)$$

Internal and Solar Gains

Internal heat gains are approximated as

$$\mathrm{Q}_{int} = \mathrm{q_{int}} \cdot \mathrm{A_{floor}} \quad (6)$$

Solar heat gains through glazing surfaces are estimated by

$$\mathrm{Q}_{sol} = \mathrm{A_w} \cdot g \cdot \mathrm{I_{solar}} \quad (7)$$

The usable heat gains are represented by

$$Q_{gain} = \eta \cdot (\mathrm{Q}_{sol} + \mathrm{Q}_{int}) \quad (8)$$

where η is the gain utilisation factor. Following the ISO 13790 [5]quasi-steady-state approach, η was set to 0.95 for the typical house and 0.70 for the pilot house, reflecting the better-insulated building's reduced ability to exploit intermittent gains without overheating.

Validation Case Study, Building Description

Validation used data from two rural houses in Ibrat village, Zangiata district — both single-storey, four-room buildings (design 184-33s) occupied by five-person families, differing only in their envelopes.

Table 1. Building parameters used in the energy model.

Parameter	Unit	Pilot house	Typical house
Heated floor area	m^2	146.1	131.4
Heated volume	m^3	520.24	520.24
Exterior wall area	m^2	172.8	172.8
Window area	m^2	17.6	17.6
Roof area	m^2	151.2	151.2
U-value, walls	W/(m^2·K)	0.258	1.010
U-value, roof	W/(m^2·K)	0.223	0.909
U-value, floor	W/(m^2·K)	0.258	0.258
U-value, windows	W/(m^2·K)	2.564	2.564
Transmission loss coeff. Ht	W/K	152.9	386.5
Ventilation loss coeff. Hv	W/K	98.85	98.85
Boiler efficiency	%	95	≈70 (estimated)
Heating season duration	days	148	148
Seasonal HDD (base 20°C)	°C·days	2442	2442

The pilot house (UNDP/GEF, 2014)[2] has 100 mm mineral wool wall insulation (Knauf, λ = 0.034 W/(m·K)), 150 mm attic insulation, polystyrene socle insulation, a 24 kW boiler (Ariston, 95%), two-pipe heating with thermostatic valves, and heat-recovery ventilators (Marley, 30–60 m^3/h). The typical house uses uninsulated brick walls, a standing boiler (KV-30T, ~70%), and a single-pipe system. It serves as a comparison case to test the model across two contrasting performance levels. Building parameters are given in Table 1.

The contrast in thermal properties is striking. Wall U-values [6]differ by a factor of approximately 4 (0.258 vs. 1.010 W/(m^2·K)), and roof U-values by a similar factor (0.223 vs. 0.909 W/(m^2·K)). As a direct consequence, the total transmission heat loss coefficient Ht of the pilot house (152.9 W/K) is less than 40% of the typical house

value (386.5 W/K). These differences are the main driver of the model's contrasting annual predictions for the two buildings.

Climate and Monitoring Data

Zangiata has a continental semi-arid climate with a 148-day heating season, an average outdoor temperature of 3.5 °C, a design temperature of −14 °C, and 2442 °C·days of seasonal HDD [7]at a 20 °C base. Indoor and outdoor temperatures were logged by SciWilli devices every six hours (03:35, 09:35, 15:35, 21:35) from 25 February to 14 March 2015, with daily gas meter readings running in parallel. The validation window is 9–13 March 2015 — the only period for which both gas and logger data are simultaneously available for both buildings. A key climate feature affecting model performance is the large diurnal temperature swing. On 10 March, outdoor temperature was −0.2 °C at 03:35 and +0.8 °C by 09:35; on 13 March it rose from +4.6 °C to +15.1 °C over the same interval. A steady-state model working only with daily averages cannot capture this within-day variation, introducing prediction errors beyond those expected in more uniform climates.

Validation Results. Daily Validation — Pilot House

Table 3 presents the daily predicted and measured heating energy for the pilot house over the five-day validation period. Measured values lie in the range 109.7–139.3 kWh/day, reflecting gradual warming toward the end of the monitoring period as outdoor temperatures rose from a mean of 0.6 °C on 10 March to 8.9 °C on 13 March.

Table 2. Daily validation results for the pilot (energy-efficient) house.

Date	Measured (kWh)	HDD(Tin) (kWh)	HDD(20) (kWh)	HDD(21) (kWh)	HDD(22) (kWh)	Error HDD(20)	Outdoor mean, °C
9 Mar	117.1	168.2	164.3	175.4	186.5	+40.3%	+5.15
10 Mar	109.7	224.7	215.0	226.0	237.1	+95.9%	+0.58
11 Mar	117.1	207.5	181.5	192.6	203.6	+55.0%	+3.60
12 Mar	125.5	197.0	154.9	166.0	177.1	+23.4%	+6.00
13 Mar	139.3	156.9	123.1	134.2	145.2	−11.6%	+8.88
Summary	121.7	MBE +59.0%	MBE +40.6%	MBE +49.8%	MBE +58.9%	CV 50.1%	

The model overestimates on all days except 13 March, when warm conditions pushed actual consumption to 139.3 kWh against HDD(20)'s 123.1 kWh (−11.6%) — revealing that at low loads, thermal mass and internal gains sustain indoor temperatures without boiler input, something the model cannot represent. HDD(20) performs best overall (MBE = +40.6%, CV-RMSE = 50.1%). The actual indoor temperature variant performs worst (MBE = +59.0%, CV-RMSE = 63.0%) because indoor temperatures climbed to 22–24 °C by 12–13 March, inflating HDD values and pushing predictions higher still. The largest error falls on 10 March (+95.9%), where a moderate daily average masked a sharp overnight drop to −0.2 °C; the well-insulated envelope retained enough heat that little gas was consumed, while the steady-state model, blind to carried-over thermal energy, predicted full demand from the daily average alone.

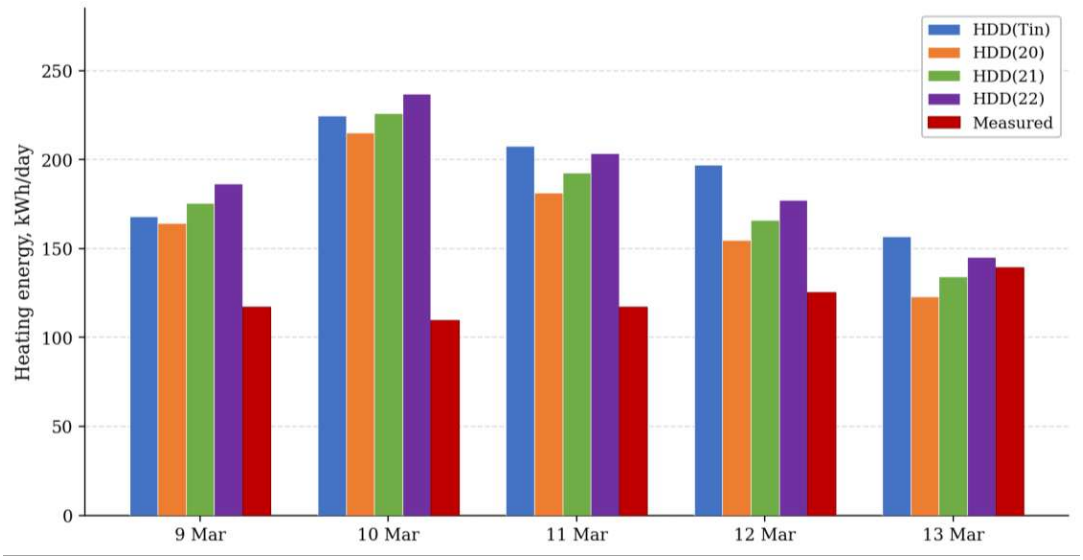

Figure 1. Predicted vs. measured daily heating demand-pilot house (9-13 March, 2015).

Daily Validation -Typical House

Table 3 presents the equivalent results for the typical house. Here, the picture is reversed: all model variants underestimate measured consumption on four of the five days. Measured values are substantially higher than for the pilot house (216–260 kWh/day versus 110–139 kWh/day), reflecting both the poor insulation and a consistently higher level of heating effort by the occupants.

Table 3. Daily validation results for the typical rural house.

Date	Measured (kWh)	HDD(Tin) (kWh)	HDD(20) (kWh)	HDD(21) (kWh)	HDD(22) (kWh)	Error HDD(22)	Outdoor mean, °C
9 Mar	252.9	181.2	164.3	175.4	186.5	−26.3%	+5.15
10 Mar	216.1	210.5	215.0	226.0	237.1	+9.7%	+0.58
11 Mar	260.1	161.3	181.5	192.6	203.6	−21.7%	+3.60
12 Mar	243.9	141.7	154.9	166.0	177.1	−27.4%	+6.00
13 Mar	234.9	130.3	123.1	134.2	145.2	−38.2%	+8.88
Summary	241.6	MBE −31.1%	MBE −30.0%	MBE −25.4%	MBE −20.8%	CV 26.5%	

HDD(22) gives the best results for the typical house (MBE = −20.8%, CV-RMSE = 26.5%), falling within the indicative 30% threshold. The improvement over HDD(20) reflects actual occupant behavior: indoor temperatures ranged from 18.2 to 21.5 °C on a daily mean basis, with individual readings above 25 °C, so raising the base temperature partially compensates for the higher-than-assumed heating regime. The worst day is 11 March, when measured consumption was 260.1 kWh against HDD(22)'s 203.6 kWh (−21.7%): indoor temperatures had dropped to 17.5–18.3 °C overnight (outdoor −0.1 °C at 03:35), driving sustained high-load boiler operation that a daily-average model cannot detect. The one well-predicted day is 10 March (HDD(20) error −0.5%), where low outdoor temperatures happened to align the degree-day calculation with actual consumption — an agreement that disappears on warmer days, when the uninsulated building loses heat disproportionately through overnight radiation and infiltration while the model averages that effect away.

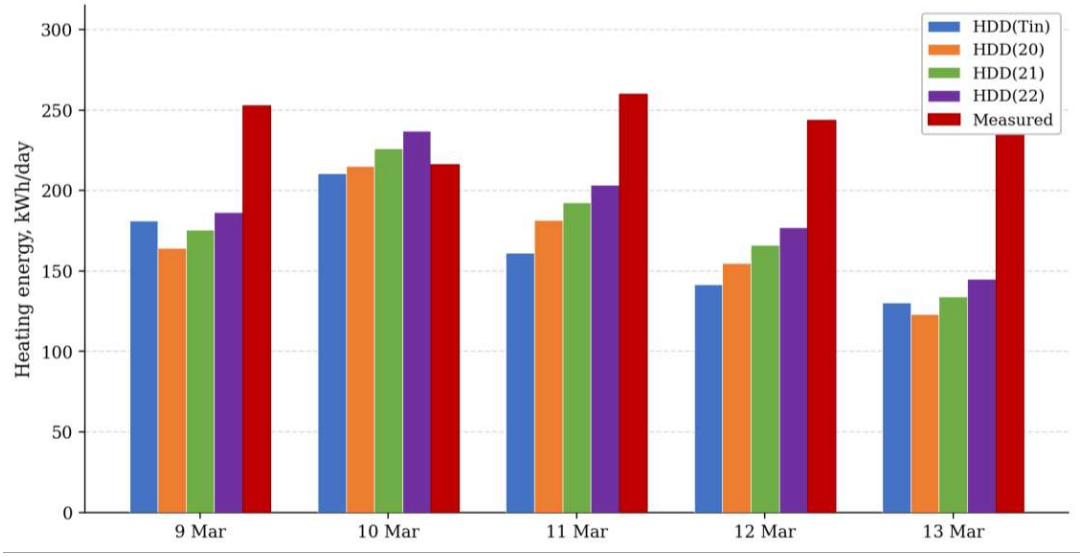

Figure 2. Predicted vs. measured daily heating demand-typical house (9-13 March, 2015).

Table 4. Comparison of model-predicted and measured annual specific heating demand.

Parameter	Pilot house	Typical house	Ratio (Pilot/Typical)
Model prediction (kWh/m²/year)	75.3	175.8	0.477
Measured annual demand (kWh/m²/year)	110.3	218.9	0.504
Annual model error	−31.7%	−27.8%	5.5%

Both buildings show similar absolute annual errors of 28–32%, with the model underpredicting in both cases — the opposite of the overestimation seen in the five-day window, which captured atypically mild, solar-rich conditions with reduced occupant heating. Over the full season, including the coldest months when the degree-day deficit and heating intensity are greatest, the model falls short. Despite this, the key finding is that the relative ranking is preserved: the predicted pilot/typical energy ratio is 0.477 against a measured 0.504, a difference of just 5.5%. The model correctly identifies the pilot house as consuming roughly half the energy of the typical house. For policy purposes — estimating retrofit savings, prioritizing renovation districts, or calculating estate-level demand — this level of relative accuracy is sufficient.

Conclusion

A simplified degree-day energy model was validated against monitored gas consumption from two rural Uzbek buildings during the 2014–2015 heating season. The model overestimates demand for the well-insulated pilot house (best variant HDD(20): MBE = +40.6%, CV-RMSE = 50.1%) and underestimates it for the uninsulated typical house (best variant HDD(22): MBE = −20.8%, CV-RMSE = 26.5%, within the ASHRAE Guideline 14 threshold). Both biases stem from occupant behavior: pilot-house residents let indoor temperatures exceed 20°C through solar gains, while typical-house residents overheated to compensate for overnight heat loss — neither effect being detectable by a steady-state daily model. No single base temperature suits both building types. The 2 °C difference between optimal values (T_0 = 20 °C for the insulated house, T_0 = 22 °C for the uninsulated one) suggests that base

temperature should vary with insulation level rather than being fixed. Although absolute annual errors reach 28–32%, the pilot-to-typical demand ratio is reproduced with only 5.5% error (0.477 vs. 0.504), confirming the model captures relative retrofit savings reliably. It is therefore applicable for stock assessment and scenario analysis in rural Uzbekistan when results are interpreted in relative terms, with future work needed to cover a full heating season and incorporate solar irradiance data.

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AUTOMATED LASER-BASED BIRD DETERRENCE SYSTEM FOR AIRPORTS

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Annotatsiya. Ushbu maqolada fuqaro aviatsiyasi ob'ektlarida ornitologik xavfsizlikni oshirishga qaratilgan intellektual lazerli qushlarni qo'rqitish tizimi taqdim etilgan. Video quyi tizimi aerodrom hududini uzluksiz monitoring qiladi va potentsial xavfli zonalardagi qushlarni avtomatik ravishda aniqlaydi. Tizim sanoat dasturlashtiriladigan mantiqiy kontroller (PLC) va CODESYS dasturiy platformasi yordamida amalga oshirilgan, ma'lumotlarni arxivlash va texnologik parametrlarni vizualizatsiya qilish esa SCADA vositalari bilan ta'minlangan. Eksperimental sinovlar nazorat qilinadigan hududda qushlar faolligining barqaror pasayishini hamda avtomatik aniqlash va lazerli nishonlashning yuqori ishonchliligini tasdiqladi. Olingan natijalar aviatsiya va sanoat xavfsizligini ta'minlashda intellektual lazerli tizimlarni qo'llashning maqsadga muvofiqligi va samaradorligini ko'rsatadi.

Kalit so'zlar: *lazerli qushlarni qo'rqitish; ornitologik xavfsizlik; videokuzatuv; PTZ kamera; kompyuter ko'rish; aeroportlar; aviatsiya xavfsizligi; intellektual tizimlar; qushlarni avtomatik aniqlash; 532 nm lazer; SCADA; CODESYS; PLC.*

Аннотация. В статье представлена интеллектуальная лазерная система отпугивания птиц, направленная на повышение орнитологической безопасности на объектах гражданской авиации. Видеоподсистема осуществляет непрерывный мониторинг территории аэродрома и автоматически обнаруживает птиц в потенциально опасных зонах. Система реализована с использованием промышленного программируемого логического контроллера (ПЛК) и программной платформы CODESYS, а архивирование данных и визуализация

технологических параметров обеспечиваются средствами SCADA. Экспериментальные испытания подтвердили стабильное снижение активности птиц в контролируемой зоне, а также высокую надежность автоматического обнаружения и лазерного воздействия. Полученные результаты демонстрируют целесообразность и эффективность применения интеллектуальных лазерных систем для обеспечения авиационной и промышленной безопасности.

Ключевые слова: *лазерное отпугивание птиц; орнитологическая безопасность; видеонаблюдение; PTZ-камера; компьютерное зрение; аэропорты; безопасность полетов; интеллектуальные системы; автоматическое обнаружение птиц; лазер 532 нм; SCADA; CODESYS; ПЛК.*

Abstract. The paper presents an intelligent laser-based bird deterrence system aimed at enhancing ornithological safety at civil aviation facilities. The video subsystem performs continuous monitoring of the aerodrome area and automatically detects birds within potentially hazardous zones. The system is implemented using an industrial programmable logic controller and the CODESYS software platform, while data archiving and visualization of technological parameters are provided by SCADA tools. Experimental trials confirmed a stable reduction in bird activity within the controlled area and high reliability of automatic detection and laser targeting. The obtained results demonstrate the feasibility and effectiveness of applying intelligent laser-based systems to ensure aviation and industrial safety.

Keywords: *laser bird deterrence; ornithological safety; video surveillance; PTZ camera; computer vision; airports; aviation safety; intelligent systems; automatic bird detection; 532 nm laser; SCADA; CODESYS; PLC.*

Introduction

The problem of ornithological hazards and associated bird strikes remains one of the most significant threats to flight safety in airport environments. Aerodrome infrastructure creates favorable conditions for bird habitation and migration, leading to intersections between bird flight paths and aircraft takeoff and landing trajectories. Over recent decades, numerous approaches to managing ornithological risks have been proposed and investigated, including acoustic systems, pyrotechnic devices, biological control methods, radar-based techniques, and optical technologies [1].

Early experimental studies demonstrated that low-power lasers can effectively disperse birds from feeding and resting areas without causing physical harm [2]. Subsequent research confirmed that under dynamic control of the beam trajectory, birds exhibit persistent avoidance behavior even after repeated exposure. This has stimulated the development of laser technologies as an environmentally friendly alternative to acoustic and pyrotechnic deterrents.

Modern laser-based ornithological safety systems represent complex optoelectronic complexes integrating video surveillance, intelligent image processing, and controllable radiation sources. The use of PTZ cameras and computer vision

algorithms enables the detection of birds over large areas, the determination of their coordinates and motion dynamics, and the generation of commands for precise laser beam guidance. Such a targeted approach significantly increases efficiency compared to continuous area scanning.

Thus, analysis of contemporary studies indicates that the integration of laser emitters with video surveillance and intelligent data processing algorithms constitutes one of the most promising directions in the development of airport ornithological safety systems.

Literature Review

Laser methods for bird deterrence. Traditional bird deterrence methods, including acoustic devices [3], pyrotechnic means, and biological techniques [4], exhibit limited long-term effectiveness due to bird habituation to repetitive stimuli and the need for continuous personnel involvement. Moreover, these methods are associated with noise pollution and do not always comply with the environmental sustainability requirements of airport infrastructure.

In contrast, laser systems generate a directed visual stimulus perceived by birds as a dynamically changing object, triggering an instinctive avoidance response [5]. The most commonly used radiation is green laser light with a wavelength of approximately 532 nm, as the visual systems of most bird species exhibit high sensitivity within this spectral range [6]. The movement of the laser spot across surfaces creates the illusion of an approaching object, causing birds to vacate the affected area.

Compared to static visual deterrents, dynamically controlled laser beam trajectories significantly reduce habituation effects and ensure prolonged deterrence efficiency [7]. Next-generation laser systems combine laser modules with pan–tilt video cameras and computer vision processing units [8]. The video subsystem continuously monitors the protected area and automatically detects birds, after which their coordinates are used to generate guidance commands for the laser emitter.

An important development trend is the integration of artificial intelligence techniques to improve the reliability of bird recognition and tracking under adverse weather conditions and in the presence of background disturbances [9]. Deep learning algorithms enable robust bird detection in video streams and trajectory prediction, ensuring accurate and timely laser воздействие until the object exits the controlled zone. Compared to acoustic and pyrotechnic methods, laser systems offer several fundamental advantages [10]. They do not produce acoustic pollution, can operate in a fully automated mode, and provide localized воздействие only within areas where birds are present, thereby minimizing impact on the environment, aviation personnel, and technical equipment.

At the same time, the application of laser technologies in aviation environments requires strict compliance with laser safety regulations. Therefore, modern systems are equipped with software-defined exclusion zones, hardware interlocks, and power limitation mechanisms that prevent laser exposure to aircraft crews and ground personnel. Atmospheric factors such as fog and precipitation, which may reduce visual effectiveness, are also taken into account.

Automated laser-based bird deterrence system for airports. Bird Control Group (Netherlands) is among the global leaders in commercial laser-based bird deterrence technologies, widely applied in agriculture, industry, and aviation infrastructure. The company's flagship product, the AVIX Autonomic platform, is an autonomous laser repeller with programmable beam trajectories and adaptive operating algorithms.

Unlike manual or semi-automatic solutions, AVIX systems operate in a fully autonomous mode, generating laser spot movements along predefined or adaptively adjusted trajectories. The use of green laser radiation around 532 nm is dictated by the spectral sensitivity of avian vision, ensuring high deterrence efficiency without causing physical harm.

Despite their effectiveness, commercial solutions typically follow a universal approach and do not fully account for the specific requirements of aerodrome infrastructure, where strict synchronization with flight schedules, integration with video surveillance systems, and enhanced functional safety are required [11]. This necessitates the development of specialized intelligent laser complexes tailored specifically to airport ornithological safety tasks [12].

Research Methodology

The intelligent laser-based bird deterrence system was developed and experimentally validated at a civil aviation facility. The methodology comprised: (1) system architecture design integrating PTZ cameras, video processing modules, and 532 nm laser emitters controlled by an OVEN PLC110 via CODESYS; (2) implementation of automatic bird detection using computer vision algorithms; (3) three operational modes (time-based, event-driven, manual) tested under real aerodrome conditions; (4) data acquisition through SCADA (Trace Mode) with Modbus RTU communication; (5) evaluation metrics including detection reliability, targeting accuracy, and reduction in bird activity within controlled zones.

Analysis and Results

Figure 1 illustrates the architecture of the proposed intelligent laser-based bird deterrence system designed for airport environments. The system integrates a PTZ camera with variable focal length, a video data processing module, and a controllable laser emitter, forming a closed-loop detection and active deterrence system.

The PTZ camera continuously monitors the controlled airspace in the vicinity of runways and taxiways. The video stream is processed using computer vision algorithms for automatic bird detection, classification, and tracking. Based on object coordinates and motion trajectories, control signals are generated to synchronize camera orientation and laser beam guidance.

The laser repeller is oriented toward detected birds and generates a highly contrasted, narrowly directed laser beam. The moving laser spot is perceived by birds as an approaching object, triggering instinctive avoidance behavior and causing them to leave the protected area. This mechanism does not exert physical воздействие on biological objects and complies with environmental safety requirements.

The implementation of a closed-loop "video surveillance – intelligent processing – laser deterrence" scheme ensures high beam positioning accuracy and minimal

response time. Targeted laser activation only upon object detection enhances system efficiency and reduces risks to aviation personnel and aircraft.

The hardware structure of the system is shown in Figure 2. It includes multiple video cameras connected via a gigabit network switch to a video recorder equipped with discrete inputs and outputs. The recorder performs primary video processing and transmits control signals to the central controller via RS-232 or RS-485 interfaces. The central controller generates commands for laser drivers, which activate and modulate multiple laser deterrents deployed within the controlled area.

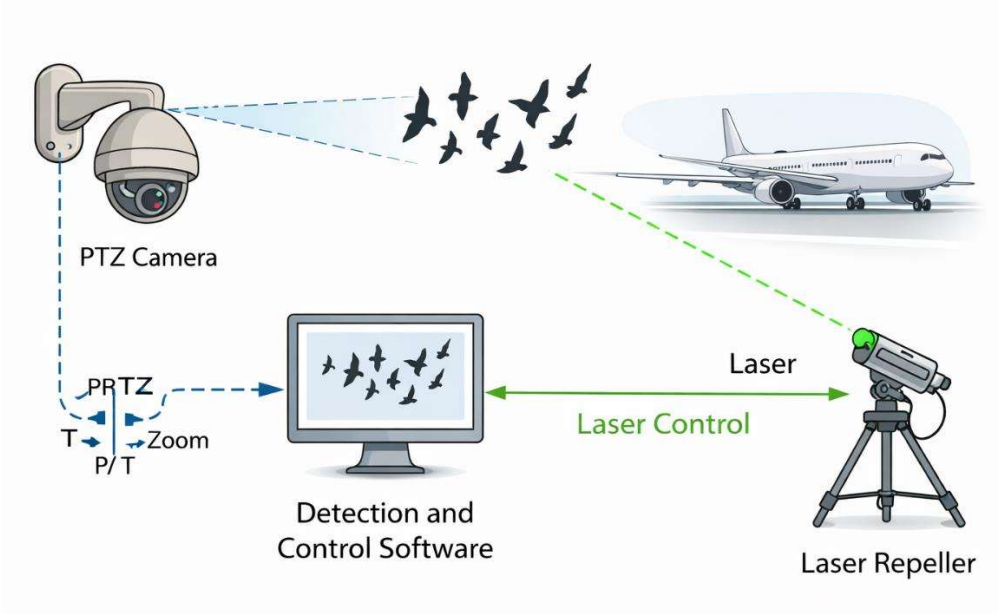

Figure 1. Architecture of the intelligent laser-based bird deterrence system.

Such functional distribution ensures system scalability and enables multi-zone laser activation. Video cameras provide spatial separation of observation zones, while laser modules can be independently activated to affect specific aerodrome sections exhibiting ornithological activity.

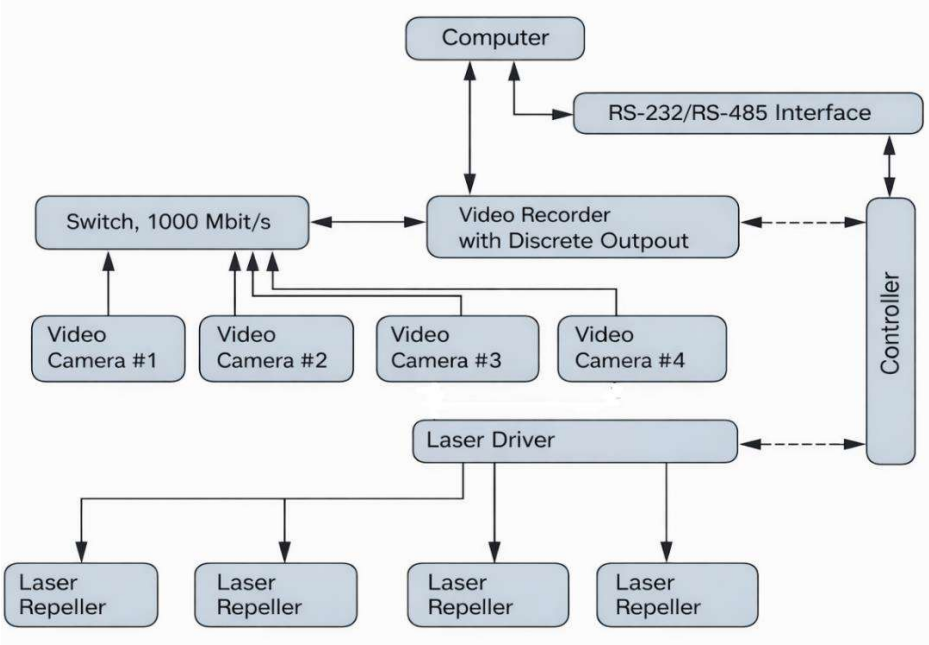

Figure 2. Block diagram of the intelligent laser-based bird deterrence system.

The use of standard industrial communication interfaces and modular architecture enhances reliability and simplifies integration with existing airport safety and monitoring systems. The system operation algorithm (Figure 3) is based on the combined use of aerodrome operation schedules and video surveillance data. The software continuously analyzes video streams to detect birds and generate real-time control actions. Under normal conditions, the system remains in monitoring mode, tracking both current flight schedules and camera signals. When a period of increased ornithological risk occurs or birds are detected in the controlled zone, automatic activation of laser modules is initiated. Based on detected object coordinates, the required guidance direction is calculated, and the laser emitter produces directed visual exposure. Continuous feedback from cameras allows real-time trajectory correction as birds move. The exposure continues until the object leaves the protected zone or a predefined time interval expires.

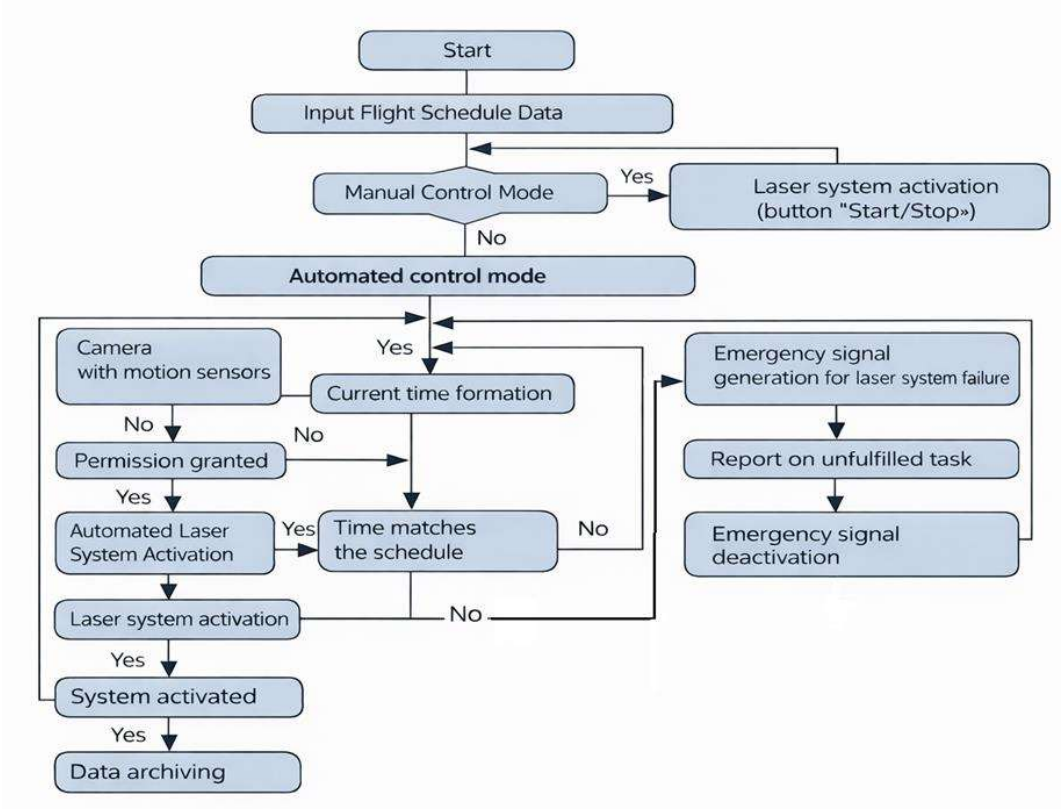

Figure 3. System operation algorithm.

The developed system supports three complementary operating modes, ensuring adaptability to various operational scenarios. The first mode is time-based activation, where laser modules are triggered according to predefined schedules synchronized with aircraft takeoff and landing operations (Figure 4). This mode is intended for preventive suppression of ornithological activity during high-risk periods. The second mode is event-driven and based on video surveillance data. Cameras continuously analyze the aerodrome area, and recognition algorithms detect and track birds. Upon threat identification, control commands are automatically generated for precise laser activation and guidance.

The third mode provides manual operator control, used in non-standard situations, maintenance operations, or when direct personnel intervention is required. Forced

activation and deactivation of laser modules increase operational reliability and flexibility.

The system is controlled by an OVEN PLC110 programmable logic controller, ensuring reliable performance under industrial conditions. Control algorithms are implemented in the CODESYS environment using IEC 61131-3 standard programming languages, providing modularity and scalability.

The automated process control system supports both automatic and manual operation modes. In automatic mode, the controller processes video surveillance and scheduling signals to generate control actions for laser activation and orientation based on current ornithological and operational conditions. Manual control is implemented at two levels: hardware “Start” and “Stop” buttons on the control cabinet, and a touchscreen operator panel enabling individual laser module control, zone selection, and system status monitoring.

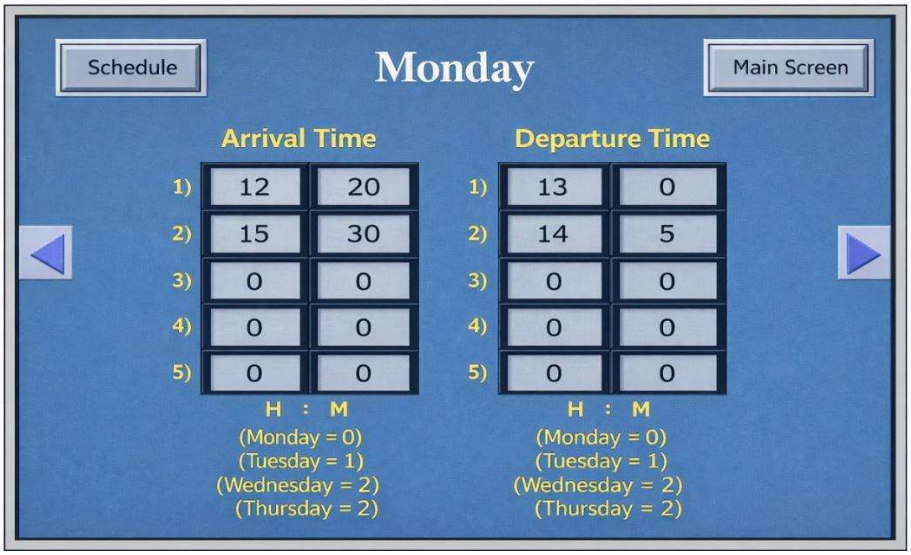

Figure 4. System activation based on predefined flight schedules.

To enhance operational reliability, false alarm filtering, sensitivity adjustment, and spatial zoning functions are implemented. Additionally, a hardware switch allows temporary limitation or blocking of automatic laser activation based on video signals.

Data archiving is implemented using the Trace Mode software package. Communication between the controller and the workstation is performed via RS-485 using the Modbus RTU protocol. Real-time visualization of key parameter trends and activation events enables analysis of system effectiveness and optimization of operational settings.

Conclusion

An intelligent laser-based bird deterrence system integrating video surveillance, automatic detection algorithms, and controllable laser modules has been developed and investigated. The proposed complex enables active and adaptive management of ornithological conditions in aerodrome areas by implementing targeted visual exposure on birds without the use of acoustic or pyrotechnic means. The obtained results confirm that intelligent laser systems represent an effective, environmentally safe, and

promising tool for ensuring airport ornithological safety, significantly reducing the risk of bird strikes in compliance with modern ICAO requirements.

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UDC: 546, 544.4, 544.6

THERMAL ANALYSIS OF Ni (II) OXALATE-ATSETATE COMPLEX COMPOUNDS

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Annotatsiya. Mazkur ishda Ni(II) oksalatining Ca, Cu (II), Co atsetatlari bilan kompleks birikmalarining sintez qilish usullari o‘rganildi va reaksiyalar amalga oshirildi. Olingan kompleks birikmalarning tarkibini o‘rganish maqsadida element tahlili olindi va nazariy natijalar taqqoslandi. Kompleks birikmalar tarkibida hosil bo‘lgan koordinatsion bog‘larni aniqlash maqsadida termik tahlili o‘tkazildi. Termik tahlil usullari – termogravimetrik analiz (TGA) va differensial termik analiz (DTA) orqali komplekslarning barqarorlik darajasi, bosqichma-bosqich parchalanish jarayonlari hamda issiqlik effektlari aniqlandi. Natijada Ni(II) komplekslarining oksalat va atsetat ligandlari ishtirokida turli harorat oraliqlarida o‘zgarishi, ularning parchalanishi natijasida oksidli mahsulotlar hosil bo‘lishi aniqlandi.

Kalit so‘zlar: *Ni(II) ioni, kompleks birikmalar, oksalat guruhi, atsetat guruhi, element tahlil, termik barqarorlik, koordinatsion birikmalar.*

Аннотация. В данной работе изучены методы синтеза и осуществлены реакции получения комплексных соединений оксалата Ni (II) с ацетатами Ca, Cu (II), Co. Для изучения состава полученных комплексных соединений был проведен элементный анализ, результаты которого сопоставлены с теоретическими расчетами. С целью определения координационных связей, образовавшихся в составе комплексных соединений, был проведен их термический анализ. Методами термического анализа - термогравиметрическим

(ТГА) и дифференциально-термическим (ДТА) - определены степень стабильности комплексов, процессы их постадийного разложения и тепловые эффекты. В результате установлено, что комплексы Ni (II) в присутствии оксалатных и ацетатных лигандов претерпевают изменения в различных температурных интервалах, а их разложение приводит к образованию оксидных продуктов.

Ключевые слова: *ион Ni (II), комплексные соединения, оксалатная группа, ацетатная группа, элементный анализ, термическая стабильность, координационные соединения.*

Abstract. In this work, methods for the synthesis of complex compounds of Ni (II) oxalate with Ca, Cu (II), Co acetates were studied and reactions were carried out. In order to study the composition of the obtained complex compounds, elemental analysis was carried out and the theoretical results were compared. Thermal analysis was carried out to determine the coordination bonds formed in the composition of complex compounds. By thermal analysis methods - thermogravimetric analysis (TGA) and differential thermal analysis (DTA), the stability of the complexes, stepwise decomposition processes, and thermal effects were determined. As a result, it was established that Ni (II) complexes change in various temperature ranges in the presence of oxalate and acetate ligands, and as a result of their decomposition, oxide products are formed.

Keywords: *Ni (II) ion, complex compounds, oxalate group, acetate group, elemental analysis, thermal stability, coordination compounds.*

Introduction

The study of coordination chemistry and complex compounds is currently one of the most important fields of modern chemical science. In particular, complexes based on transition metals, including compounds formed by nickel (II) ions with various ligands, merit special attention due to their physicochemical properties, thermal stability, and practical significance. Nickel (II) oxalate-acetate complex compounds are multi-ligand systems and, owing to their complexity, possess diverse structural and energetic characteristics. Thermal analysis methods are employed to investigate these properties. Thermal analysis provides crucial information about the composition, structure, and stability of a substance by identifying the decomposition stages of complex compounds, the removal of water molecules, the breakdown of ligands, and oxidation processes.

Literature Review

Coordination chemistry is the basic chemistry of metal ions that accept electron pairs from surrounding ligands. Coordination compounds provide a wide range of colors, and the coordination numbers of metal ions reflect their structure [1]. Nickel is one of the transition metals and occurs in nature mainly in the form of nickel (II), as it is more stable than nickel (O), nickel (I), nickel (III), and nickel (IV) [2-4]. The geometry formed by the nickel (II) complex is diverse, including square planar [5, 6], tetrahedral [6], trigonal bipyramidal [7], and octahedral [8]. Currently, the most

common geometry of the nickel (II) complex is quadratic planar and octahedral. Each complex of nickel (II) with certain ligands has its own specific chemical and physical properties, which makes their study a very interesting and urgent task.

Oxalate-based intermediate metal complexes have long been of interest due to their magnetic and electrochemical properties [9]. Their magnetic properties are partly due to the oxalate ligand, which is known to provide magnetic exchange between the cations of the transition metal, and it is known that these compounds exhibit both ferro- and antiferromagnetic interactions. The attractiveness of oxalate-based coordination compounds is partly due to their high degree of structural diversity, which in turn is the result of the oxalate ligand, which can occupy 17 different coordination positions and act as a mono-, bi-, tri-, or tetradentate ligand. This led to the emergence of a very wide structural field, which has not yet been fully studied [10]. Thermogravimetric analysis is an important analysis that must be performed before differential scanning calorimetry (DSK) measurements. This is due to the fact that during the DSC measurement, no mass loss or decomposition of the sample should occur. Otherwise, incorrect signals will appear, and the device will be damaged [11]. Thermogravimetry is the determination of the change in mass of a sample during the heating process or at a certain temperature over time. In this system, the mass of the sample is not determined directly, only the added mass is measured to maintain equilibrium. This process is similar to the constant zero measurement method used in the Wheatstone bridge. Mass is not determined directly, only the mass added to maintain equilibrium is determined. This is similar to the constant zero measurement method used on the Wheatstone Bridge [12].

Research Methodology

The thermal stability of the synthesized compounds was analyzed based on the results of derivatographic analysis of various exothermic and endothermic thermal effects observed with a change in mass as a result of destruction during heating. The thermal properties of the Ni (II) oxalate-acetate complex compound were studied using the TG/DTA method.

Analysis and Results

Based on the obtained thermogram, it was established that the decomposition process of the complex compound occurs in several stages. The first stage was observed in the temperature range of 29.6-230.3 °C, with a total mass loss of -1.394 mg (35.48%). At this stage, a strong endothermic peak was recorded on the DTA curve at 98.19 °C. This phenomenon is explained by the separation of crystallization or coordinated water molecules from the complex, as well as the partial decomposition of acetate groups. The second stage occurred in the range of 230.3-453.9 °C, and the mass loss was -0.331 mg (8.43%). At this stage, the thermal process proceeds relatively slowly. A small effect was observed on the DTA curve at around 261.56 °C, which is associated with the beginning of the decomposition of oxalate groups. At this stage, the main organic ligand of the complex - oxalate ions - decomposes through a decarboxylation reaction. The third stage occurs in the range of 453.9-601.7 °C and the mass loss is -0.127 mg (3.23%). At this stage, complete decomposition of the remaining organic fragments and the formation of an inorganic residue are observed.

As a result of this process, there is a high probability of NiO formation as a thermally stable final product. The thermal effects observed at high temperatures on the DTA curve are associated with the destruction of the internal structure of the complex and complete destruction of the crystal lattice. From the obtained results, it can be seen that the complex compound has a multi-stage thermal decomposition mechanism, initially water and weakly bound ligands are separated, in subsequent stages the decomposition of oxalate and acetate groups occurs, ultimately a thermally stable inorganic residue - metal oxide is formed, and these results confirm that the thermal stability of the Ni (II) oxalate-acetate complex compound is moderate, and its decomposition occurs in sequential, specific stages (Figure 1).

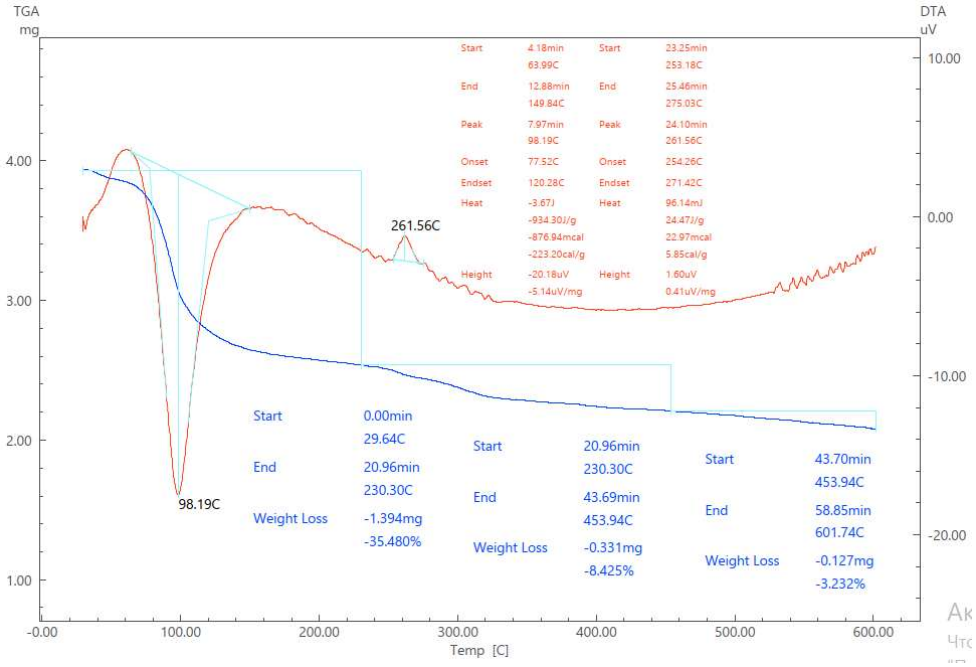

Figure 1. DSK-TG-DTG graph of the $[(NiC_2O_4)_2 \cdot Co(CH_3COO)_2]$ complex.

Thermal analysis of the Ni (II) oxalate-acetate complex compound was studied based on TG/DTA curves. As a result of the analysis, it was established that the decomposition of the substance occurs in several stages. The first stage was observed in the range of ~40-130 °C, with a mass loss of 22.20%. A strong endothermic peak was noted in DTA at 61.75 °C. This process is explained by the separation of crystallization water. The second stage occurs in the range of ~130-250 °C, where a thermal effect is observed at 169.82 °C. At this stage, the decomposition of acetate and partially oxalate ligands begins. The third stage continues in the range of ~250-400 °C and is characterized by a peak at 267.44 °C. This stage is the main stage of oxalate group decomposition. Subsequent stages are observed at 394.29°C and 452.72 °C, associated with complete decomposition of organic residues and structural changes.

In the final stage, the total mass loss in the range of 250-600 °C is ~29.03%. As a result, it was established that the complex compound decomposes step by step, and finally, a thermally stable product - NiO - is formed (Figure 2).

Analysis of the TG/DTA of the Ni (II) oxalate-acetate complex showed that its decomposition proceeds in stages. The first stage is observed in the range of ~50-120

°C and is characterized by an endothermic peak at 80.06 °C. At this stage, crystallization water is released.

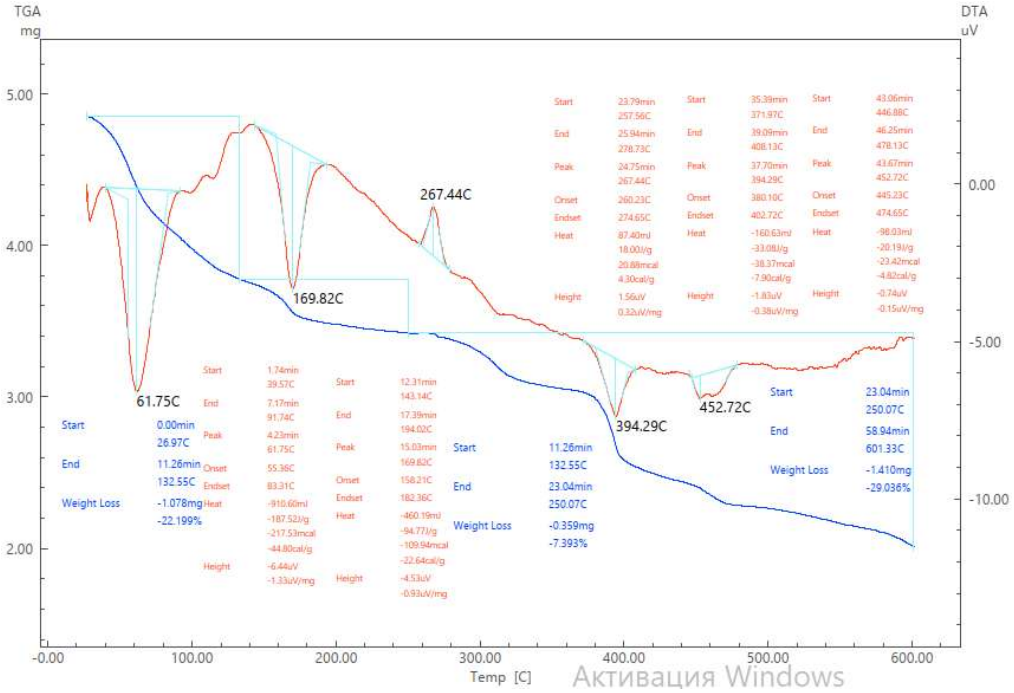

Figure 2. DSK-TG-DTG graph of the $[(NiC_2O_4)_2 \cdot Ca(CH_3COO)_2]$ complex.

The second stage occurred in the range of ~120-200 °C, and thermal effects were recorded at 139.97 °C and 186.48 °C. This process is associated with the decomposition of acetate and partially oxalate ligands. The next stage continues in the range of ~255-600 °C, and a significant peak is observed at 375.39 °C. At this stage, complete decomposition of oxalate groups and combustion of organic residues occur.

According to the results of the EG, the total mass loss in the two main stages is ~32.61% and ~31.21%, which indicates a gradual decomposition of the complex composition. In the final stage, the formation of a thermally stable inorganic residue - NiO is determined (Figure 3). As can be seen from Figure 3, the synthesized coordination compounds decompose at relatively low temperatures. In this case, the maximum mass loss does not exceed half the mass of the sample, and no change in mass is observed after 400°C. Based on this, it can be concluded that the ligands directly combine with the coordination bond and are located in the inner sphere, and at a relatively low temperature, the breaking of this weak bond occurs.

The results of thermal analysis of complex compounds based on Ni (II) oxalate with various metal acetates (Ca^{2+}, $Co^{2+,}$ Cu^{2+}) in different molar ratios (1:4 or 1:2) showed the presence of general patterns in their decomposition processes. Based on the TG-DTG-DTA methods, the following conclusions were made. All complex compounds did not show significant mass loss in the range of 25-100 °C, which indicates the absence of free or crystalline water molecules in them. This confirms their structural stability and the good drying of the synthesized compounds.

The decomposition temperature of the oxalate ion directly depends on the secondary metal cation participating in the compound. As the ionic radius and valence level decrease, the decay temperature decreases. The decomposition of acetate groups occurs at high temperatures in all complexes.

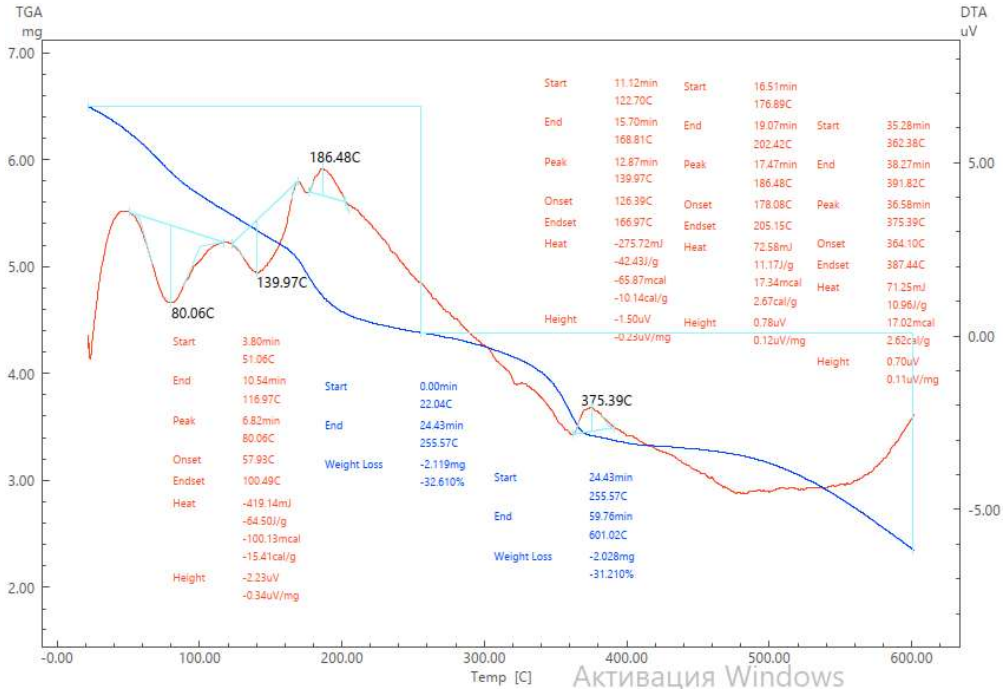

Figure 3. DSK-TG-DTG graph of the $[(NiC_2O_4)_2 \cdot Ca(CH_3COO)_2]$ complex.

Conclusion

When studying the thermal properties of Ni (II) oxalate-acetate complex compounds using the TG/DTA method, it was established that their decomposition proceeds according to a complex and multi-stage mechanism. Analysis of thermograms shows that the decomposition process initially begins at low temperatures with the separation of weakly bound components, in particular, crystallization and coordinated water molecules.

In subsequent stages, the organic ligands in the complex - acetate and oxalate ions - undergo thermo-oxidative destruction. This process is characterized by decarboxylation, the release of gaseous products (CO, CO_2), and the disruption of the internal coordination structure of the complex. The endothermic and exothermic effects observed on the DTA curves confirm the structural changes and chemical reactions at these stages. In the high-temperature region, the complete decomposition of organic fragments is completed, and a thermodynamically stable inorganic phase is formed.

According to the research results, in all cases, the formation of nickel (II) oxide (NiO) with a crystalline structure is determined as the final product. The obtained results show that the thermal stability of Ni (II) complexes directly depends on their coordination medium, the nature of the ligands, and bond strength. Also, the study of the mechanism of thermal decomposition of these complexes confirms their important scientific and practical significance in the synthesis of functional materials, in particular, in the production of metal oxides.

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EFFECT OF INTERGRANULAR BARRIERS ON CHARGE CARRIER MOBILITY IN Mg_3Sb_2 MATERIAL

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Annotatsiya. Ushbu maqolada Mg_3Sb_2 asosidagi termoelektrik materiallarda zaryad tashuvchilar harakatchanligiga donalar chegarasida hosil bo‘luvchi potensial to‘siqlarning ta’siri tahlil qilindi. Ko‘rsatildiki, ushbu to‘siqlar harakatchanlikni kamaytiradi, biroq energiya filtratsiyasi orqali Zeebek koeffitsientini oshirishi mumkin. Donalar o‘lchamini boshqarish, doping va sinterlash orqali ularni nazorat qilish mumkin.

Kalit so‘zlar: *Mg_3Sb_2, termoelektrik materiallar, harakatchanlik, donalar chegarasi, potensial barer.*

Аннотация. В статье рассмотрено влияние потенциальных барьеров на границах зёрен на подвижность носителей заряда в термоэлектрических материалах на основе Mg_3Sb_2. Показано, что данные барьеры снижают подвижность, но могут повышать

коэффициент Зеебека за счёт энергетической фильтрации. Управление размером зёрен, легирование и оптимизация спекания позволяют контролировать данный эффект.

Ключевые слова: *Mg_3Sb_2, термоэлектрические материалы, подвижность носителей, границы зёрен, потенциальный барьер.*

Abstract. This study analyzes the effect of grain-boundary potential barriers on charge carrier mobility in Mg_3Sb_2-based thermoelectric materials. These barriers reduce mobility but may enhance the Seebeck coefficient via energy filtering. Their effects can be controlled through grain size engineering, doping, and sintering optimization.

Keywords: *Mg_3Sb_2, thermoelectric materials, carrier mobility, grain boundary, potential barrier.*

Introduction

In recent years, improving energy efficiency and recovering waste heat have become issues of significant importance. In this context, thermoelectric materials have attracted special attention due to their ability to directly convert thermal energy into electrical energy. In particular, the Zintl-type compound Mg_3Sb_2 is considered a promising material owing to its low density, the availability of raw materials, and its high thermoelectric performance within the temperature range of 300–700 K.

The thermoelectric performance is evaluated by the dimensionless figure of merit, ZT, which depends on electrical conductivity, the Seebeck coefficient, and thermal conductivity. In polycrystalline Mg_3Sb_2 materials, charge carrier transport is determined not only by the band structure and intrinsic parameters but also by microstructural factors, particularly grain boundaries. Defects, dopants, and charge accumulation at grain boundaries give rise to potential barriers that act as one of the main limiting factors for charge carrier mobility. This effect becomes especially pronounced in fine-grained materials. At the same time, these barriers can enhance the Seebeck coefficient through energy filtering by selectively scattering low-energy carriers, thereby establishing a trade-off between carrier mobility and thermoelectric performance [1].

In the Mg_3Sb_2 system, various approaches such as doping, grain size control, and optimization of sintering processes are employed to regulate intergranular potential barriers. However, the mechanism of the influence of these barriers on charge carrier mobility has not yet been sufficiently and systematically elucidated. Therefore, in this study, the effect of intergranular potential barriers on charge carrier mobility in Mg_3Sb_2 materials is summarized based on a literature review, and the transport mechanisms as well as strategies for improving thermoelectric performance through microstructural control are identified [2].

Literature Review

In recent years, the influence of grain boundaries on charge carrier mobility in Mg_3Sb_2- and $Mg_3(Sb, Bi)_2$-based thermoelectric materials has become one of the most important research topics. Early studies primarily focused on achieving high ZT values in these materials through doping, defect engineering, and phase stability. However,

subsequent investigations identified potential barriers at grain boundaries as one of the key factors limiting electrical transport parameters. In particular, the thermally activated behavior of carrier mobility observed in polycrystalline Mg_3Sb_2 samples near room temperature indicates that carrier transport across grain boundaries plays a crucial role in this system [3].

To more accurately evaluate the effect of grain boundaries, a comparison between single-crystalline and polycrystalline states is of particular importance. In this regard, the study by K. Imasato, C. Fu, Y. Pan, et al., published in *Advanced Materials* in 2020, entitled *"Metallic n-type Mg_3Sb_2 single crystals demonstrate the absence of ionized impurity scattering and enhanced thermoelectric performance,"* serves as a key reference. This work demonstrated that the mobility in single-crystal Mg_3Sb_2 samples is significantly higher due to the near absence of grain boundaries. Similar conclusions were reported by Pan Y., Yao M., Hong X., Zhu Y., Fan F., Imasato K., et al. in their 2020 paper published in *Energy & Environmental Science*, titled *"$Mg_3(Bi, Sb)_2$ single crystals towards high thermoelectric performance."* The authors synthesized single-crystal $Mg_3(Bi, Sb)_2$ samples and showed that transport properties improve significantly when grain boundary resistance is effectively eliminated. This leads to a general conclusion for both binary Mg_3Sb_2 and its Bi-alloyed systems: achieving high carrier mobility is difficult without controlling grain-boundary-induced potential barriers [4, 5].

In 2022, Z. Liu et al. published a study in *Nature Communications* entitled *"Maximizing the performance of n-type Mg_3Bi_2-based materials for room-temperature power generation and thermoelectric cooling,"* where the concept of eliminating internal grain boundary resistance through microstructural design plays a central role. Although this work focuses primarily on Mg_3Bi_2-based materials, it has broad methodological relevance for the Mg_3Sb_2–Mg_3Bi_2 family. The authors demonstrated that rational microstructural design can significantly reduce grain boundary resistance and lead to high thermoelectric performance near room temperature. This approach is also highly relevant for Mg_3Sb_2, confirming that controlling sintering processes, grain growth, and interface chemistry is essential for minimizing mobility losses associated with grain boundaries [6,7].

Research Methodology

This study is devoted to a comprehensive investigation of the effect of intergranular potential barriers on charge carrier mobility in Mg_3Sb_2-based thermoelectric materials and is conducted using a systematic literature review approach. In the course of the research, recent publications in high-impact international scientific journals were carefully selected and analyzed. Particular attention was given to studies published in leading journals such as Energy & Environmental Science, Advanced Materials, Advanced Functional Materials, and Nature Communications. These sources provide extensive insights into charge carrier transport, grain boundary physics, and microstructural engineering strategies in Mg_3Sb_2 and related $Mg_3(Bi, Sb)_2$ systems.

A comparative analysis methodology was employed as the primary research approach. Specifically, the transport properties of single-crystalline and polycrystalline

Mg_3Sb_2 materials were systematically compared in order to evaluate the influence of grain boundaries on charge carrier mobility. This approach enabled a clear identification of the role of grain boundaries as a critical factor governing charge transport behavior.

From a theoretical perspective, several well-established physical models were utilized to interpret charge carrier transport mechanisms. The Seto model was applied to describe carrier transport across grain-boundary-induced potential barriers. Debye screening theory was used to evaluate the extent of charge screening effects, while the charge trapping mechanism provided an explanation for carrier localization due to defects and dopant segregation. In addition, the energy filtering model was employed to describe the selective scattering of low-energy carriers at grain boundaries.

Furthermore, particular emphasis was placed on the analysis of microstructural control strategies. The effects of grain size engineering, doping (especially with elements such as Nb), and optimization of sintering processes on charge carrier mobility were systematically evaluated. This methodological framework made it possible to identify effective approaches for reducing grain-boundary-induced potential barriers and improving thermoelectric transport properties.

As a result, based on the collected and analyzed scientific data, a unified conceptual framework describing the formation of grain-boundary potential barriers and their impact on charge carrier transport in Mg_3Sb_2 materials was established.

Analysis and Results

The conducted systematic analysis clearly confirms that grain boundaries play a decisive role in determining charge carrier mobility in Mg_3Sb_2-based thermoelectric materials. The results indicate that Mg deficiency, structural defects, and dopant segregation at grain boundaries lead to the formation of localized charge trapping centers. These trapped charges give rise to potential barriers at grain interfaces. As a consequence, charge carriers must overcome these barriers, which requires additional energy and results in a significant reduction in carrier mobility.

At the same time, grain-boundary-induced potential barriers exhibit a dual effect. While they impede charge carrier mobility, they can also selectively scatter low-energy carriers and allow high-energy carriers to pass. This phenomenon, known as energy filtering, results in an increase in the Seebeck coefficient. However, this improvement is accompanied by a decrease in mobility, indicating the presence of a trade-off between carrier mobility and thermoelectric performance. Therefore, achieving optimal performance requires a careful balance between these competing factors. Overall, the results demonstrate that charge carrier mobility in Mg_3Sb_2-based thermoelectric materials is not solely governed by the electronic band structure but is also strongly influenced by complex physicochemical processes occurring at grain boundaries. Consequently, precise microstructural control is essential for achieving high thermoelectric performance.

Conclusion

In general, the analyzed literature indicates that the influence of grain boundaries on charge carrier mobility in Mg_3Sb_2 materials manifests through three main mechanisms. First, Mg deficiency, defects, and the segregation of dopants at grain

boundaries create localized charge traps, leading to the formation of potential barriers. Second, as grain size decreases, the number of grain boundaries increases, causing carriers to encounter additional resistance at each grain interface, which reduces mobility. Third, these barriers can be mitigated through doping, optimization of sintering temperature, and grain-boundary engineering. Thus, according to current scientific understanding, achieving high electrical conductivity and enhanced carrier mobility in Mg_3Sb_2 is not only dependent on optimizing the electronic band structure but is also intrinsically linked to precise control over the physics and chemistry of grain boundaries.

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MODELING OF THE STRUCTURAL AND ELECTRONIC PROPERTIES OF THE $(InSb)_{1-x}(Sn_2)_x$ SOLID SOLUTION

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Annotatsiya. Ushbu ishda Quantum ESPRESSO doirasidagi zichlik funktsional nazariyasidan foydalangan holda $(InSb)_{1-x}(Sn_2)_x$ qattiq eritmasining strukturaviy va elektron xususiyatlarini birinchi tamoyil asosida o‘rganish taqdim etiladi. Natijalar shuni ko‘rsatadiki, Sn qo‘shilishi InSb ning to‘g‘ri zonali xususiyatini saqlab qolgan holda elektron strukturani o‘zgartiradi, past konsentratsiyalarda (x = 0,05) valentlik zona maksimumi va o‘tkazuvchanlik sohasining minimumi qiymatlari Γ nuqta yaqinida qoladi. Sn ning mavjudligi qo‘shimcha holatlarni keltirib chiqaradi va Fermi sathi yaqinida dispersiya o‘zgaradi. Tor zonali yarimo‘tkazgichlarda kirishma tasiriga mos keladigan zona o‘zgarishi kuzatiladi. Yarim lokal yaqinlashuvlar orqali zona oralig‘ining ma’lum darajada kam baholanishiga qaramay, natijalar ishonchli sifat o‘zgarishlarini aniq tavsiflab beradi. Umuman olganda, hatto oz miqdordagi Sn ham InSb ning elektron xususiyatlariga sezilarli ta’sir ko‘rsatadi, bu uning zona oralig‘i muhandisligi va optoelektronik qo‘llanilishi uchun istiqbilni ko‘rsatadi.

Kalit so‘zlar: *$(InSb)_{1-x}(Sn_2)_x$ qattiq qitishma, zichlik funktsional nazariyasi (DFT), Quantum ESPRESSO, elektron zona tuzilishi, birinchi tamoyillar bo‘yicha hisoblashlar, III–V yarimo‘tkazgichlar.*

Аннотация. В данной работе представлено исследование структурных и электронных свойств твердого раствора $InSb)_{1-x}(Sn_2)_x$ на основе теории функционала плотности в Quantum ESPRESSO. Результаты показывают, что включение Sn изменяет электронную структуру, сохраняя при этом прямую зонную структуру InSb, при этом максимум

валентной зоны и минимум зоны проводимости остаются вблизи точки Г при низких концентрациях (x = 0,05). Присутствие Sn вводит дополнительные состояния и нарушает дисперсию зон вблизи уровня Ферми. Наблюдается изменение ширины запрещенной зоны, согласующееся с эффектами легирования в узкозонных полупроводниках. Несмотря на известную недооценку ширины запрещенной зоны в полулокальных приближениях, результаты дают надежное качественное описание. В целом, даже небольшое количество Sn значительно влияет на электронные свойства InSb, указывая на его потенциал для инженерии зонной структуры и оптоэлектронных применений.

Ключевые слова: *твердый раствор* $(InSb)_{1-x}(Sn_2)_x$, *теория функционала плотности (DFT), Quantum ESPRESSO, электронная зонная структура, расчеты из первых принципов, полупроводники III–V групп.*

Abstract. This work presents a first-principles study of the structural and electronic properties of the $(InSb)_{1-x}(Sn_2)_x$ solid solution using density functional theory within the Quantum ESPRESSO framework. The results show that Sn incorporation modifies the electronic structure while preserving the direct band-gap nature of InSb, with the valence-band maximum and conduction-band minimum remaining near the Γ point at low concentrations (x = 0.05). The presence of Sn introduces additional states and perturbs the band dispersion near the Fermi level. A modification of the band gap is observed, consistent with alloying effects in narrow-gap semiconductors. Despite the known underestimation of the band gap by semilocal approximations, the results provide a reliable qualitative description. Overall, even a small amount of Sn significantly influences the electronic properties of InSb, indicating its potential for band-gap engineering and optoelectronic applications.

Keywords: $(InSb)_{1-x}(Sn_2)_x$ *solid solution, density functional theory (DFT), quantum ESPRESSO, electronic band structure, semiconductor alloys, first-principles calculations, III–V semiconductors.*

Introduction

In recent years, the modification of semiconductor properties through the formation of solid solutions has become an effective approach for tuning electronic and optical characteristics. In particular, incorporating group IV elements into III–V compounds enables control over band structure, lattice parameters, and carrier concentration. In this regard, the $(InSb)_{1-x}(Sn_2)_x$ solid solution is a promising material system.

However, comprehensive theoretical studies of its structural, electronic, and optical properties remain limited, especially concerning the influence of Sn concentration on band structure and density of states using first-principles methods.

In this work, we perform a first-principles investigation of the structural and electronic properties of $(InSb)_{1-x}(Sn_2)_x$ solid solutions using density functional theory within the

Quantum ESPRESSO framework. The study focuses on the effect of Sn incorporation on band structure, density of states, and optical response.

Experimentally, this material system has already been realized. Epitaxial films of $(InSb)_{1-x}(Sn_2)_x$ $(0 \le x \le 0.05)$ have been grown on GaAs substrates by liquid-phase epitaxy, confirming high-quality single-crystal formation [1]. Additionally, n-GaP–p$(InSb)_{1-x}(Sn_2)_x$ heterostructures have been studied, showing a band gap in the range of 0.1–0.18 eV and multiple charge transport mechanisms [2].

Despite these experimental results, a systematic theoretical analysis of this system is still lacking. Therefore, this work aims to provide a detailed first-principles study of the $(InSb)_{1-x}(Sn_2)_x$ solid solution [3-6].

Research Methodology

The structural, electronic, and optical properties of pristine InSb were investigated using the all-electron FHI-aims package, which employs numerically tabulated atom-centered orbitals (NAO) as basis functions. In contrast to pseudopotential-based approaches, this framework explicitly treats both core and valence electrons on equal footing, thereby eliminating transferability errors associated with effective core approximations. Geometry optimization was carried out at the meta-GGA level using the r²SCAN exchange–correlation functional, with full relaxation of lattice vectors and atomic positions. High-accuracy "tight" NAO basis sets, together with dense radial and angular integration grids, were employed to ensure robust convergence of total energies and forces. Brillouin zone integrations were performed using a 12×12×12 Monkhorst–Pack k-point mesh, and scalar relativistic effects were included via the atomic ZORA formalism [7-9].

Within this all-electron framework, the electronic configurations of the constituent atoms were explicitly treated, with In described by a $5s^25p^1$ valence configuration (including semicore $4d^{10}$ states) and Sb by a $5s^25p^3$ valence configuration (also including $4d^{10}$ semicore states). The electronic structure, including band dispersion, was subsequently computed using the screened hybrid functional HSE06. The fraction of exact exchange ($\alpha = 0.35$) and the screening parameter ($\omega = 0.106$ $bohr^{-1}$) were carefully tuned to reproduce the experimental band gap with high accuracy. Spin–orbit coupling (SOC), which is essential for accurately describing narrow band-gap semiconductors such as InSb, was included in a non-self-consistent manner.

The electronic properties of the $(InSb)_{1-x}(Sn_2)_x$ alloy were investigated within the plane-wave pseudopotential framework as implemented in Quantum ESPRESSO. Prior to alloy modeling, systematic convergence tests with respect to the plane-wave cutoff energy and k-point sampling were carried out separately for pristine InSb and elemental Sn.

For the evaluation of electronic properties, hybrid functionals such as HSE06 were not employed due to their substantial computational cost for large supercells. Instead, all calculations were performed at the semilocal PBEsol level using standard pseudopotentials.

Analysis and Results

Structural properties. Based on total energy convergence criteria, optimal parameters were identified as 70 Ry with a 10×10×10 Monkhorst-Pack grid for InSb, and 60 Ry with an 8×8×8 grid for Sn (Figure 1 a, b). These parameters were subsequently adopted for all alloy calculations to ensure consistency and accuracy. The resulting optimized lattice constant (Figure 1 c, d) (~6.55 Å, corresponding to 12.2535 Bohr) is in excellent agreement with experimental values [1, 3].

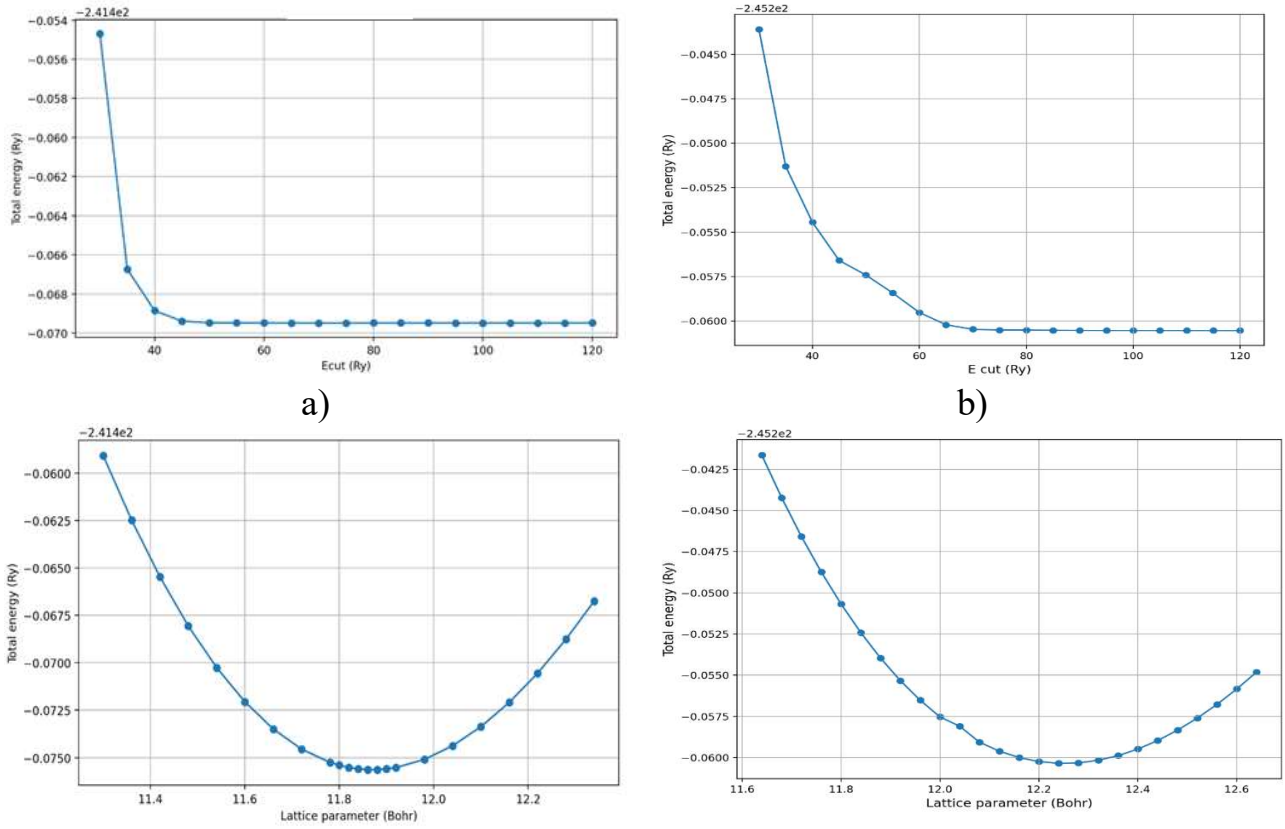


Figure 1. Convergence of total energy and plane waves cutoff (a-Sn, b-InSb) and optimization of total energy and lattice constant (c-Sn, d-InSb).

For a representative composition of x = 0.05, a 1×1×5 supercell (40 atoms) of InSb was constructed (Figure 2). To model Sn incorporation, one pair of nearest-neighbor In and Sb atoms was simultaneously substituted by two Sn atoms, forming a local Sn–Sn defect complex within the host lattice. Structural optimization was performed using the variable-cell relaxation (vc-relax) method within the BFGS algorithm, allowing full relaxation of both lattice parameters and internal atomic coordinates. The calculations employed PBEsol-based SG15 norm-conserving pseudopotentials, with kinetic energy cutoffs of 70 Ry for the wavefunctions and 280 Ry for the charge density. Brillouin zone integration was carried out using a 10×10×2 k-point mesh, appropriate for the elongated supercell geometry.

Electronic properties. Despite the experimental realization of $(InSb)_{1-x}(Sn_2)_x$ solid solutions by liquid-phase epitaxy and the investigation of their structural, electrical, and optical properties, detailed studies of their electronic band structure remain very limited.

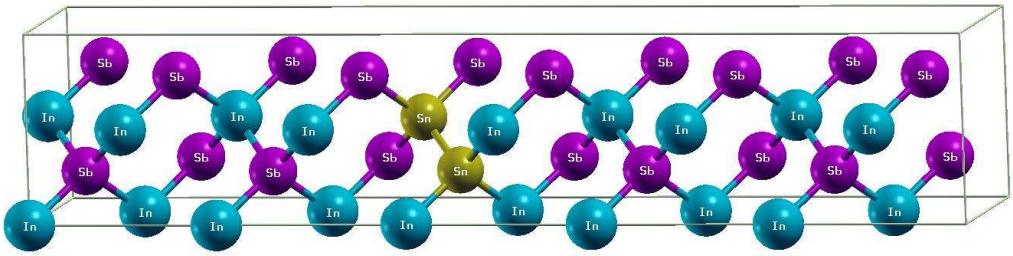
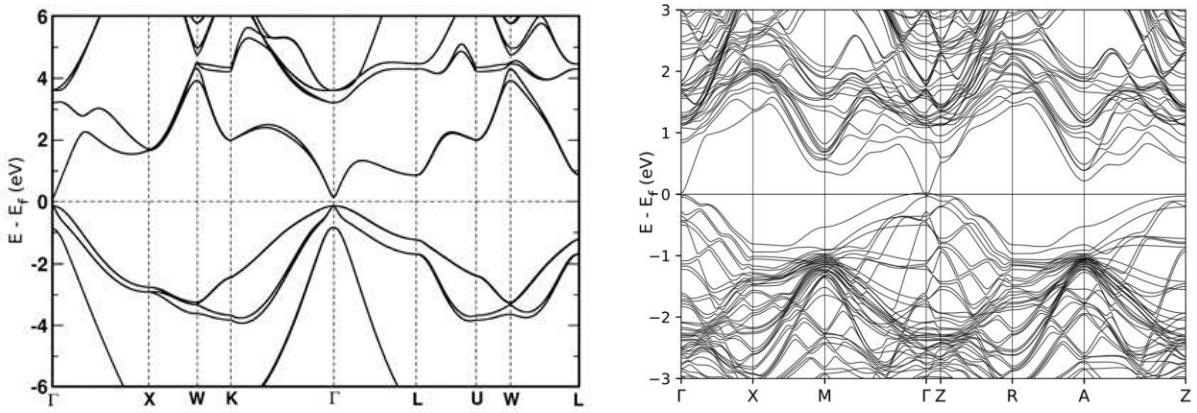


Figure 2. The relaxed crystal structure of solid solution $(InSb)_{1-x}(Sn_2)_x$ (x=0.05).

Available works mainly focus on heterostructure behavior, current–voltage characteristics, and impurity-related effects, rather than full band dispersion calculations along high-symmetry directions. This lack of band structure data is likely related to the complex nature of the alloy, involving molecular substitution and structural disorder, which complicates first-principles modeling.



a) b)

Figure 4. The band structure of a pristine InSb (a) and solid solution $(InSb)_{1-x}(Sn_2)_x$ (x=0.05) (b).

To validate the reliability of the computational approach, the electronic band structure of pristine InSb was first calculated and is shown in Fig. 4a. The obtained dispersion curves along the high-symmetry directions (Γ–X–W–K–Γ–L–U–W–L) are in good agreement with previously reported theoretical and experimental results [3].

In particular, the band structure clearly demonstrates that InSb is a direct band-gap semiconductor, with both the valence-band maximum (VBM) and conduction-band minimum (CBM) located at the Γ point. This observation is consistent with classical k·p theory and modern hybrid-functional calculations reported in the literature [7-11].

These results confirm that the adopted computational parameters and methodology are adequate for describing the electronic structure of InSb and can therefore be reliably extended to the study of the $(InSb)_{1-x}(Sn_2)_x$ solid solution.

The calculated electronic band structure of the $(InSb)_{1-x}(Sn_2)_x$ solid solution with x=0.05 is shown in Figure 4 b. The dispersion curves were obtained along the high-symmetry directions of the Brillouin zone (Γ–X–M–Γ–Z–R–A–Z).

It can be observed that the overall band topology is preserved compared to pristine InSb, with the valence-band maximum (VBM) and conduction-band minimum (CBM) located in the vicinity of the Γ point, indicating that the material retains a direct band-

gap character at low Sn_2 concentration. However, noticeable modifications in the band dispersion are observed due to the incorporation of Sn_2.

In particular, the bands near the Fermi level become more dispersive and slightly perturbed, which can be attributed to the introduction of impurity states and local potential fluctuations associated with Sn incorporation. The presence of additional states in the vicinity of the band edges suggests partial hybridization between InSb states and Sn-derived electronic states.

Furthermore, a slight narrowing (or modification) of the band gap is observed compared to pure InSb, which is consistent with the expected behavior of narrow-gap III–V semiconductors upon alloying. This effect may be related to band anticrossing interactions and the perturbation of the conduction band by Sn-related states.

The computed band structure exhibits a vanishing (zero) band gap, reflecting the well-known limitation of semilocal density functional approximations in describing narrow band-gap semiconductors. Despite this limitation, the adopted approach provides a reliable qualitative description of the electronic structure and enables a systematic assessment of the impact of Sn incorporation on the $(InSb)_{1-x}(Sn_2)_x$ system.

Overall, the obtained results indicate that even a small concentration (x=0.05) of Sn_2 significantly influences the electronic structure of InSb, while preserving its fundamental direct-gap nature. These findings provide important insight into band-gap engineering in $(InSb)_{1-x}(Sn_2)_x$ solid solutions [12, 13].

Conclusion

The structural and electronic properties of the $(InSb)_{1-x}(Sn_2)_x$ solid solution were investigated using density functional theory. The results show that Sn incorporation modifies the electronic structure while preserving the direct band-gap nature of InSb at low concentration (x = 0.05), with band edges remaining near the Γ point.

Additional electronic states and slight perturbations in band dispersion are observed due to Sn incorporation, along with a modification of the band gap. Despite the known limitations of semilocal approximations, the calculations provide a reliable qualitative description.

Overall, the results indicate that even a small amount of Sn significantly influences the electronic properties of InSb, highlighting its potential for band-gap engineering and optoelectronic applications.

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UDC: 5, 51, 311

A LINEAR EVASION GAME PROBLEM WITH GGr – CONSTRAINTS ON CONTROLS OF PLAYERS

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Annotatsiya. Ushbu maqolada o‘yinchilarning (quvuvchi va qochuvchi) chiziqli harakat dinamikasi uchun quvuvchining boshqaruviga geometrik chegaralanish (yoki G-chegaralanish), qochuvchining boshqaruviga esa Gronuoll tipidagi chegaralanish (yoki Gr-chegaralanish) qo‘yilgan holda quvish differensial o‘yini tadqiq qilinadi. Bu yerda qochish masalasini yechish uchun qochuvchiga alohida strategiya taklif etiladi va o‘yinchilar orasidagi masofani aniqlovchi funksiyaning xossalari o‘rganiladi.

Kalit so‘zlar: *chiziqli differensial o‘yin, quvuvchi, qochuvchi, strategiya, quvish, kafolatlangan quvish vaqti.*

Аннотация. В данной статье исследуется дифференциальная игра преследования для случая линейной динамики движения игроков

(преследователя и убегающего), когда управление преследователя подчинено геометрическому ограничению (или G-ограничению), а управление убегающего ограничению типа Гронуолла (или Gr-ограничению). Для решения задачи предлагается специальная стратегия для убегающего игрока и изучается функция, определяющая расстояния между игроками.

Ключевые слова: *линейных дифференциальные игры, преследователь, убегающий, стратегия, преследование, гарантированное время поимки.*

Abstract. In this article, a differential game of evasion is explored for the linear motion dynamics of players (Pursuer and Evader) when the Pursuer control is subject to geometric constraint (or G-constraint) and the Evader control is subject to Grönwall-type constraint (or Gr-constraint). To solve the evasion problem, we propose a particular strategy for evader and study its structure depending on the parameters.

Keywords: *linear differential game, pursuer, evader, strategy, pursuit, guaranteed capture time.*

Introduction

Differential games represent a specific class of problems related to dynamical systems, particularly those involving moving objects. This theory centers on key concepts such as conflict, control, optimization, real-time information, and equilibrium. In practice, differential games are widely applied in areas including industry, technology, economics, artificial intelligence, and many other fields.

In the 1950s, Isaacs first investigated certain game problems and used the concept of Differential Game in his book [1]. Moreover, special problems for further research were proposed in [1]. Some of these problems have been studied by Petrosjan [2]. According to the fundamental approaches in the Theory of Differential Games developed by Pontryagin [3] and Krasovskiy [4], the differential game is considered as a control problem from the point of view of either a Pursuer or an Evader. Depending on this view, the game reduces to a pursuit (convergence) problem and evasion (escape) problem, respectively.

Literature Review

In the Theory of Differential games, the pursuit-evasion and “lifeline” problems with geometric constraint on controls were thoroughly studied in the works of Isaacs [1], Petrosjan [2], Pshenichnyi [5], Azamov [6], and, besides, the parallel convergence strategy, which later became known as the Π-strategy, was applied efficiently to solve those problems. The Π-strategy for a simple motion differential game of pursuit with geometric constraints on controls served as the initial point for the growth of the pursuit approach in games with many pursuers.

Differential games for the case where linear, linear-geometric, integro-geometric, and their mixed constraints are imposed on controls were considered in detail in the works [7-12], and the Π-strategy for all the cases was constructed. In [13], the term of Grönwall type constraint on controls was first brought in, and the pursuit-evasion and

"lifeline" games were comprehensively studied by the parallel pursuit strategy, which was formulated for the Pursuer.

In the present paper, we have considered the pursuit problem in a linear differential game for the case where Pursuer's control is subjected to a geometric constraint and Evader's control is subjected to Grönwall type constraint. In order to solve the pursuit problem, the parallel convergence strategy (shortly, the Π-strategy) for the Pursuer is constructed, and sufficient conditions of pursuit have been found.

Research Methodology

Statement of the problems. Suppose that in R^na controlled object P called the Pursuer, chases another controlled object E called the Evader. Denote by x the position of the Pursuer and denote by y the position of the Evader in R^n. In the present work, we consider the pursuit-evasion problems when the objects move in accordance with the equations:

$$P: \quad \dot{x} = bx + u, \quad x(0) = x_0, \tag{1}$$

$$E: \quad \dot{y} = by + v, \quad y(0) = y_0, \tag{2}$$

respectively, where $b > 0$, and $x, y, u, v \in R^n, n \geq 2$; x_0 and y_0 are the initial position of the objects accordingly, and it is assumed that $x_0 \neq y_0$; u and v are the control parameters of the objects correspondingly, and they denote the velocity vectors which depend on the time $t \geq 0$.

On the control u of the Pursuer, we impose the G −constraint described in the form

$$|u(t)| \leq \alpha \text{ for almost every } t \geq 0, \tag{3}$$

where α is given positive number which expresses the maximal speed of the Pursuer.

Defenition 1. The function $u(\cdot) = \left(u_1(\cdot), u_2(\cdot), \dots, u_n(\cdot)\right)$ is called control of the Pursuer respectively if the condition (3) is valid for these functions correspondingly.

We denote a set of all the admissible control functions $u(\cdot)$ by U_G.

To the control of the Evader we propose the Gr-constraint

$$\left|v(t)\right|^2 \leq \sigma^2 + 2k \int_0^t \left| v(s)\right|^2 ds \text{ for almost every } t \geq 0 \tag{4}$$

where σ and k are given positive numbers.

Definition 2. The function $v(\cdot) = \left(v_1(\cdot), v_2(\cdot), \dots, v_n(\cdot)\right)$ is called control of the Evader respectively if the condition (4) is valid for these functions correspondingly.

We denote a set of all the admissible control functions $v(\cdot)$ by V_{Gr}.

Definition 3. For $(x_0, u(\cdot)), u(\cdot) \in \mathrm{U}_G$ the following solution of equation (1)

$$x(t) = e^{bt}\left(x_0 + \int_0^t e^{-bs}\, u(s) ds\right)$$

is called a trajectory of the Pursuer on the interval $t \geq 0$.

Definition 4. For $(y_0, v(\cdot)), v(\cdot) \in \mathrm{V}_{Gr}$ the following solution of equation (2)

$$y(t) = e^{bt}\left(y_0 + \int_0^t e^{-bs}\, v(s) ds\right)$$

is called a trajectory of the Evader on the interval $t \geq 0$.

The chief target of the object P (Pursuer) is to capture the object E (Evader), i.e., to achieve the equality $x(T) = y(T)$ at some finite moment $T > 0$ (Pursuit Game).

While the object E struggles not to be captured (Evasion Game), i.e., to keep the condition $x(t) \neq y(t)$ for every t, $t \geq 0$, or to lengthen the encounter time T.

Definition 5. A function $\boldsymbol{v}(\mathrm{t})\colon R_+ \to R^n$ is called a strategy of the Evader if

1) $\boldsymbol{v}(\mathrm{t})$ is a Lebesgue measurable function with respect to t;
2) $\boldsymbol{v}(\cdot) \in \mathrm{V}_{Gr}$.

Definition 6. We say that a control function $\boldsymbol{v}(t) \in \mathrm{V}_{Gr}$ guarantees that the evader wins in time interval $[0, \infty)$ in the linear differential game (1)–(4) if for any $u(\cdot) \in \mathrm{U}_G$, a solution $z(t)$ of the Cauchy problem

$$\dot{z} = bz + u(t) - \boldsymbol{v}(t), \quad z(0) = \dot{z}_0$$

is not equal to zero, i.e., $z(t) \neq 0$ for all $t \geq 0$.

Analysis and Results

Solution of the GGr-Game of Evasion.

Definition 7. In the GGr −Game of Evasion, we call the control function [13, 14]

$$\boldsymbol{v}_{GGr}(t) = -\sigma e^{kt}\xi_0, \ t \geq 0, \tag{5}$$

a strategy of the Evader, where $\xi_0 = \frac{z_0}{|z_0|}$.

According to the equations (1), (2), for any $\boldsymbol{v}_{GGr}(\cdot) \in \mathrm{V}_{Gr}$ and $u(\cdot) \in \mathrm{U}_G$ the pairs $(x_0, \mathrm{u}(\cdot))$ and $(y_0, \boldsymbol{v}_{GGr}(\cdot))$ generate the trajectories

$$x(t) = e^{bt}\left(x_0 + \int_0^t e^{-b}\ u(s)ds\right) \tag{6}$$

$$y(t) = e^{bt}\left(y_0 + \int_0^t e^{-bs}\,\boldsymbol{v}_{GGr}(s)ds\right) \tag{7}$$

of the Pursuer and Evader, respectively.

Lemma 1. If the condition $\alpha \leq \sigma$ is satisfied, then the following equation

$$Ae^{kt} + Be^{bt} + \frac{\alpha}{b|z_0|} = 0 \tag{8}$$

has no solution on the time interval $[0, \infty)$, where

$$A = \frac{\sigma}{(k-b)|z_0|}, \quad B = 1 - \frac{\alpha}{b|z_0|} - \frac{\sigma}{(k-b)|z_0|}.$$

Proof. Let's rewrite the equation (8) in the following form:

$$\mathrm{F}(t) = Ae^{kt} + Be^{bt} + \frac{\alpha}{b|z_0|}. \tag{9}$$

Now, we consider the behavior of the function $\mathrm{F}(t)$ in this consequence:

a) $\mathrm{F}(0) = 1 > 0$
b) $\mathrm{F}'(t) = e^{bt}G(t)$, where

$$G(t) = \frac{\sigma k}{(k-b)|z_0|}e^{(k-b)t} + b - \frac{\alpha}{|z_0|} - \frac{\sigma b}{(k-b)|z_0|}.$$

Now, we consider the behavior of the function $\mathrm{G}(t)$ in this consequence:

$$\mathrm{G}(0) = \frac{\sigma k}{(k-b)|z_0|} + b - \frac{\alpha}{|z_0|} - \frac{\sigma b}{(k-b)|z_0|} \geq b > 0$$

$$\mathrm{G}'(t) = \frac{\sigma k}{|z_0|}e^{(k-b)t} > 0$$

Thus, $G(t)$ is an increasing function. Then $\mathrm{F}'(t) > 0$ holds.

Theorem 1. If $\alpha \leq \sigma$, then the strategy (5) guarantees evasion in the time interval $[0, \infty)$.

Proof. Let's assume that the Evader implements the strategy (5) for any control function $u(\cdot) \in \mathrm{U}_G$ of the Pursuer. Taking account of $z(t) = x(t) - y(t)$ and from the trajectories (6), (7) we obtain the function

$$z(t) = e^{bt}\left(z_0 + \int_0^t e^{-bs}u(s)ds - \int_0^t e^{-b}\ \boldsymbol{v}_{GGr}(s)ds\right). \tag{10}$$

$$|z(t)| = \left|e^{bt}\left(z_0 + \int_0^t e^{-bs}u(s)ds + \int_0^t e^{-bs}\sigma e^{ks}\xi_0 ds\right)\right| \geq$$

$$\geq e^{bt}\left|z_0 + \sigma\xi_0\int_0^t e^{(k-b)s}ds\right| - e^{bt}\left|\int_0^t e^{-bs}u(s)ds\right| \geq$$

$$\geq e^{bt}\left(|z_0| + \sigma\int_0^t e^{(k-b)s}ds\right) - \alpha e^{bt}\int_0^t e^{-bs}ds =$$

$$= \frac{\sigma}{k-b}e^{kt} + \left(|z_0| - \frac{\sigma}{k-b} - \frac{\alpha}{b}\right)e^{bt} + \frac{\alpha}{b}$$

$$|z(t)| \geq |z_0|F(t)$$

According Lemma1, we can assert that the inequality $|z(t)| > 0$ is satisfied in the time interval $[0, \infty)$. This confirms that $z(t) = 0$, i.e., $x(t) \neq y(t)$ holds for all $t \in [0, \infty)$. This finishes the proof.

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ON THE SELF-SIMILAR STRUCTURE OF NONLINEAR DIFFUSION SYSTEMS WITH COUPLED DYNAMICS

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Annotatsiya. Ushbu maqolada o‘zaro bog‘langan dinamika sharoitidagi nochiziqli diffuziya sistemalarining avtomodel tuzilishi o‘rganiladi. Bunda komponentlar o‘rtasidagi o‘zaro ta’sir uzoq muddatli evolyutsiya jarayoniga hamda singulyar rejimlarning shakllanishiga sezilarli ta’sir ko‘rsatadi. Tadqiqotda boshlang‘ich parabolik sistema maxsus masshtablash o‘zgarishlari yordamida avtomodel masalaga keltirilib, yechim profillarining sifat va miqdoriy tavsifi beriladi. Yechimlarni taqqoslash prinsipi hamda nochiziqli ajratish usullari asosida kuchsiz yechimlar uchun konstruktiv yuqori va quyi baholar olindi hamda chekli vaqt ichida blow-up yuzaga kelishi bilan global vaqt davomida mavjud bo‘ladigan yechimlarni ajratuvchi parametrik sohalar aniqlandi.

Asimptotik tahlil natijasida kompakt tayanchli avtomodel profillar shakllanishi, nochiziqli diffuziya bilan bog‘liq lokalizatsiya mexanizmi hamda bog‘langan manba hadlarining erkin chegaraning tarqalishidagi roli ochib berildi. Bundan tashqari, interfeys yaqinidagi asimptotik yoyilmalar qurildi hamda yechim dinamikasini boshqaruvchi chegaraviy avtomodel attraktorlar tavsiflandi. Olingan natijalar nochiziqlik, o‘zaro bog‘lanish va masshtablash o‘rtasidagi murakkab o‘zaro ta’sirni tahlil qilish uchun yagona

nazariy asos yaratadi hamda chekli ayirmali sxemalar va iteratsion algoritmlar yordamida ishonchli sonli verifikatsiyani ta'minlaydi.

Kalit so'zlar: *Avtomodel yechimlar, nochiziqli diffuziya sistemalari, o'zaro bog'langan dinamika, asimptotik xulq-atvor, yuqori va quyi baholar, blow-up, global kuchsiz yechimlar, kompakt tayanch, lokalizatsiya, erkin chegara, taqqoslash prinsipi.*

Аннотация. В данной работе исследуется автомодельная структура класса нелинейных диффузионных систем с сопряжённой динамикой, в которых межкомпонентные взаимодействия существенно влияют на долговременную эволюцию решений и формирование сингулярных режимов. Основное внимание уделено качественному и количественному описанию профилей решений посредством масштабных преобразований, сводящих исходную параболическую систему к соответствующей автомодельной задаче. С использованием принципа сравнения решений и методов нелинейного расщепления получены конструктивные верхние и нижние оценки слабых решений, а также выделены параметрические области, разграничивающие режимы, конечно, временного blow-up и глобального существования решений.

Асимптотический анализ выявил формирование автомодельных профилей с компактным носителем, механизм пространственной локализации, обусловленный нелинейной диффузией, а также влияние сопряжённых источниковых членов на распространение свободной границы. Кроме того, построены асимптотические разложения вблизи интерфейса и описаны предельные автомодельные аттракторы, определяющие динамику решений. Полученные результаты формируют единую теоретическую основу для анализа взаимодействия нелинейности, сопряжения и масштабных свойств, а также обеспечивают надёжную численную верификацию на основе конечно-разностных схем и итерационных методов.

Ключевые слова: *автомодельные решения, нелинейные диффузионные системы, сопряжённая динамика, асимптотическое поведение, верхние и нижние оценки, blow-up, глобальные слабые решения, компактный носитель, локализация, свободная граница, принцип сравнения.*

Abstract. This paper investigates the self-similar structure of a class of nonlinear diffusion systems with coupled dynamics, where cross-interactions between components substantially affect the long-time evolution and the formation of singular regimes. We focus on the qualitative and quantitative description of solution profiles through scaling transformations that reduce the original parabolic system to an associated self-similar problem. By combining comparison principles with nonlinear splitting techniques, we derive constructive upper and lower estimates for weak solutions and identify parameter regimes that distinguish finite-time blow-

up from global-in-time behavior. The asymptotic analysis reveals the emergence of compactly supported self-similar profiles, the localization mechanism driven by nonlinear diffusion, and the role of coupled source terms in shaping the free-boundary propagation. In addition, we establish asymptotic expansions near the interface and describe the limiting self-similar attractors governing the solution dynamics. The obtained results provide a unified framework for assessing the interplay between nonlinearity, coupling, and scaling, and they support reliable numerical verification through finite-difference discretizations and iterative solvers.

Keywords: *Self-similar solutions, nonlinear diffusion systems, coupled dynamics, asymptotic behavior, upper and lower estimates, blow-up, global weak solutions, compact support, localization, free boundary, comparison principle.*

Introduction

This paper investigates the qualitative behavior of solutions to a doubly nonlinear diffusion system with coupled dynamics, where cross-interactions between components significantly influence long-time evolution and singularity formation. Using scaling transformations, the original parabolic system is reduced to an associated self-similar problem. By combining comparison principles with nonlinear splitting techniques, we derive constructive upper and lower estimates for weak solutions and identify parameter regimes distinguishing finite-time blow-up from global-in-time behavior. The asymptotic analysis reveals compactly supported self-similar profiles, localization mechanisms driven by nonlinear diffusion, and the role of coupled source terms in free-boundary propagation. The results provide a unified framework for assessing the interplay between nonlinearity, coupling, and scaling.

Literature Review

Numerous investigations have been conducted under different parameter configurations of nonlinear diffusion systems [1–4], establishing various qualitative properties of solutions. Studies on alternative equations (p=2 or m=1) have demonstrated the phenomenon of finite perturbation propagation velocity [2,4,6]. It has been shown that solutions exhibit finite propagation speed, with free boundaries defined by surfaces $|x|=h_1(t)$ and $|x|=h_2(t)$ [1,3,7,9]. When $h_1(t),h_2(t)<\infty$ for all $t>0$, the solution is termed spatially localized [2,4,7,8,14]. Previous work has also addressed blow-up cases for nonlinear differential inequalities [10] and asymptotic constructions for self-similar systems [11,13,14]. However, developing an extended mathematical model for problem (1)–(2) remains an important theoretical challenge, motivating the present self-similar approach.

Research Methodology

We examine, within the domain $Q_t = \{(t,x):\ t>0,\ x \in R_+\}$ he qualitative properties of solutions to the Cauchy problem associated with a doubly nonlinear diffusion system

$$\begin{cases} \rho_1(x)u_t = div\left(\rho_2(x)u^{m_1-1}\left|\nabla u^{k_1}\right|^{p-2}\nabla u^{l_1}\right) + \rho_3(x)\varepsilon_1 v^{k_1} \\ \rho_1(x)v_t = div\left(\rho_2(x)v^{m_2-1}\left|\nabla v^{k_2}\right|^{p-2}\nabla v^{l_2}\right) + \rho_3(x)\varepsilon_2 u^{k_2} \end{cases} \quad (1)$$

$$\begin{cases} u(0,x) = u_0(x) \geq 0 \\ v(0,x) = v_0(x) \geq 0, x \in R_+^2 \end{cases} \quad (2)$$

where $k_1, k_2 \geq 1, k \geq 0, \quad m_1, m_2 \geq 1, \quad p \geq 2, \rho_1(x) = |x|^l, \rho_2(x) = |x|^n, \rho_3(\chi) = |x|^k, \varepsilon_1, \varepsilon_1 \geq 1, l_1, l_2 \geq 1$ are given parameters, $\nabla(.) - \underset{x}{grad}(.)$.

For the problem (1)–(2), numerous investigations have been carried out under different configurations of the governing parameters (see [1–4]), leading to the derivation of various qualitative properties of solutions. Nevertheless, in view of the contemporary demands arising in the theory of nonlinear filtration processes, the development of an extended mathematical model for problem (1)–(2) remains an актуal theoretical challenge.

In order to construct such a model, the solutions of system (1) are sought within the framework of self-similar transformations. A self-similar solution is understood as a special class of invariant solutions that enables the reduction of the original partial differential system to a lower-order problem through an appropriate scaling transformation. This approach, originally proposed by A.S. Samarskii in the study of nonlinear heat conduction, serves as an effective tool for analyzing complex nonlinear transport phenomena.

The implementation of this method proceeds in two stages. At the first stage, the homogeneous component of the system is reduced by introducing similarity variables. At the second stage, the inhomogeneous part is treated via a nonlinear separation procedure, which further simplifies the governing structure of the problem.

Below, we summarize several results established in earlier studies concerning system (1).

The analysis of solutions to problem (1)-(2) in the context of alternative equations (such as p=2 or m=1) has been extensively studied by numerous researchers (see [2, 4, 6]). Furthermore, it has been demonstrated in [1, 3, 4, 6] that the phenomenon of finite perturbation propagation velocity arises in these cases. When analyzing system (1), we assert that if there exist continuous functions$h_1(t), h_2(t)$, Then the solution of system (1) exhibits the behavior of a finite propagation velocity, such that $u(t,x) \equiv 0$ and $v(t,x) \equiv 0$ for $|x| \geq h_1(t)$ and $|x| \geq h_2(t)$. The surfaces $|x| = h_1(t)$ and $|x| = h_2(t)$ are referred to as the free boundary or the interface in the context of mathematical modeling [1, 3, 7, 9]. In the case when $h_1(t), h_2(t) < \infty$ for $\forall t > 0$, In this case, the solution is referred to as spatially localized [2, 4, 7, 8, 14].

To achieve this, we seek the solutions of system (1) in the form of

$$\begin{cases} u(t,x) = (T+t)^{-\alpha_1} w(\tau(t), x), \\ v(t,x) = (T+t)^{-\alpha_2} z(\tau(t), x), \end{cases} \quad (3)$$

where α_1, α_2 represents the coefficients to be determined, and the unknown function $\tau(t)$, upon substituting (3) into (1) and performing straightforward calculations, is defined as follows:

$$\tau(t) = \int (T+t)^{(m_2-1)\alpha_1+k_1k_2l_1l_2(p-2)\alpha_2} dt$$
$$= \int (T+t)^{(m_1-1)\alpha_2+k_1k_2l_1l_2(p-2)\alpha_1}\, dt.$$

For $1-(m_1-1)\alpha_2+k_1k_2l_1l_2(p-2)\alpha_1 > 0$, the evaluation of the integral for $\tau(t)$ yields the following result

$$\tau(t) = (T+t)^{p_1}/p_1, p_1 = 1-(m_1-1)\alpha_2+k_1k_2l_1l_2(p-2)\alpha_1.$$

As a result, a new system will be obtained

$$\begin{cases} \frac{\partial w}{\partial \tau} = \nabla\left(z^{m_1-1}\left|\nabla w^{k_1}\right|^{p-2}\nabla w^{l_1}\right) + \frac{\alpha_1}{(1-\alpha_2(m_1-1)+k_1k_2l_1l_2\alpha_1(p-2))\tau(t)} w, \\ \frac{\partial z}{\partial \tau} = \nabla\left(w^{m_2-1}\left|\nabla z^{k_2}\right|^{p-2}\nabla z^{l_2}\right) + \frac{\alpha_2}{(1-(m_2-1)\alpha_1+k_1k_2l_1l_2(p-2)\alpha_2)\tau(t)} z, \end{cases} \quad (4)$$

Observe that, when calculating the integral at $(m_2-1)\alpha_1+k_1k_2l_1l_2(p-2)\alpha_2 \neq 1$ the following expression is obtained for $\tau(t)$

$$\tau(t) = T+t \quad (5)$$

In the case where $(m_2-1)\alpha_1+k_1k_2l_1l_2(p-2)\alpha_2 > 1$, considering the expression for$\tau(t)$, is rewritten according to equation (5), it becomes as follows:

$$\begin{cases} \frac{\partial w}{\partial \tau} = div\left(z^{m_1-1}\left|\nabla w^{k_1}\right|^{p-2}\nabla w^{l_1}\right) + (b_1/\tau)w, \\ \frac{\partial z}{\partial t} = div\left(w^{m_2-1}\left|\nabla z^{k_2}\right|^{p-2}\nabla z^{l_2}\right) + (b_2/\tau)z, \end{cases} \quad (6)$$

where

$$\begin{cases} b_1 = \frac{\alpha_1}{1-(m_1-1)\alpha_2+k_1k_2l_1l_2(p-2)\alpha_1}, \\ b_2 = \frac{\alpha_2}{1-(m_1-1)\alpha_1+k_1k_2l_1l_2(p-2)\alpha_2}. \end{cases}$$

for the function$f(\xi), \psi(\xi)$ the following new self-similar system of equations is derived

$$\begin{cases} \zeta^{1-N}\frac{d}{d\xi}\left(\zeta^{N-1}\psi^{m_1-1}\left|\frac{df^k}{d\zeta}\right|^{p-2}\frac{df^l}{d\zeta}\right) + \frac{\xi}{p}\frac{df}{d\zeta} + b_1 f = 0, \\ \zeta^{1-N}\frac{d}{d\xi}\left(\zeta^{N-1}f^{m_2-1}\left|\frac{d\psi^k}{d\zeta}\right|^{p-2}\frac{d\psi^l}{d\zeta}\right) + \frac{\xi}{p}\frac{d\psi}{d\zeta} + b_2\psi = 0, \end{cases} \quad (7)$$

were

$$\begin{cases} b_1 = \frac{\alpha_1}{1-(-1+m_1)\alpha_2-kl\alpha_1(-2+p)}, \\ b_2 = \frac{\alpha_2}{1-(-1+m_2)\alpha_1-kl\alpha_2(-2+p)}. \end{cases}$$

satisfy in region $|\xi| < a^{(p-1)/p}$ the self-similar system:

$$\begin{cases} \xi^{1-N}\frac{d}{d\xi}\left(\xi^{N-1}\psi^{m_1-1}\left|\frac{df^{k_1}}{d\xi}\right|^{p-2}\frac{df^{l_1}}{d\xi}\right) + \frac{\xi}{p}\frac{df}{d\xi} + \frac{N}{p}f = 0, \\ \xi^{1-N}\frac{d}{d\xi}\left(\xi^{N-1}f^{m_2-1}\left|\frac{d\psi^{k_2}}{d\xi}\right|^{p-2}\frac{d\psi^{l_2}}{d\xi}\right) + \frac{\xi}{p}\frac{d\psi}{d\xi} + \frac{N}{p}\psi = 0 \end{cases} \quad (8)$$

Note that the functions $u_+(t,x), v_+(t,x)$ have the property:

$$u_+(t,x) \equiv 0, v_+(t,x) \equiv 0 \text{ at } |x| \geq l(t), v_+(t,x) \geq l(t) = a^{(p-1)/p}[\tau(t)]^{1/p}.$$

Analysis and Results

Qualitative properties and main results.

Theorem 1. Let $m_i + k_i + l_i + p - 1 > 0$, $\beta_i > \frac{m_{3-i}+k_i+l_i+p-1}{m_i+k_i+l_i+p-1}, i = 1,2,$ $\frac{\beta_1+1}{\beta_1\beta_2-1} a_1 \geq N/p$, $\frac{\beta_2+1}{\beta_1\beta_2-1} a_2 \geq N/p$ and

$$\begin{cases} u_+(0,x) \geq u_0(x) \\ v_+(0,x) \geq v_0(x) \end{cases}, x \in R_+^2.$$

Then for sufficiently small $u_0(x), v_0(x)$ the following estimates hold in Q,

$$\begin{cases} u(t,x) \geq A_1 u_+(t,x), \\ v(t,x) \geq A_2 v_+(t,x) \end{cases} \quad (9)$$

to solve problem (1), (2), where $u_+(t,x), v_+(t,x)$ are the functions defined above, $A_1 > 0, A_2 > 0$ are constants.

Theorem 2. Let $m_i + k_i + l_i + p - 1 > 0$, $\beta_i > \frac{m_{3-i}+k_i+l_i+p-1}{m_i+k_i+l_i+p-1}$, $i = 1,2,$

$a_1\left(\frac{\beta_1+1}{\beta_1\beta_2-1} + a^{q_2\beta_1-q_1}\right) < \frac{N}{p}$, $a_2\left(\frac{\beta_2+1}{\beta_1\beta_2-1} + a^{q_1\beta_2-q_1}\right) < \frac{N}{p}$, $a_2\left(\frac{\beta_2+1}{\beta_1\beta_2-1} + a^{q_1\beta_2-q_1}\right) < \frac{N}{p}$

and

$$\begin{cases} u_+(0,x) \geq u_0(x), \\ v_+(0,x) \geq v_0(x), \end{cases} x \in R_+^2.$$

Then, for sufficiently small initial data $u_0(x), v_0(x)$, the following estimates are valid for the weak solution at Q,

$$\begin{cases} u(t,x) \leq A_3 u_+(t,x) \\ v(t,x) \leq A_4 v_+(t,x) \end{cases} \quad (10)$$

where $u_+(t,x), v_+(t,x)$- functions defined above, $A_3 > 0, A_4 > 0$- constants.

From **Theorem 2**, we obtain the following value for the Fujita-type critical exponent:

$$\frac{\beta_i + 1}{\beta_i\beta_{3-i} - 1} = \frac{s}{p + (p + m_i - 3)s}, i = 1,2$$

for system (1).

Theorem 3. Let $\varepsilon_1 > 0, \varepsilon_2 > 0, 1 - (m_1 - 1)\alpha_2 + k_1k_2l_1l_2(p-2)\alpha_1 \geq 0$, $\frac{\alpha_1}{1-(m_1-1)\alpha_2+k_1k_2l_1l_2(p-2)\alpha_1} \leq N/p$, $\frac{\alpha_2}{1-(m_2-1)\alpha_1+k_1k_2l_1l_2(p-2)\alpha_2} \leq N/p$. Then the solution of problem (1) has the property of finite velocity diffusion if

$$u_0(x) \leq u_+(o,x), v_0(x) \leq v_+(0,x), x \in R_+^2,$$

where $u_+(t,x), v_+(t,x)$ and $\bar{f}(\xi), \bar{\psi}(\xi)$ are the functions defined above.

It follows from the proven theorem that the free boundary satisfies the given estimate

$$|x| \leq l(t) = a^{(p-1)/p}[\tau(t)]^{1/p} = a^{(p-1)/p}(T+t)^{p_1/p}/p_1,$$

$$p_1 = 1 - \frac{[(m_1-1)(m_2+1-p) + (p-2)(m_1+1-p)]N}{(m_2+1-p)(p+(p-2)N) + (m_2-1)(m_1+1-p)N)}$$

Now, let us proceed to the study of the asymptotics of solutions to the self-similar system (8) under the following boundary conditions for

$$\begin{cases} f'(0) = 0, f(\infty) = 0, \psi'(0) = 0, \psi(\infty) = 0, \\ f(0) = a_1 > 0, f(d) = 0, \psi(0) = a_2 > 0, \psi(d) = 0, d < \infty, \\ f(0) = a_1 > 0, f(\infty) = 0, \psi(0) = a_2 > 0, \psi(\infty) = 0. \end{cases} \quad (11)$$

Among the results obtained, we present one theorem dedicated to the asymptotic analysis of the model.

Theorem 4. Let $\gamma_1 > 0, \gamma_2 > 0$. Then the solution of problem (8)-(12) for $\eta \to \infty \left(\eta = -ln(a - \xi^{p/(p-1)}\right)$ has the asymptotic representation

$$\begin{cases} f(\xi) = A_1 \bar{f}(\xi)(1 + o(1)) \\ \psi(\xi) = A_2 \bar{\psi}(\xi)(1 + o(1)) \end{cases}$$

where the coefficients $A_i > 0, i = 1,2$ are the solution to the system of algebraic equations [5-6, 8, 10, 15].

The theorem demonstrates that asymptotic analysis serves to simplify the treatment of the self-similar system, while in other cases analogous asymptotic constructions may likewise be developed [11, 13, 14].

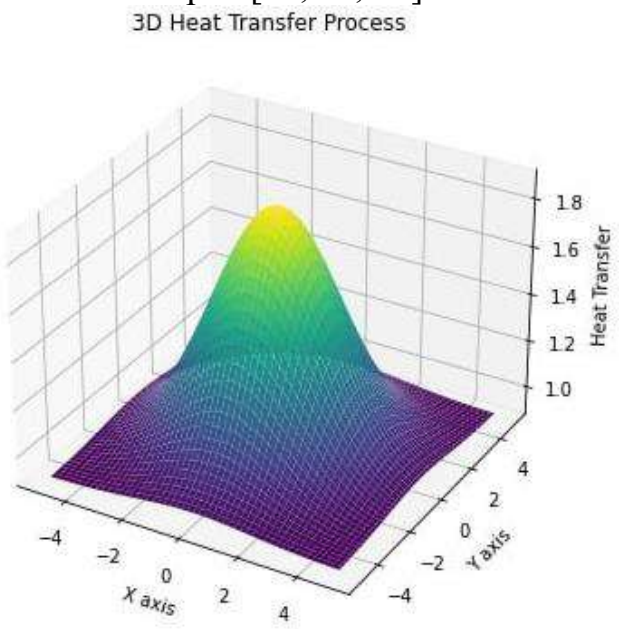

Figure 1. Three-dimensional visualization of the diffusion process for the parameter values $m_1 = 2, p = 2.5, \beta_1 = 0.5, \varepsilon_1 = -1, k = 1.1, l = 1.2$.

To validate the obtained theoretical results and to analyze the spatiotemporal behavior of the solutions, numerical simulations were carried out for selected parameter values. The evolution dynamics of the constructed self-similar solutions are illustrated through three-dimensional graphical representations. The 3D visualization clearly demonstrates the localization of the diffusion process, the formation of solution profiles, and their convergence toward the asymptotic regime given as Figure 1.

Conclusion

In this study, the qualitative behavior of solutions to the Cauchy problem for a doubly nonlinear diffusion system was investigated within the framework of self-similar transformations. By applying a two-stage reduction procedure, the original

system was transformed into a self-similar form, enabling the analysis of its structural properties.

It was shown that the system admits solutions exhibiting finite propagation speed and spatial localization under appropriate parameter conditions. The existence of a free boundary was established, and estimates for weak solutions were obtained. Furthermore, a Fujita-type critical exponent was derived for the considered system.

Finally, the asymptotic structure of the self-similar solutions was examined, providing an effective description of their behavior and simplifying the analysis of the underlying nonlinear diffusion processes.

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COGNITIVE MECHANISMS OF STUDENTS' SOCIAL THINKING IN THE DIGITAL SOCIETY: A THEORETICAL ANALYSIS AND INTEGRATIVE FRAMEWORK

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Annotatsiya. Ushbu maqolada raqamli jamiyat sharoitida talabalarning ijtimoiy tafakkurining kognitiv mexanizmlari nazariy jihatdan tahlil qilinadi. Axborot-kommunikatsiya texnologiyalarining rivojlanishi ijtimoiy persepsiya, atributsiya, empatiya va kognitiv sxemalarning shakllanishiga sezilarli ta'sir ko'rsatadi. Tadqiqotda klassik va zamonaviy yondashuvlar asosida ijtimoiy tafakkurning tuzilmasi va asosiy komponentlari yoritiladi. Shuningdek, ijtimoiy axborotni qabul qilish va interpretatsiya qilish jarayonlarini tushuntiruvchi integrativ nazariy model taklif etiladi. Natijalar talabalarning ijtimoiy kompetensiyalarini rivojlantirish va psixologik intervensiyalarni takomillashtirishda muhim ahamiyatga ega.

Kalit so'zlar: *ijtimoiy tafakkur, kognitiv mexanizmlar, raqamli jamiyat, ijtimoiy persepsiya, atributsiya, empatiya, kognitiv sxemalar.*

Аннотация. В статье теоретически анализируются когнитивные механизмы социального мышления студентов в условиях цифрового общества. Развитие информационно-коммуникационных технологий оказывает значительное влияние на формирование социальной перцепции, атрибуции, эмпатии и когнитивных схем. На основе классических и современных подходов раскрывается структура социального мышления и его основные компоненты. Предлагается интегративная теоретическая модель, объясняющая процессы восприятия и интерпретации социальной информации. Результаты имеют важное значение для развития социальных компетенций студентов и совершенствования психологических интервенций.

Ключевые слова: *социальное мышление, когнитивные механизмы, цифровое общество, социальная перцепция, атрибуция, эмпатия, когнитивные схемы.*

Abstract. This article provides a theoretical analysis of the cognitive mechanisms of students' social thinking in the digital society. The development of information and communication technologies significantly influences the formation of social perception, attribution, empathy, and cognitive schemas. Based on classical and contemporary approaches, the structure of social thinking and its key components are examined. An integrative theoretical model is proposed to explain the processes of

perceiving and interpreting social information. The findings are important for enhancing students' social competencies and improving psychological interventions.

Keywords: *social thinking, cognitive mechanisms, digital society, social perception, attribution, empathy, cognitive schemas.*

Introduction

The rapid development of the digital society has transformed how individuals perceive, process, and interpret social information. The widespread use of information and communication technologies not only expands access to information but also reshapes cognitive processes involved in social thinking. In this context, understanding the cognitive mechanisms underlying students' social thinking is a key scientific issue.

Social thinking is a complex phenomenon shaped by cognitive, social, and cultural factors. According to Lev Vygotsky, higher mental functions develop through social interaction and are mediated by cultural tools [1]. Similarly, Jean Piaget emphasized that cognitive development occurs through active interaction with the environment, leading to the construction of mental structures [2].

Albert Bandura's social learning theory explains that individuals acquire cognitive patterns through observation and interaction [3], a process that becomes more complex in digital environments. Attribution processes, defined by Fritz Heider, further explain how individuals interpret others' behavior [4].

Research in social cognition shows that individuals rely on cognitive schemas and heuristics when processing information [5]. While efficient, these mechanisms may lead to biases, especially in digital contexts characterized by rapid information flow and limited face-to-face interaction, as noted by Daniel Kahneman [6].

Manuel Castells' concept of the network society highlights how digital communication reshapes social interaction and cognition [7]. Sherry Turkle and Nicholas Carr also emphasize its impact on empathy, attention, and interpersonal depth [9, 10].

Despite extensive research, there is still a lack of integrative frameworks explaining how cognitive mechanisms of social thinking operate in digital contexts, as most studies examine these components separately.

Therefore, this study aims to analyze the cognitive mechanisms of students' social thinking in the digital society and to develop an integrative model explaining the interaction between social perception, attribution, empathy, and cognitive schemas.

Literature Review

The concept of social thinking has been widely studied within the framework of social cognition, which examines how individuals perceive, interpret, and respond to social information. Its foundations lie in the cultural-historical approach of Lev Vygotsky, who emphasized that cognitive development is socially mediated and shaped by cultural tools [1], highlighting the role of socio-cultural interaction.

In contrast, Jean Piaget's cognitive-developmental theory focuses on the internal construction of cognitive structures through developmental stages [2]. While Piaget emphasizes individual cognition, Vygotsky highlights social interaction; together, they provide a comprehensive understanding of social thinking as both internally

constructed and socially mediated. Albert Bandura's social learning theory expands this perspective by identifying observational learning as a key mechanism [3], particularly relevant in digital environments where interaction is technology-mediated and shapes social cognition. Attribution, a core component of social thinking, was conceptualized by Fritz Heider as the process of explaining behavior through internal and external causes [4]. In digital contexts, limited cues increase the likelihood of attribution errors.

Research by Susan T. Fiske and Shelley E. Taylor shows that individuals rely on cognitive schemas to process social information efficiently [5]. While schemas facilitate understanding, they may also reinforce biases under conditions of information overload. Daniel Kahneman's work on heuristics demonstrates that intuitive thinking often dominates in complex environments, leading to systematic errors [6]. In the digital society, such cognitive shortcuts become more pronounced.

The transformation of social interaction in the digital age is reflected in Manuel Castells' concept of the network society, emphasizing the impact of digital communication on cognition [7]. Similarly, Sherry Turkle and Nicholas Carr highlight its influence on empathy, attention, and interpersonal depth [9, 10]. Despite extensive research on perception, attribution, and empathy, there remains a lack of integrative approaches explaining their interaction in digital contexts. Most studies address these mechanisms separately without offering a unified framework.

Therefore, there is a need for a comprehensive theoretical model that integrates key cognitive mechanisms of social thinking and explains their transformation in the digital society. This gap underpins the present study.

Research Methodology

The cognitive mechanisms underlying students' social thinking in the digital society can be conceptualized as a dynamic system in which multiple psychological processes interact within technology-mediated environments. Based on the analysis of classical and contemporary theories, this study proposes an integrative model combining key components of social cognition, including social perception, attribution, empathy, and cognitive schemas.

At the first stage, digital environments act as primary sources of social information. Unlike face-to-face communication, digital interaction is characterized by limited non-verbal cues and greater reliance on symbolic content. From a cultural-historical perspective, cognitive processes are shaped by mediating tools and signs [1], indicating that digital technologies transform how social information is encoded and transmitted.

The second stage involves social perception and initial information processing. Individuals construct their understanding based on prior knowledge and expectations [2]. However, in digital contexts, reduced feedback may lead to incomplete or distorted perception.

At the third stage, attribution mechanisms are activated to interpret social behavior. Individuals assign internal or external causes to others' actions [4], but in online environments, limited contextual information increases the likelihood of attribution errors.

The fourth stage includes the activation of cognitive schemas, which organize and interpret social information. While schemas enhance processing efficiency, they may also reinforce cognitive biases, especially under conditions of information overload.

Empathy represents another essential component, integrating cognitive and affective processes. Although digital platforms expand opportunities for communication, the absence of direct interaction may reduce emotional engagement and weaken empathic responses [10, 11].

In addition, decision-making in social contexts is influenced by heuristic processing. According to dual-process theory, individuals often rely on intuitive thinking in complex situations. In digital environments, this tendency becomes more pronounced due to the rapid flow of information.

The broader context of the digital society, conceptualized as a network system, also shapes cognitive processes. Digital communication transforms interaction patterns and influences attention, memory, and critical thinking.

Based on this analysis, the proposed model can be represented as an interactive system:

Digital Environment → Social Information Flow → Social Perception → Attribution → Cognitive Schemas → Empathy → Social Thinking

Importantly, this process is not linear; feedback loops exist between components. For instance, schemas influence perception, while empathy affects attribution. This interaction reflects the complexity of social thinking in digital contexts.

Overall, the proposed model integrates classical psychological theories with contemporary perspectives, providing a comprehensive framework for understanding cognitive mechanisms of social thinking in the digital society.

Analysis and Results

The analysis of theoretical sources shows that cognitive mechanisms of social thinking in the digital society are significantly transformed by changes in social interaction and information processing. Digital environments—characterized by high information density, mediated communication, and reduced non-verbal cues—directly influence cognitive functioning. The study identifies four core mechanisms underlying social thinking: social perception, attribution, cognitive schemas, and empathy, which operate as an interconnected system.

In digital contexts, social perception becomes more selective and dependent on limited cues, increasing the risk of distortions. Attribution processes are influenced by uncertainty, often leading to biased interpretations due to incomplete information. Cognitive schemas organize information efficiently, under overload, and reinforce stereotypes and heuristic thinking. Empathy shows a dual transformation: while digital platforms expand communication, reduced direct interaction weakens emotional depth and accuracy.

These findings support the development of an integrative theoretical model in which cognitive processes function within a dynamic system shaped by digital environments. The main results are as follows: the digital environment restructures cognitive mechanisms of social thinking; social perception becomes more schema-

dependent; attribution processes are more error-prone; empathy shows both enhancement and reduction; cognitive mechanisms function as an integrated system. Thus, social thinking in the digital society requires an integrative approach that accounts for the interaction between cognitive mechanisms and the digital context.

Conclusions

This study presents a theoretical analysis of the cognitive mechanisms underlying students' social thinking in the digital society, demonstrating that it is a complex system shaped by internal cognitive processes and socio-digital factors. The findings show that key mechanisms—social perception, attribution, cognitive schemas, and empathy—function in a dynamic and interdependent way. The digital environment transforms these processes, increasing cognitive distortions and influencing empathic responses. A key contribution of the study is the development of an integrative theoretical model explaining the interaction of these mechanisms in digital contexts. Unlike fragmented approaches, the model highlights their interconnected and feedback-based nature. The study also expands the theoretical framework of social cognition by integrating digital influences and linking classical theories with modern realities. Practically, the findings can support the development of students' social competencies and targeted psychological and educational interventions.

In conclusion, the transformation of social thinking in the digital society requires integrative approaches and further empirical validation of the proposed model.

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MAHMUDKHODJA BEHBUDI IS ONE OF THE LEADING REPRESENTATIVES OF THE JADIDIST MOVEMENT

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Annotatsiya. Mazkur maqolada jadidchilik harakatining yirik namoyandalaridan biri Mahmudxo‘ja Behbudiyning hayoti, ijtimoiy-siyosiy faoliyati va ma’rifatparvarlik g‘oyalari tahlil qilingan. Mahmudxo‘ja Behbudiy milliy uyg‘onish jarayonlarida asosiy tutgan o‘rn egallagan. Mahmudxo‘ja Behbudiyning yangi usul maktablarini tashkil etishdagi xizmatlari, darsliklar yaratish va matbuot orqali jamiyatni isloh qilish borasidagi faoliyati diqqatga sazovvor.

Kalit so‘zlar: *jadidchilik, Mahmudxo‘ja Behbudiy, ma’rifatparvarlik, yangi usul maktabi, milliy uyg‘onish, matbuot, islohot.*

Аннотация. В данной статье анализируется жизнь, социально-политическая деятельность и просветительские идеи Махмудходжи Бехбуди, одной из главных фигур движения джадидов. Махмудходжа Бехбуди сыграл ключевую роль в процессах национального возрождения. Следует отметить его заслуги в организации новых школ усул, создании учебников и реформировании общества посредством прессы.

Ключевые слова: *джадидизм, Махмудходжа Бехбуди, просвещение, новая школа метод, национальное возрождение, пресса, реформа.*

Abstract. This article analyzes the life, socio-political activities, and ideas of enlightenment of Mahmudkhodja Behbudi, one of the major figures of the Jadid movement. Mahmudkhodja Behbudi played a key role in the processes of national revival. Mahmudkhodja Behbudi's services in organizing new usul schools, creating textbooks and reforming society through the press are noteworthy.

Keywords: *Jadidism, Mahmudkhodja Behbudi, enlightenment, new method school, national revival, press, reform.*

Introduction

The social, political, and cultural changes that took place in Turkestan at the end of the 19th and the beginning of the 20th century laid the groundwork for the formation of the Jadidism movement. This movement was linked to the activities of intellectuals who promoted ideas of national awakening, enlightenment, and reform, among whom Mahmudkhodja Behbudi held a special place. As a playwright, publicist, educator, and public figure, Mahmudkhodja Behbudi strove to lead society toward progress [1].

Mahmudkhodja Behbudi's activities were associated with reforming the national education system, developing the press, and renewing social thought.

Literature Review

Mahmudkhodja Behbudi was born in 1875 in the village of Baxshitepa near Samarkand into a family of muftis. On his father's side, he was descended from Khwaja Ahmad Yasawi, and on his mother's side, his family also belonged to an intellectual milieu. These factors played an important role in his spiritual and intellectual development [2]. At the age of six or seven, Mahmudkhodja Behbudi learned to read and write in Samarkand with the help of his uncles, and later studied the Holy Qur'an under his father's guidance. At the age of fifteen, he began his clerical service under Qazi Muhammad Siddiq, becoming acquainted with legal and administrative affairs. Later, serving as mufti, he acquired deep knowledge of fiqh, inheritance, and judicial matters. Some studies regard Behbudiy's views in the field of judicial law as one of the earliest theoretical foundations of modern reforms. He promoted the idea of prioritizing social justice, humanity, and the public interest in criminal and penal matters. According to sources, he analyzed the social consequences of punishments and emphasized the need to widely apply the concept of "amnesty" in legal practice [3].

Mahmudkhodja Behbudi's interest in enlightenment was linked to his family environment. Mahmudkhodja Behbudi's father was a prominent specialist in Islamic jurisprudence who wrote commentaries on the work "Hidoya." This work played an important role in Behbudiy's intellectual development [4]. In 1899, Mahmudkhodja Behbudi went on the hajj pilgrimage, visiting cities in Arabia, Egypt, and Turkey. During the eight-month journey, he became acquainted with the education system, cultural environment, and reforms in those places. He visited the Al-Azhar Mosque in Cairo and brought back new books. This journey marked a significant turning point in his political and social views. He came to realize that the key to progress was enlightenment and reform.

In 1903–1904, he traveled to the cities of Kazan and Ufa, where he became acquainted with the activities of the New Method schools. He established close ties with Tatar intellectuals, especially Ismail Gaspirinsky. Gaspirinsky's newspaper, "Tarjumon," became an important spiritual and intellectual platform for Behbudi.

Mahmudkhodja Behbudi established new method schools with the aim of reforming national education. In 1903, in cooperation with Siddiqiy Ajziy and Abduqodir Shakuriy, Mahmudkhodja Behbudi opened new method schools in villages around Samarkand. In 1908, the school was moved to the city of Samarkand and operated in its courtyard.

Analysis and Results

During the research process, the factors that influenced the formation of Mahmudkhodja Behbudi's enlightenment views were analyzed comprehensively, and the following scientific findings were identified. It was determined that the formation of Mahmudkhodja Behbudi's enlightenment views was directly linked to the complex historical and socio-political processes in the Turkestan region. In the late 19th and early 20th centuries, the region's incorporation into a colonial system following the Russian Empire's conquest of Turkestan prompted local intellectuals to seek new paths for

national development. In this context, enlightenment and education began to be regarded as the primary means of societal renewal. Under the influence of this process, Behbudi also advanced the idea of reforming the education system [5].

Research findings have shown that the Eastern scientific and philosophical heritage played an important role in the formation of Mahmudkhodja Behbudi's worldview. In particular, the ideas of thinkers such as Abu Nasr al-Farabi, Abu Rayhan al-Biruni, and Abu Ali ibn Sina on science, knowledge, and human perfection served as a methodological foundation for the formation of Behbudi's pedagogical views. Mahmudkhodja Behbudi continued this tradition, interpreting knowledge as the main factor in society's development.

Analysis of the research results shows that Mahmudkhodja Behbudi enlightenment views were formed in organic connection with the historical development of Turkistan society. The studied sources and scientific research indicate that Behbudi's activities cannot be limited to pedagogical or literary work alone, but must be assessed within the broader socio-educational movement of Jadidism. In this regard, Behbudi's views manifest as an important component of the intellectual landscape of the national awakening period.

In the current era, the issues of modernizing the education system, introducing innovative pedagogical technologies, and developing a person-centered education concept are of great importance. The ideas proposed by Mahmudkhodja Behbudi for modernizing education, acquiring modern knowledge, and developing national consciousness also have methodological significance for today's education system. Overall, the results of the discussion show that, Mahmudkhodja Behbudi's enlightenment views are closely linked with the general ideological foundations of the Jadidism movement, and historical conditions, cultural heritage, and modern scientific ideas played an important role in their formation. Therefore, Behbudi's pedagogical and educational legacy is not only of historical importance but also serves as a significant scientific and methodological resource for the development of the modern education system.

Conclusion

Mahmudkhodja Behbudi was a great enlightener and one of the leading representatives of the Jadidism movement, who promoted the ideas of national awakening and progress. Mahmudkhodja Behbudi believed that a free and progressive society could be built through the reform of society, the modernization of the education system, and the widespread promotion of modern knowledge. His activities and works play an important role in the development of Uzbek national thought and the education system.

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NEUROCOGNITIVE ASPECTS OF DIGITAL LEARNING IN HIGHER EDUCATION

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Annotatsiya. Ushbu maqolada jamiyatning raqamli transformatsiyasi sharoitida talabalarning kognitiv kompetensiyalarini rivojlantirishning asosiy omili sifatida raqamli ta'limning roli o'rganiladi. DigComp raqamli kompetensiyalar tizimi kabi xalqaro yondashuvlarning tahlili amalga oshiriladi. Raqamli ta'lim muhiti tanqidiy fikrlash, analitik qobiliyatlar va o'quvchining mustaqilligini rivojlantirishga yordam berishi asoslangan.

Kalit so'zlar: *raqamli ta'lim, kognitiv kompetensiyalar, raqamli muhit, DigComp, neyrokognitiv yondashuv, ta'lim texnologiyalari.*

Аннотация. В статье рассматривается роль цифрового образования как ключевого фактора развития когнитивных компетенций студентов в условиях цифровой трансформации общества. Проведен анализ международных подходов, включая рамки цифровых компетенций DigComp. Установлено, что цифровая образовательная среда способствует развитию критического мышления, аналитических способностей и самостоятельности обучающихся.

Ключевые слова: *цифровое образование, когнитивные компетенции, цифровая среда, DigComp, нейрокогнитивный подход, образовательные технологии.*

Abstract. This article examines the role of digital education as a key factor in the development of students' cognitive competencies in the context of the digital transformation of society. An analysis of international approaches, including the DigComp digital competence framework, is conducted. It is established that the digital educational environment contributes to the development of critical thinking, analytical skills, and learner autonomy.

Keywords: *digital education, cognitive competencies, digital environment, DigComp, neurocognitive approach, educational technologies.*

Introduction

The specificity of modern education is determined by the requirement to implement a competency-based approach, the realization of which предполагает transforming educational programs based on key competencies, including cognitive competencies that form an integral cognitive competence. Future educators, prepared

to work in modern schools, colleges, and universities, must not only possess certain knowledge but also be able to apply this knowledge in their professional activities, demonstrating creativity, mobility and flexibility of thinking, as well as the ability to learn and to teach—in other words, a whole комплекс of cognitive competencies.

Cognitive competence, as a system of such individual competencies (creative interpretation of the world, critical or reflective understanding of oneself and the world, flexibility and mobility in understanding oneself and the world, the ability to learn and the ability to teach, etc.), is formed in the context of university education through two main pathways: spontaneous and purposeful. The integration of digital technologies into the education of youth and adults makes it possible to significantly intensify this process, making it more conscious, structured, and effective.

Literature Review

The theoretical and methodological foundations of the informatization of education, as well as issues related to the formation of cognitive and digital competencies, are reflected in the works of a number of scholars from the CIS countries. In particular, the studies of Beshenkov S.A., Gein A.G., Gavrilov B.M., Kaymin V.A., Kushnirenko A.G., Lapchik M.P., Latyshev V.L., Makarova N.V., Selevko G.K., Semakin I.G., Boronenko T.A., Davydov V.V., Sergeev A.N., and Ugrinovich N.D. are devoted to issues of integrating ICT into the educational process, developing information culture, and enhancing students' intellectual abilities [1-5]. In developed countries, research in the field of digital education and students' cognitive development is interdisciplinary in nature and encompasses the fields of pedagogy, psychology, and neuroscience. Significant contributions to this area have been made by such scholars as Kameas A., Radford A.W., Ryan S., Yuan L., Koole M., Monahan T., Fallman D., and A. Šorgo [3-8].

Scholars of the Republic of Uzbekistan have conducted a substantial amount of research aimed at improving the higher education system, implementing information and communication technologies, and developing students' cognitive competencies in the context of educational digitalization. The theoretical, methodological, and practical aspects of the informatization of education are reflected in the works of such national scholars as Abduqodirov A.A., Olimov Q.T., Aripov M.M., Begalov B., Begimqulov U.Sh., Zokirova F.M., Boqiev R.R., Tayloqov N.I., Makhmudov A.Kh., Yuldashev U.Y., Sattorov A., Mo'minov B.B., Muradova F.R., Ashirova A., Isoqov I., Po'lotov A.M., Fayziev M.A., and A.G'. Hayitov [8-10].

Significant attention to the issues of digitalization in higher education is reflected in the research of Uzbek scholars devoted to analyzing the integration of digital technologies into the educational process. Thus, in the work of A.S. Kucharov, the process of digital transformation of higher education institutions in Uzbekistan is examined, emphasizing that the implementation of digital technologies contributes to improving the quality of education and the development of students' intellectual abilities. A special place in national research is occupied by the problem of developing students' academic, research, and cognitive competencies within the framework of the credit-modular system. In the works of U.I. Murtazaeva and co-authors, it is demonstrated that the integration of digital technologies and interactive teaching

methods contributes to the development of research skills, critical thinking, and students' cognitive activity.

Research Methodology

To improve the quality of digital learning, including the enhancement of students' cognitive competencies in the process of digital education, it is necessary to identify the components, levels, conditions, criteria, as well as the mechanisms for the development of cognitive competencies in order to ensure their targeted formation and development within e-learning environments.

Analysis and Results

The targeted formation of the substantive components (essence, structure, levels, criteria, and indicators) of cognitive competence increases the effectiveness (success) of digital learning. The process of teaching students based on an e-learning system will be successful: within the e-learning process, the concept of "cognitive competence" is clarified and operationalized, including the identification of its structural components, levels, conditions, criteria, and mechanisms; a comprehensive structural and content-based model for the formation and development of students' cognitive competence based on e-learning systems is theoretically substantiated, developed, and implemented in practice; the processes of formation and development of cognitive competence in e-learning are regulated and assessed through specially designed tools (based on the structural and content model of cognitive competence development).

Cognitive competence is an integrative characteristic of knowledge, skills, abilities, and personal experience in working with academic and professional information within the context of e-learning systems and other formats of educational activity. Students' cognitive competence includes, as one of its components, the ability to effectively use digital devices, technologies, and software in both learning and self-learning processes. It also encompasses the ability to learn and to teach, the capacity for critical and reflective understanding of oneself and the world, as well as educational processes and outcomes, the ability to creatively process information about oneself and the surrounding world, and the skills required for research-oriented and flexible understanding of academic and professional situations and their content. Among international models of digital competencies in education, the following are distinguished: the Technological Pedagogical Content Knowledge (TPACK) model; the Substitution, Augmentation, Modification, Redefinition (SAMR) model; and the European Digital Competence Framework for Educators (DigCompEdu).

Table 1. Twenty-two core competencies are classified into six groups.

Name of the competence group
Professional engagement
Digital resources
Teaching and learning
Assessment
Empowering learners
Facilitating learners' digital competence

This article examines the Digital Competence Framework for Educators (DigCompEdu) model [2]. The list of competence groups within the DigCompEdu model is presented in Table 1.

Each area includes a set of competencies that educators should possess in order to implement innovative educational strategies [4], create conditions for inclusive education, and enhance the effectiveness of their professional activities through the use of digital tools.

Let us briefly describe the content of each area.

1. Professional engagement involves the use of digital technologies and resources for professional communication with learners, parents, colleagues, and other stakeholders. This area also includes self-reflection, critical evaluation of professional activity, and continuous professional development of educators.
2. Digital resources include the ability to work with digital content (using ready-made materials, modifying them, and creating one's own), selecting digital resources according to educational goals, managing them, and ensuring their safe use.
3. Teaching and learning consist of the use of digital technologies in pedagogical practice, mentoring, organizing learner interaction, and supporting learners' autonomy in the learning process.
4. Within the assessment area, digital technologies are used to implement assessment strategies, analyze learning outcomes, plan instruction, and provide feedback to learners.
5. Empowering learners through digital technologies involves creating an inclusive and accessible learning environment, personalizing learning, and engaging students in active participation.
6. Facilitating learners' digital competence involves developing students' information and media literacy, digital communication and collaboration skills, digital content creation, problem-solving in digital environments, and the responsible use of technologies.

Many studies in the field of education have been based on constructivist approaches, as well as on disciplinary and professional didactics, various psychological approaches—including those related to cognitive sciences—and sociological and anthropological perspectives. The task of analyzing these different approaches is to properly correlate individual processes (including cognitive functioning) with the complexity of teaching and learning situations.

Thus, some digital competencies are in the focus of mass awareness, while others, which require no less development, remain on their periphery. Among the most important of these competencies in pedagogy are interaction competencies (communication and collaboration in the sense of cooperation), as well as self-learning competencies, including lifelong learning. Competencies that are rarely mentioned by leaders of educational organizations are also insufficiently developed and require special efforts for their mastery, not only by learners but also by teaching staff.

Conclusion

The study of international experience, in particular various models, has made it possible to establish that digital competencies are considered a key component of modern education, closely linked to the cognitive development of the individual. These models provide a systematic approach to the formation of skills related to information processing, communication, and the use of digital technologies in learning activities. It has been shown that the level of digital competencies is assessed based on the characteristics of a teacher's core professional activities within the context of modern digital technologies.

The neurocognitive approach is essential for understanding the effectiveness of digital learning. Taking into account the особенностей of brain functioning makes it possible to design more effective educational environments, reduce cognitive load, and improve the quality of knowledge acquisition.

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