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Intelligent Decision Support System for Optimizing Irrigation and Minimizing Operational Costs in Agribusiness

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Abstract: Increasing pressure on water resources, rising energy costs, and the need to improve the economic efficiency of agricultural production determine the relevance of developing intelligent decision support systems for optimizing irrigation and minimizing operational costs in agribusiness. The aim of the article is to analyze theoretical and methodological approaches to the formation and application of intelligent systems that support managerial decision making in irrigation management under conditions of uncertainty and resource constraints.

The research employed methods of scientific literature analysis to examine current scholarly developments in the selected topic, as well as methods of generalization and systematization to present the research findings. The study reveals that irrigation optimization should be considered a complex economic and technological process aimed at achieving a balance between resource consumption and production outcomes. The structure of operational costs in agricultural enterprises is analyzed, and the main factors influencing their formation are identified, including energy intensity, technological level, and environmental conditions. It is established that the use of intelligent decision support systems enables more efficient allocation of water and energy resources, reducing operational costs while maintaining or increasing crop yields. It is noted that such systems are based on a multi-level architecture that integrates data collection, processing, and analysis modules, ensuring the transformation of heterogeneous data into actionable recommendations. It is found that the application of machine learning and optimization algorithms increases the accuracy and adaptability of irrigation planning. It is substantiated that the effectiveness of system implementation should be evaluated using a combination of economic, operational, and environmental indicators.

The conclusions state that intelligent systems have significant potential to enhance the resilience and competitiveness of agribusiness, although their successful implementation depends on technological readiness, data availability, and organizational adaptation.

Keywords: water resource management, digitalization of agricultural production, operational efficiency, agricultural analytics, automation of production processes, managerial decision making, resource conservation.

Інтелектуальна система підтримки прийняття рішень для оптимізації зрошення та мінімізації операційних витрат в агробізнесі

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Анотація: Посилення тиску на водні ресурси, зростання вартості енергії та необхідність підвищення економічної ефективності сільськогосподарського виробництва зумовлюють актуальність розроблення інтелектуальних систем підтримки прийняття рішень для оптимізації зрошення й мінімізації експлуатаційних витрат в агробізнесі. Метою статті є аналіз теоретичних та методологічних підходів до формування й застосування інтелектуальних систем, що підтримують прийняття управлінських рішень в організації зрошення в умовах невизначеності та обмеженості ресурсів. У процесі дослідження застосовано методи аналізу наукової літератури – для дослідження поточних наукових напрацювань з обраної тематики; узагальнення та систематизації – для представлення результатів дослідження.

У результаті дослідження з'ясовано, що оптимізацію зрошення варто розглядати як комплексний економічно-технологічний процес, спрямований на досягнення балансу між споживанням ресурсів та результатами виробництва. Проаналізовано структуру операційних витрат сільськогосподарських підприємств та визначено основні чинники, що впливають на їх формування, зокрема енергоємність, технологічний рівень та екологічні умови. Встановлено, що використання інтелектуальних систем підтримки прийняття рішень дозволяє ефективніше розподіляти водні та енергетичні ресурси, зменшуючи операційні витрати при збереженні або підвищенні врожайності. Зазначено, що такі системи базуються на багаторівневій архітектурі, яка інтегрує модулі збору, обробки та аналізу даних, забезпечуючи перетворення неоднорідних даних у практичні рекомендації. Встановлено, що застосування алгоритмів машинного навчання й оптимізації підвищує точність та адаптивність планування зрошення. Обґрунтовано, що ефективність впровадження системи варто оцінювати за допомогою комбінації економічних, операційних та екологічних показників.

У висновках зазначено, що інтелектуальні системи мають значний потенціал для підвищення стійкості й конкурентоспроможності агробізнесу,

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хоча їх успішне впровадження залежить від технологічної готовності, доступності даних та організаційної адаптації.

Ключові слова: управління водними ресурсами, цифровізація аграрного виробництва, операційна ефективність, аграрна аналітика, автоматизація виробничих процесів, управлінські рішення, ресурсозбереження.

Introduction. The problem of developing and implementing intelligent decision support systems for irrigation optimization and minimization of operational costs in agribusiness is becoming increasingly relevant under conditions of resource scarcity, climate variability, and intensifying competition in agricultural markets. Modern agro-industrial enterprises face a dual challenge: ensuring stable production volumes while simultaneously reducing operational costs, particularly those associated with water, energy, and labor use. Traditional irrigation management approaches, often based on fixed schedules or limited empirical observations, do not adequately account for the dynamic interaction of environmental, technological, and economic factors, leading to inefficient resource use and increased production risks. At the same time, the spread of digital technologies and data-driven management tools creates new opportunities for improving decision-making processes; however, the lack of integrated, adaptive, and economically oriented systems limits their practical effectiveness. This indicates an imbalance between the availability of technological solutions and their systemic application in agribusiness management, which necessitates the implementation of comprehensive intelligent systems for irrigation optimization and reduction of operational costs while ensuring the sustainability and competitiveness of production.

Literature Review. A range of contemporary scientific studies is devoted to the implementation of digital and intelligent technologies in the agricultural sector, addressing various aspects of improving agribusiness efficiency, cost management, and optimization of production processes. Thus, Yu. Pereguda examines the economic efficiency of innovative technologies in the production of organic fertilizers for small and medium-sized enterprises, which expands the understanding of resource conservation and cost optimization in agricultural production [1]. The features of digital technology application in agribusiness are investigated by D. Samoilenko, emphasizing their important role in improving the accuracy of managerial decisions and modernizing production processes [2]. The significance of intelligent agriculture as a determinant of innovative development in the agro-industrial complex, highlighting the strategic role of automated management systems, is substantiated by V. Adamchuk, N. Perepelytsia, and M. Hrytsyshyn [3]. The dynamics of sown area structure, which indirectly affects resource demand formation and irrigation management efficiency, is analyzed by S. Melnychenko and L. Bohadorova [4]. N. Yurchuk and S. Kiporenko highlight the features of digital technology use in agribusiness, emphasizing their importance for enhancing enterprise competitiveness [5]. E. Kryvokhyzha, A. Voitik, and V. Reznichenko analyze global trends in the implementation of artificial intelligence in agronomy and their impact on ensuring sustainable development, forming a theoretical basis for the intellectualization of resource management [6]. Adamenko I. examines intelligent digital systems for agricultural production management, emphasizing the improvement of managerial processes through automation and data analytics [7]. R. Lohosha investigates innovative agribusiness management technologies in the context of systems management, emphasizing the need to integrate digital solutions into strategic enterprise management [8]. T. Kolomiiets and O. Furdyk define directions for strategic cost management in agricultural enterprises, which is important for forming effective mechanisms for minimizing operational costs in the agricultural sector [9].

Unresolved Aspects of the General Problem. Despite a significant number of scientific studies devoted to the digitalization of the agricultural sector, intelligent

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technologies, and cost management, issues related to the comprehensive integration of intelligent systems into irrigation optimization processes, taking into account economic efficiency criteria, remain insufficiently investigated. In the scientific literature, either technological aspects of agribusiness digitalization or general approaches to strategic cost management are predominantly considered; however, a holistic approach to combining water use analytics with the minimization of operational costs based on intelligent systems is lacking. Methodological foundations for assessing the effectiveness of such systems under real agricultural production conditions, considering uncertainty and resource constraints, also remain underdeveloped.

The contribution of this article lies in the formation of a comprehensive approach to the integration of intelligent systems into irrigation management processes, which combines water use analytics with economic cost assessment and refines the methodological principles for determining their effectiveness under conditions of uncertainty.

Formulation of the Article Objectives (Problem Statement). The aim of the article is to analyze theoretical and methodological approaches to the development and application of intelligent systems that support managerial decision making in irrigation management under conditions of uncertainty and resource constraints.

In accordance with this aim, the following objectives were set:

1) to investigate the economic essence and significance of irrigation optimization in agribusiness;

2) to analyze the structure and factors shaping operational costs in agricultural enterprises;

3) to synthesize theoretical and methodological approaches to the development of intelligent decision support systems;

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4) to substantiate the features of their application for improving irrigation management efficiency under conditions of uncertainty and resource constraints.

Results of the Study. The theoretical and methodological foundations of irrigation optimization and cost management in agribusiness are based on the intersection of resource economics, production efficiency theory, and modern data-driven management approaches. In the context of increasing climate variability, water resource scarcity, and rising production factor costs, irrigation is transforming from a purely technological process into an economic instrument that directly determines financial outcomes and sustainability parameters of agricultural enterprises.

From an economic perspective, irrigation optimization can be defined as the process of determining the optimal volume, timing, and method of water application that ensures the maximum possible yield or profit under existing resource constraints [8]. This involves balancing the marginal benefits of additional water use, reflected in increased yields, against the marginal costs associated with water extraction, energy consumption, labor, and infrastructure maintenance. Therefore, the significance of irrigation optimization is manifested not only in yield improvement but also in enhanced resource use efficiency, reduced environmental pressure, and strengthened competitiveness of agro-industrial enterprises in both domestic and global markets.

Production costs for agricultural enterprises are a complex, multi-level category that encompasses all expenses directly related to the production process. In irrigated agriculture, their structure includes costs for water supply, energy for pumping and distributing water, labor costs for operating and maintaining systems, depreciation of irrigation equipment, as well as costs for fertilizers and plant protection products, the effectiveness of which depends significantly on irrigation regimes. The structure of operating costs depends on the scale of production, crop types, irrigation technologies used, and regional climatic conditions. For example,

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energy costs can account for a significant share in regions where groundwater extraction requires intensive pumping, while labor costs may dominate in systems with low levels of automation. Operating costs are also influenced by a wide range of external and internal factors, including fluctuations in energy prices, water tariffs, technological modernization, soil characteristics, and management practices [9]. Due to the dynamic and uncertain nature of these factors, it is necessary to apply flexible and adaptive management approaches that allow for real-time responses to changing conditions.

In this context, the integration of intelligent systems into the decision-making processes of agricultural enterprises is an important methodological achievement. Intelligent decision-support systems are designed to process large volumes of heterogeneous data, including meteorological information, soil moisture indicators, crop growth indicators, and economic parameters, with the aim of generating recommendations for optimizing irrigation schedules and resource allocation. The role of such systems goes beyond simple automation. They provide a systematic framework for analyzing complex interdependencies between variables and for identifying optimal solutions under conditions of uncertainty. By leveraging artificial intelligence, machine learning, and predictive analytics, these systems are capable of continuously improving their performance based on historical data and real-time feedback. This enables managers to shift from reactive to proactive decision-making, reducing risks associated with suboptimal irrigation practices and inefficient cost management.

In addition, intelligent systems facilitate the standardization of management processes, which is crucial for large agribusiness enterprises where decision-making is often decentralized. They allow economic criteria, such as cost minimization and profit maximization, to be directly incorporated into operational decisions, aligning technological measures with strategic business objectives. From a methodological perspective, the use of intelligent systems facilitates the development of integrated

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models that combine agronomic, environmental, and economic components, ensuring a holistic approach to irrigation optimization [10, p. 200–201]. As a result, the implementation of such systems not only improves operational efficiency but also facilitates the transition to sustainable and precision agriculture, where resource use is optimized with consideration for both economic and environmental factors.

Based on the theoretical and methodological foundations outlined above, researchers are increasingly viewing intelligent decision-support systems for irrigation optimization as integrated, multi-level structures that combine data collection, analytical processing, and management decisions within a single digital environment [11]. Within the scope of this study, it is important to note that such systems are not monolithic solutions, but rather modular structures whose effectiveness depends on the coherence of their structural components and the quality of their interaction. A model of an intelligent system for irrigation optimization typically comprises several interconnected elements, each of which performs a distinct function within the overall decision-making cycle, ranging from real-time monitoring to the generation of economically sound recommendations.

In the scientific literature, the structure of these systems is typically characterized as a combination of sensory, control, analytical, and application levels, which together ensure the transformation of raw data into practical management conclusions [12]. The sensor level is responsible for collecting high-frequency data on soil moisture, climatic conditions, and crop status, creating a foundational basis for further analysis. The data management level ensures the storage, preprocessing, and integration of heterogeneous datasets, typically using cloud infrastructures to ensure scalability and availability. The system's analytical core uses modern algorithms, including machine learning models and optimization methods, to identify patterns, forecast irrigation needs, and evaluate alternative decision-making scenarios. Finally, the application layer transforms analytical results into user-

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oriented recommendations, interfaces, and control signals that can be directly integrated into production processes.

Table 1 presents the generalized characteristics of the main structural components of the intelligent irrigation optimization system model, summarized based on the analyzed studies.

Table 1

Characteristics of the structural components of the intelligent irrigation optimization system model

Structural component	Functional Purpose	Key technologies and tools	Expected results
Data collection subsystem	Real-time collection of environmental and agronomic data	Internet of Things (IoT) sensors, weather stations, remote sensing	Accurate and timely input data
Data management subsystem	Storage, integration, and preprocessing of heterogeneous datasets	Cloud platforms, databases, data cleansing algorithms	Structured and reliable data environment
Analytics subsystem	Data processing and analysis, modeling and forecasting of irrigation needs	Machine learning, predictive analytics, optimization algorithms	Data-driven recommendations and scenario evaluation
Decision support interface	Visualization of results and interaction with end users	Dashboards, mobile apps, decision support tools	Improvement of the management decision-making process
Execution subsystem	Real-time implementation of irrigation decisions	Automated control systems, smart irrigation equipment	Effective and timely implementation of irrigation measures

Source: created by the author based on [11–15]

The architecture of intelligent decision-support systems for irrigation optimization is typically built on a multi-level or distributed paradigm, which ensures flexibility, scalability, and adaptability to various production conditions. At the lowest level, physical devices and sensors form the infrastructure for data generation, while intermediate levels are responsible for data transmission, storage, and processing. The upper levels encompass analytical modules and user interfaces that facilitate interaction between the system and decision-makers. This architecture ensures a continuous flow of data and real-time feedback loops, which is essential for dynamic optimization under conditions of uncertainty and variability. Importantly, the modular nature of the architecture allows for the integration of new data sources and analytical methods without the need for a complete system redesign, which is crucial given the rapid development of digital technologies in agriculture.

The use of data and analytical algorithms forms the basis of the system's intelligence and determines its ability to facilitate effective decision-making. In the approaches discussed, data sources are becoming increasingly diverse, encompassing not only traditional agronomic and meteorological data but also satellite imagery, historical yield data, and economic indicators. Analytical methods range from statistical models and rule-based systems to more complex machine learning methods, such as regression and models, neural networks, and reinforcement learning algorithms [16, p. 1478]. These methods are used to forecast soil moisture dynamics, assess crop water requirements, and optimize irrigation schedules under various constraints. In particular, optimization algorithms play a crucial role in balancing multiple objectives, such as minimizing water use, reducing energy consumption, and maintaining or increasing crop yields. The integration of predictive and prescriptive analytics allows the system not only to forecast future conditions but also to recommend optimal courses of action, thereby increasing its practical relevance for agribusiness management.

One of the key aspects highlighted in the scientific literature is the integration of intelligent decision-support systems into existing agribusiness production processes [17]. Effective integration requires compatibility with farm management systems, irrigation infrastructure, and organizational workflows. This encompasses both technical and institutional aspects, including data format standardization, interoperability between different software platforms, and alignment of system outputs with management decision-making procedures. In practice, integration enables automated or semi-automated control of irrigation processes, where recommendations generated by the system can be directly translated into practical actions, such as adjusting irrigation times or water volumes. At the same time, human oversight remains a crucial component, as managers interpret the system's output in light of broader strategic goals and contextual factors.

In the context of the analysis conducted, it was established that the successful implementation of intelligent systems depends not only on their technological sophistication but also on the level of integration into the economic and organizational structures of agro-industrial enterprises. The combination of data-driven analytics, advanced system architecture, and practical integration mechanisms creates the foundation for more efficient, responsive, and economically rational irrigation management. Accordingly, intelligent decision-support systems are increasingly viewed as a key driver of digital transformation in agriculture, facilitating the transition from traditional resource management methods to more precise, adaptive, and cost-effective production models.

Based on an analysis of intelligent decision-support systems for irrigation optimization, one of the key aspects addressed in current research is the evaluation of their effectiveness post-implementation, as well as the practical conditions that determine their applicability and potential for long-term development. It is worth noting that the evaluation of such systems is inherently multidimensional and encompasses not only direct economic outcomes but also operational, technological, and environmental impacts [18]. Implementation effectiveness is typically assessed using a combination of quantitative and qualitative indicators that reflect both measurable productivity improvements and broader organizational implications. In particular, the implementation of smart systems leads to a more rational allocation of resources, improved synchronization between irrigation activities and crop needs, and increased transparency in decision-making processes.

From an economic perspective, efficiency is often assessed using indicators such as reduced operating costs, return on investment, and changes in profitability associated with the optimization of irrigation methods. Studies consistently show that cost savings are primarily driven by reduced water consumption, lower energy consumption due to optimized pumping schedules, and reduced labor requirements resulting from automation. At the same time, indirect economic benefits may include increased crop yields and improved product quality, which contribute to higher incomes. However, the magnitude of these effects varies significantly depending on farm size, technological maturity, and regional conditions, indicating that generalizations are inappropriate and necessitating an assessment of effectiveness within specific production contexts. In addition to economic indicators, operational effectiveness is assessed using metrics such as system responsiveness, the accuracy of recommendations, and the degree of alignment between predicted and actual irrigation needs [17–18].

Methodological approaches to evaluating the effectiveness of such systems are typically based on comparative analysis, which compares indicators before and after their implementation, as well as on modeling, which allows for forecasting results under various development scenarios. Furthermore, the consideration of environmental criteria, such as water use efficiency and resource conservation, reflects the growing importance of sustainable development issues in agribusiness management. In this context, smart systems are increasingly viewed as tools that not only improve economic performance but also promote compliance with environmental standards and the responsible use of natural resources.

A summary of the key indicators used to evaluate smart irrigation systems, as well as the corresponding expected effects, is presented in Table 2.

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Table 2

Key indicators for evaluating the effectiveness of smart irrigation systems

Evaluation category	Indicator	Measurement method	Expected effect
Economic efficiency	Reduction in operating costs	Comparison of costs before and after implementation	Reduction in water, energy, and labor costs
	Return on Investment (ROI)	Ratio of net benefits to system implementation costs	Positive financial results over time
Production results	Yield	Yield per hectare	Growth due to optimized irrigation regimes
	Product quality	Quality standards and market value	Increased product competitiveness
Operational efficiency	Accuracy of recommendations	Deviations between predicted and actual parameters	More accurate irrigation planning
	System response time	Time required to process and provide recommendations	Acceleration of decision-making processes
Environmental impact	Water use efficiency	Yield per unit of water consumed	Reduction of water loss and over-irrigation
	Resource sustainability	Long-term trends in resource consumption	More sustainable agricultural practices

Source: created by the author based on [17–21]

In addition to evaluation, the practical use of intelligent decision-support systems is influenced by a range of technological, organizational, and economic factors that determine the feasibility and scalability of their implementation. One of the key factors is data availability and quality, as the reliability of the system's output

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directly depends on the accuracy and completeness of the input information. In many agricultural contexts, limitations in sensor infrastructure, data connectivity, or technical expertise can hinder the effective use of such systems. Accordingly, successful implementation often requires not only the deployment of digital technologies but also the development of supporting capabilities, such as staff training, data management practices, and institutional readiness for innovation.

Another important practical aspect concerns the integration of intelligent systems into existing management structures and decision-making procedures. The literature notes that resistance to change, distrust of automated recommendations, and the need to adapt organizational processes can pose significant challenges in the early stages of implementation. At the same time, phased implementation strategies, user-friendly interfaces, and the ability to combine automated decision-making approaches with the human factor are identified as key factors contributing to acceptance and effective use. Economic constraints, particularly the initial investments required to implement the system, also play a decisive role, especially for small and medium-sized enterprises, where cost-benefit considerations are more restrictive.

Conclusions. The study found that the structure of operating costs in irrigated agriculture is multifaceted and encompasses expenditures for water supply, energy, maintenance, labor, and related agrochemical resources. Their dynamics are determined by a combination of technological, economic, and natural-climatic factors, which necessitates the use of adaptive approaches to cost management under conditions of uncertainty.

It has been demonstrated that intelligent decision support systems establish a new level of irrigation management organization by integrating large datasets, analytical processing, and the generation of managerial recommendations. Their operation is based on a combination of sensor, analytical, and application components, which allows for the transformation of raw data into practical solutions that consider economic efficiency criteria.

It is demonstrated that the effectiveness of implementing such systems is multifaceted and manifests in reduced operating costs, increased productivity, and improved resource efficiency indicators. At the same time, it has been proven that the scale of the obtained effects is variable and depends on the level of technological development of farms, their size, and the specifics of the production environment, which makes generalization of assessments inappropriate and requires contextual analysis.

It has been established that the most robust approaches to evaluating the effectiveness of intelligent systems involve a combination of comparative analysis and scenario modeling, which allows consideration of both the actual results of implementation and the potential development trajectories of the systems under various operating conditions.

In conclusion, it can be stated that the implementation of intelligent decision support systems in irrigation creates the prerequisites for a transition to more precise, adaptive, and economically grounded models of agricultural production management; however, their effectiveness is determined not only by technological characteristics but also by the quality of integration into the organizational and economic system of enterprises.

Prospects for further scientific research lie in the development of adaptive models of intelligent systems that take into account industry-specific characteristics, the refinement of methods for evaluating their effectiveness, and the integration of economic and environmental criteria into the managerial decision-making process.

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