ЕКОНОМІКА ПРОМИСЛОВОСТІ
ECONOMY OF INDUSTRY

ЕКОНОМІКО-ТЕОРЕТИЧНІ ПРОБЛЕМИ ВИРОБНИЦТВА

ECONOMIC AND THEORETICAL PROBLEMS OF PRODUCTION

http://doi.org/10.15407/econindustry2025.03.023
UDC 338.4:631
JEL: O32, O33, Q16

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DIGITAL CONVERGENCE OF AGRICULTURE AND INDUSTRY 4.0: OPPORTUNITIES AND ORGANISATION INTERFACES

This paper explores the role of digital-based high-tech agriculture as a central driver of innovation and sustainability in the agro-industrial complex. Emphasis is placed on the strategic importance of technology transfer, foresight-based planning and data-driven solutions to improve productivity and enhance resilience. The findings reinforce the notion that high-tech agriculture is not an isolated phenomenon but an integral part of a broader digitalized industrial economy. This paper presents a systems-based digitally supported approach for the transfer and commercialization of agricultural technologies.

Keywords: *agriculture, technology transfer, ICT, innovation network, agri-tech innovations.*

The agricultural sector plays a key role in ensuring food security, the sustainability of ecosystems and economic development. According to UN forecasts, in 30 years humanity will need 1,7 times more food than is currently produced (FAO, 2023). Such results cannot be achieved without serious modernization of agriculture (Alston & Pardey, 2014; FAO, 2017). The answer to global challenges can be technologies: sensors, drones, unmanned harvesters and robots. Technologies automate harvesting and sowing campaigns, optimize the use of fertilizers and chemical plant protection products and significantly reduce water consumption. However, rapid changes in climate, demographics and technological progress are creating new challenges for the agricultural sector (Badiane, 2014). For the growth of these clicks, it is important to promote new technologies, as well as ensure effective technology transfer between countries and regions.

The development of the country's agriculture at the present stage is associated with the transition to new technologies and a strategic factor in strengthening the competitiveness of domestic agriculture is to increase its technological level. According to scientists and agricultural experts, the weakest link in the production of agricultural products is technical equipment and technological modernization, which leads to incomplete use of resource potential, decrease in production performance, deterioration in the quality of work performed and ultimately, to the unprofitability of the industry (Shevchenko, Omelyanenko et al., 2025). At the same time, the social and economic transformations taking place recently have revealed a discrepancy between management methods and the technological capabilities of agriculture. This is due to the fact that the field of process management is less supported by research and in management theory it is given only

Cite: Omelyanenko V. A. Digital convergence of agriculture and Industry 4.0: opportunities and organisation interfaces. *Econ. promisl.* 2025. № 3 (111). P. 23—38. http://doi.org/10.15407/econindustry.2025.03.023

a secondary role, in contrast to the study of production management as a whole.

Based on the above, technology transfer is an important process in the agricultural sector and the economy as a whole. To effectively manage technology transfer from a strategical point of view, it is important to focus on *forecasts for the development of innovation*. Foresight in the field of agriculture can be defined as systematic analytics with the aim of identifying the long-term future of science, technology, economy and society in order to identify areas of strategic research and the emergence of new high technologies that promise to bring the greatest economic and social benefits.

Sustainability of agricultural innovation projects is influenced by a dynamic interplay of community engagement, technology adoption, and local capacity building (Mgendi, Shiping, & Xiang, 2019). When agricultural technology is transferred, it can boost productivity, but this may also reduce the community's dependence on external support. As a result, the system seeks a balance between increased output and long-term project sustainability. A critical factor is how the local community perceives the benefits of the new technology. Positive perceptions enhance community participation, which strengthens stakeholder networks and builds trust and commitment. This collective engagement improves the project's operating environment, making it more conducive to long-term success. Local autonomy and the ability to rely on indigenous resources play a reinforcing role. As communities become more self-reliant and effectively use local assets, their ownership over the projects deepens. This empowerment leads to better integration of transferred technologies, greater sustainability, and reduced need for continuous external input. Stakeholders' support and effective collaboration further enhance the benefits perceived by the community, feeding back into stronger participation and better outcomes. Over time, these reinforcing processes create a resilient foundation for agricultural cooperation that adapts to both external inputs and internal developments.

High-tech agricultural production is production with the rational use of technologies that increase productivity and quality of cultivated crops, using scientifically based standards that ensure increased productivity and economic efficiency of agricultural producers. The production of high-tech products requires the formation of large-scale specialized zones of operation, development and improvement of interregional connections. The *institutional environment for technology transfer* in agricultural production presupposes economic and geographical unity, similar social and economic conditions. The use of technology responds to the growth of available data for analysis and decision-making (Fig. 1).

Scientists in other countries are also exploring high-tech solutions to combat the severe impacts of climate change, including drought and loss of arable land due to desertification and to meet the growing food needs of a growing global population. As technology advances, smart farming is transforming agriculture from a practice largely dependent on grower experience and intuition to a data-driven industry, opening up the possibility of involving a wider range of participants in the process.

E.g. the importance of Internet of Things (IoT) for the further development of agricultural technologies is approximately the same as the synergy effect for the economy — this is when the combination of several components gives a greater result than using them separately. Sometimes synergy is also called the 2 + 2 = 5 effect. Thus, IoT acts as a tool that combines various technologies and forms a single ecosystem out of them. This symbiosis of data in one source will allow for better data management, which increases the efficiency of using these technologies. Research service Business Intelligence (BI) predicts that the use of IoT devices will increase from 30 million in 2015 to 75 million in 2020, an annual growth rate of about 20 %. In 2014, the average farm generated 190 thousand data points, then in 2050 there will be 4.1 million. Now one of the main users of IoT are American farmers and on average they produce 7.34 tons of grain per 1 hectare, while the global average is 3.85 tons of grain per hectare. In addition, OnFarm conducted a study that found that IoT increased the average American farm's yield by 1.75 %, reduced energy costs by $7 to $13 per acre and reduced irrigation water use by 8 %[1]. This is despite the fact that US farmers are already quite technologically advanced, adhere to cultivation technologies and are already showing high efficiency. If we talk about Ukraine, the potential for yield growth due to the introduction of IoT technologies will be much higher.

[1] Pylypchuk A. (2021). Why IoT and Precision Farming Are the Future of Agriculture. *Aggeek.* https://app.agro-online.com/21242/details/ (Access: 07.07.2025).

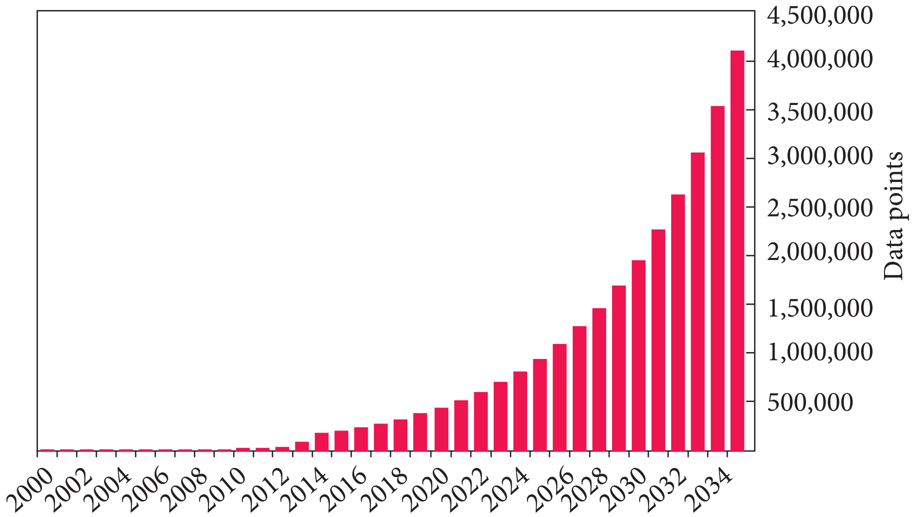

Fig. 1. Estimated volume of data received by one farm per day
Source: Pylypchuk A. (2021). Why IoT and Precision Farming Are the Future of Agriculture. *Aggeek*. https://app.agro-online.com/21242/details/ (Access: 07.07.2025).

High-tech agriculture is no longer a standalone sector; it is deeply interwoven with various branches of modern industry, forming a synergistic *agri-industrial ecosystem* (Table 1). This integration transforms traditional farming into a digitally enabled, innovation-driven field that draws upon industrial advancements for efficiency, sustainability and scalability.

Precision agriculture, leveraging IoT, Artificial intelligence (AI) and GIS technologies, mirrors the principles of Industry 4.0 by introducing data-driven decision-making (Vyshnevskyi, Anufriiev, Bozhyk, Gulchuk, 2024) and automation into the farming process. Robotics and autonomous machinery, developed in high-tech engineering industries, are now routinely deployed in fields and greenhouses, demonstrating the crossover between mechatronics and agriculture. Biotechnological innovations, such as genetically improved seeds and microbial treatments, showcase the connection between agriculture and the biotech and pharmaceutical industries. Similarly, vertical farming systems depend on industrial environmental control, lighting systems and green technologies typically used in advanced manufacturing. In the post-harvest phase, agriculture connects to smart food processing industries through the use of automation, robotics and quality control systems. Blockchain and digital platforms support transparency and certification across the supply chain, linking agriculture to the fintech and digital infrastructure sectors. Cloud computing and big data analytics play a key role in managing farm data, highlighting the dependence on the ICT and software industries. At the same time, the integration of renewable energy into farming operations (solar irrigation or biomass reuse) brings agriculture into the green industrial and environmental engineering space.

Modern agriculture also relies on smart logistics, cold chain solutions and transportation systems developed by industrial logistics providers, ensuring safe and timely delivery of agricultural products. Finally, the rise of agri-tech startups and platform-based solutions reflects the growing involvement of venture capital and innovation ecosystems in agricultural transformation. These connections demonstrate that high-tech agriculture functions as a core part of the modern industrial economy, driving both rural development and technological advancement.

The aim of this research is to explore and critically analyze the convergence between agriculture and Industry 4.0 through the integration of digital technologies with a focus on identifying organizational interfaces, innovation potentials and implementation challenges. In doing so, the research aims to provide a systematic understanding of the opportunities and limitations associated with the digitalization of agriculture, assess the readiness of organizational structures to adapt to these changes and offer strategic recommendations for policy and technological diffusion in agribusiness sectors.

Table 1. **High-tech agriculture and its connection to modern industry**

Agricultural technology/trend	Connected industrial sector	Nature of connection
Precision agriculture (IoT, AI, GIS)	Industry 4.0 / Smart manufacturing	Data-driven control systems, predictive analytics, automation techniques
Drones, robots, autonomous machinery	Robotics & Mechatronics industry	Shared platforms for automation, sensor fusion, control software
Biotech crops & microbial inputs	Biopharmaceutical & Biotech industry	Genetic engineering, lab-to-field translation, molecular product development
Vertical farming & hydroponics	Green tech / Industrial design	Use of controlled environment systems, lighting, ventilation and nutrient technologies
Agri-food processing automation	Food industry / industrial Processing	Smart factories, robotic sorting, digital quality control
Blockchain traceability systems	FinTech / Supply chain management	Transparency in production chains, anti-fraud, certification, digital transactions
Big data & cloud platforms	ICT / Software industry	Platform-based analytics, farm management systems, mobile data services
Renewable energy integration	Energy & Environmental engineering	Solar irrigation, biomass reuse, integration with green industrial parks
Smart logistics & cold chains	Transportation & Logistics	Temperature-controlled supply chains, real-time GPS tracking, efficiency optimization
Agri-tech startups and platforms	Innovation ecosystems / Venture capital	Incubators, accelerators and tech clusters linking agri-sector with startup ecosystems

Source: author`s generalization based on Alston & Pardey, 2014; FAO, 2017; Dror, 2016; Moussa S. (2002). Technology Transfer for Agriculture Growth in Africa; African Development Bank: Tunis, Tunisia. https://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/00157678-FR-ERP-72.PDF (Access: 07.07.2025); Pylypchuk A. (2021). Why IoT and Precision Farming Are the Future of Agriculture. *Aggeek*. https://app.agro-online.com/21242/details/ (Access: 07.07.2025); Piddubna A. (2024, April 20). The Future of AgriTech: Trends and Innovations in Agriculture to Watch in 2023. *Intellias*. https://intellias.com/innovations-in-agriculture/ (Access: 07.07.2025).

Concurrent engineering approach for digital support of transfer of agri-tech

The author`s approach is based on the ideas of using the *concurrent engineering methodology for the transfer of agricultural technologies*. The key stage in the life cycle of agricultural technology is the design stage (Méndez-Zambrano et al, 2023). Any mistake at this stage can be costly in terms of design changes and impact on the production process, delays in the release of products to the market with the potential threat of loss of market position and product recall, significant financial losses and damage to the company's reputation. Hence, emphasis must be placed on design to make sure that the product reaches the market flawlessly and as quickly as possible. Doing it right the first time, which is all the more important in the global market, is only possible with a good project.

Current trends in the agricultural industry indicate the need for companies throughout the increasingly complex agricultural machinery and technology supply chain to invest in improving their development processes[2]. This can be achieved through the acquisition of collaborative and interoperable digital design tools of a multi-dimensional parallel engineering approach, as well as through the integration of universities and engineers who will practice the design and development of digital agricultural machines in such environments (dos Reis, Medeiros, Fernando, et al., 2020).

According to Dror (2016) the main objectives of sectoral innovation management include the following three issues:

- development of the system of agricultural innovations;
- studying the evolution of technology-based approaches to solving problems of agriculture;

[2] Piddubna A. (2024, April 20). The Future of AgriTech: Trends and Innovations in Agriculture to Watch in 2023. *Intellias*. https://intellias.com/innovations-in-agriculture/ (Access: 07.07.2025).

• development of various forms of participation and appropriate tools.

Concurrent engineering methodology involves the joint work of experts from various functional areas of technology development (scientists, engineers, users) at the earliest possible stage of development in order to achieve high quality, functionality and manufacturability in the shortest possible time with minimal costs (Facco et al., 2017). Concurrent engineering is an expression of the desire to increase the competitiveness of products by reducing the product life cycle, as well as improving quality and reducing prices (Prasad, 2018; Deshpande, 2018).

According to ESA concurrent engineering methodology provides a "*collaborative, co-operative, collective and simultaneous engineering working environment*" [3]. Table 2 outlines the core components of concurrent engineering as applied in innovation networks, highlighting its connections to industry sectors, digital tools and organizational models that support agile and synchronized innovation processes.

Through the analysis of complex real-world applications and experiences, the study of Stjepandić, Wognum & Verhagen (2015) demonstrates that concurrent engineering is widely used in many industries and that the same basic design principles can also be applied to emerging new industries. Among such industries there is high-tech agriculture, which in modern conditions is developing due to digitalization and the development of complex technologies. Such case of IoT device placements for agriculture based on concurrent engineering is presented in study Tirupathi & Niranjan (2022).

From the point of view of agriculture, it is important that new products and technologies meet the goals of sustainable development. The sustainability of a product or technology can be most influenced early in product development through the Quality Function Deployment (QFD) method and the 'sustainability house', which translates sustainability requirements into technical solutions for the product (Rihar & Kušar, 2021). From this research we can outline such tasks relevant for agriculture:

• establishment of criteria for continuous improvement of products and processes by creating added value of products;

• increasing the potential for innovation and solutions to create environmentally friendly products;

• identification of opportunities and risks in sustainable product development;

• strengthening competitive advantage through innovative solutions for the development of products that have a low impact on the environment;

• designing and planning the introduction of sustainable products by choosing cleaner technologies (eco-technologies);

• creation of requirements for product processing and production of new products from renewable raw materials;

• sustainable procurement of materials with less impact on the environment;

• bringing together all stakeholders in the procurement-production-supply chain to coordinate shared responsibility and risks related to environmental requirements and reduce environmental fines.

In the table 3 we present the key technologies that define high-tech agriculture and outline their major benefits. It also reflects how these technologies link agriculture to broader innovation systems and industrial value chains, supporting the transition toward sustainable, resilient and future-oriented food systems.

Concurrent engineering is positioned as a transformative methodology that shifts traditional, sequential development models toward *integrated real-time collaboration*. Expectations from this approach span from incremental efficiency gains to comprehensive process automation across innovation networks. By replacing the conventional linear sequence of design, testing and implementation with a parallelized framework, concurrent engineering accelerates development cycles, reduces costs and enhances responsiveness to change. It ensures that all stages (design, production, operational management, support services, end-of-life disposal) are considered simultaneously from the project's inception. This holistic perspective, supported by advanced ICT tools, enables synchronized actions across diverse innovation actors and strengthens the agility, resilience and performance of the entire network.

In the era of interconnected innovation ecosystems ICT play a foundational role in enabling collaboration, knowledge sharing and system-level integration across diverse actors. Innovation networks comprise research institutions, industries, startups, public agencies and users and require real-time coordination, data transparency and intelligent

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[3] ESA (2024). What is concurrent engineering? https://www.esa.int/Enabling_Support/Space_Engineering_Technology/CDF/What_is_concurrent_engineering (Access: 07.07.2025).

Table 2. **Concurrent engineering in innovation networks**

Component	Description	Role in innovation networks	Example tools / platforms
Integrated multi-stakeholder collaboration	Promotes real-time, cross-disciplinary collaboration among all partners	Enables distributed actors to co-develop solutions	Microsoft Teams, Miro, Confluence
Parallel development processes	Multiple development tasks proceed simultaneously rather than sequentially	Reduces overall project time, increases adaptability in complex ecosystems	Trello, Asana
Early involvement of partners	All relevant actors (design, manufacturing, etc.) are involved from the start	Ensures alignment and avoids late-stage friction or failures	Stakeholder mapping tools, CRM systems
Shared digital infrastructure	Centralized access to designs, data and prototypes across locations	Enhances transparency and trust among network participants	Cloud PLM, shared Git repositories, CAD platforms
Continuous feedback loops	Constant testing and refinement based on live inputs from various actors	Improves innovation quality and user-centric design	Digital twins, A/B testing tools, simulation apps
Agile knowledge sharing	Knowledge is exchanged iteratively across the network	Accelerates learning and knowledge-based decision-making	Knowledge hubs, open innovation portals
Rapid prototyping & scaling	Designs can be prototyped and scaled simultaneously in different nodes of the network	Enhances speed of innovation and responsiveness to market needs	3D printing hubs, living labs, fab labs
Design for network resilience	Solutions are designed considering interoperability, sustainability and adaptability	Supports long-term network viability and modular innovation	Modular design software, sustainability scoring

Source: author`s generalization based on Alston & Pardey, 2014; FAO, 2017; Dror, 2016; Moussa S. (2002). Technology Transfer for Agriculture Growth in Africa; African Development Bank: Tunis, Tunisia. https://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/00157678-FR-ERP-72.PDF (Access: 07.07.2025); Pylypchuk A. (2021). Why IoT and Precision Farming Are the Future of Agriculture. *Aggeek*. https://app.agro-online.com/21242/details/ (Access: 07.07.2025); Piddubna A. (2024, April 20) The Future of AgriTech: Trends and Innovations in Agriculture to Watch in 2023. *Intellias*. https://intellias.com/innovations-in-agriculture/ (Access: 07.07.2025).

infrastructure to co-create and scale solutions efficiently. ICT tools support not only communication and data management but also strategic functions such as forecasting, modeling, simulation and lifecycle monitoring.

As innovation processes become increasingly digital and distributed, ICT enables the implementation of advanced methodologies such as concurrent engineering, digital twins and smart project management (Prokopenko, Järvis, Omelyanenko, Maslov, Lopes, 2025). These tools help align processes across geographically dispersed teams, synchronize workflows and reduce development cycles. In the table 4 we outline how ICT contributes to the functionality and effectiveness of innovation networks, highlighting core technological enablers, their roles and their impact on innovation performance and sustainability.

The concept of ICT support of innovation network is based on several basic principles (Brookes, & Blackhouse, 1996; Brookes & Blackhouse, 1998) that can be solved with model ICT applications (Thorat, Patle, & Kashyap, 2023):

1) early detection of the problem; the later the problem is discovered, more effort and time and consequently, money, is spent on eliminating it;

2) early decision making; in the early stages there are much more opportunities to make changes to the project, the “window of opportunity” is much wider;

3) structuring of work; the entire process must be divided into jobs in such a way that each job can be performed independently of the others so that it can be handled by a person, a computer or a machine;

4) close teamwork; will achieve optimal results in terms of combined knowledge and insights. A strong team is more than the sum of its people;

5) use of knowledge for decision making; modern products are so complex that it is impossible to create expert systems and decision support systems

Table 3. **High-tech agriculture: key technologies and impacts**

Technology	Function	Benefits
Precision farming (Smart Farming)	Uses GPS, sensors and data analytics to manage variability in fields	Optimized inputs, increased yields, reduced waste
Drones and UAVs	Aerial surveillance, crop monitoring, spraying	Real-time data, efficient spraying, reduced labor
IoT sensors (Soil & Climate)	Monitor soil moisture, nutrients, weather and crop health	Better irrigation, timely intervention, data-driven decisions
AI	Analyzes big data for forecasting, decision-making and automation	Predictive analytics, disease detection, optimized operations
Robotics and automation	Automates harvesting, weeding, planting and sorting	Labor savings, precision, 24/7 operation
Vertical farming	Indoor, stacked cultivation using controlled environments	Urban farming, resource efficiency, year-round production
Hydroponics & aquaponics	Soil-free systems using water/nutrient circulation or fish integration	Space saving, efficient water usage, pesticide-free production
Blockchain	Tracks agricultural supply chains and ensures product traceability	Food safety, fraud prevention, transparency
Genetically modified crops (GMO)	Engineered for traits like drought resistance or pest control	Higher productivity, reduced chemical use
Satellite imagery & remote sensing	Monitors large-scale changes and crop health remotely	Early warning systems, regional planning, crop insurance
Big Data analytics	Aggregates and analyzes diverse farm-related datasets	Smarter resource allocation, profitability tracking

Source: author`s idea.

for all occasions. However, human knowledge and experience always remains the most important tool;

6) mutual understanding; If each member of a work group knows what the other is doing, the whole group works better. For example, the designer knows what difficulties the technologist will encounter when changing some design parameters;

7) possession; groups work with enthusiasm when they have the freedom to make decisions and when they are given "ownership" and responsibility for the product they produce;

8) constancy of purpose; you need to change your thinking away from the indicators of each specific department to the indicators of the entire company as a whole. Focusing on the goals of the entire company will allow everyone to contribute to the common good.

The principle of concurrent engineering involves performing the processes of developing and designing a technology simultaneously with modeling the processes of its practical operation. This also includes the simultaneous design of various components of a complex product. With concurrent engineering, many problems that may arise at later stages of the life cycle of agricultural technology are identified and solved at the design stage. This approach allows to improve quality, reduce time to market and reduce costs.

The differences between concurrent engineering and the traditional approach to organizing scientific and engineering processes are:

- eliminating traditional barriers between the functions of individual specialists and organizations by creating and if necessary, subsequent transformation, multidisciplinary working groups, including geographically distributed ones, which is important for agricultural technologies in order to most effectively localize application;
- iterative process of approaching the required result.

Multidisciplinary working groups in modern agriculture include specialists from different fields and are created to solve specific problems. For example, representatives of the operator, general developer and component supplier, i.e. specialists from different organizations can be brought together into one group to solve problems that arise during operation.

The main patterns of agricultural development, which require the practice of organizing communi-

Table 4. **ICT support of innovation network**

Component	Function in innovation network	Expected benefits
Knowledge management	Store, organize and share innovation-related knowledge	Enhanced knowledge continuity and onboarding
Collaboration platforms	Facilitate cross-organizational teamwork and virtual meetings	Real-time cooperation and reduced communication delays
Innovation portals	Centralized access to open calls, R&D initiatives, idea submissions	Better visibility and participation in innovation initiatives
Data analytics & business intelligence	Extract insights from data to guide strategy	Evidence-based decision-making
CRM & stakeholder management	Map and manage relationships with ecosystem actors	Stronger stakeholder engagement and coordination
Project & portfolio management	Track innovation project status, risks and ROI	Transparency, prioritization and resource optimization
Cloud infrastructure & storage	Provide scalable, shared access to computing and data resources	Agility, scalability and cost-efficiency
Cybersecurity & identity management	Protect innovation data, IP and communications	Security, compliance and trust in digital environments
Digital twin / simulation tools	Model systems, test innovations virtually	Lower prototyping costs, faster iteration
Blockchain & smart contracts	Ensure trust and traceability in collaborative innovation settings	Transparency, trust, automated execution
Open data platforms	Enable access to datasets for co-creation and experimentation	Data-driven innovation and civic tech engagement
Artificial intelligence & ML	Predict trends, personalize solutions, automate processes	Acceleration of complex problem-solving
IoT platforms & sensors	Collect real-world data for smart infrastructure and urban innovation	Real-time monitoring and adaptive systems
Incubation & mentoring platforms	Support early-stage innovators and connect them to mentors and investors	Nurturing of startups and access to capital
Community & networking tools	Build relationships and shared identity among ecosystem actors	Sustained engagement and knowledge exchange

Source: author`s idea.

cations within the framework of multidisciplinary working groups, include the need to adapt agricultural technologies to local conditions; development of agricultural technologies with maximum environmental safety; formation of specialized industry; digitalization of agricultural production; broad integration of agricultural science and education into agricultural production systems.

Concurrent engineering involves replacing the traditional sequential approach with a set of operations overlapping in time, aimed at systematically improving the solution being developed until the desired result is achieved.

The initial understanding of the problem leads to the first version of documented requirements, from which the initial design solution is developed. It gives rise to new questions and allows us to clarify the formulation of the problem.

Effective implementation of this approach is impossible outside of the information system. The possibility of applying the principles of concurrent engineering arises due to the fact that in the information system all work results are presented in electronic form, are up-to-date, accessible to all participants and can be easily adjusted (Jha, Ranjan, & Gaur, 2020).

Applied decision for digital support of agri-tech transfer

The *information & analytical system* is designed to support and manage the process of development and transfer of agricultural technologies. The system is based on a concurrent engineering model and allows to create an environment for communication between science and business for the joint development of technology. The proposed model involves the simultaneous implementation of various stages of development and testing of new technology, which significantly reduces the costs of adapting technology to new conditions that are significant for agricultural production.

The scheme of the system's operation is based on the analysis of existing solutions to the problem of concurrent engineering and the stages of process planning in the development of a new product, as well as an object-oriented information model of the process (Thankachan, Bhasi, & Madhu, 2010), which includes classes of necessary information. The environment formed through the use of concurrent engineering unites project participants through an information system that allows for the exchange of knowledge, establishes effective mechanisms for coordinating project activities and reduces development time (Aguilar-Virgen et al, 2021).

Taking into account the above requirements, we have developed a formalized conceptual model of an *agent-oriented environment* for the development of innovation, which is the basis for representing the structure and algorithms of operation of the developed information and analytical knowledge management system about the innovative development of the economy, its functionality and component software modules.

The main goal of creating an information & analytical system is to prepare and maintain multidimensional information that displays a related set of data that serves as the basis for prompt and informed decision-making on the development and transfer of agricultural technologies.

The information & analytical system is based on the concept of integrating information from various subject areas, the ability to quickly access it, keep it up to date, use effective tools for analyzing and displaying aggregated and interconnected subsets of information, its retrospective analysis and providing access to it for users of various levels in in accordance with their authority.

The basis of the information & analytical system is a unified information base in which relationships are established between the main information components, which include:

- register of territorial units;
- register of users with powers according to the user matrix;
- register of information events;
- register of documents and regulatory information.

The information & analytical system consist of three subsystems:

- data management subsystem;
- information and cartographic subsystem;
- information and analytical subsystem.

Main ideas of information & analytical system:

1. A system for constructing a unified information space, containing a communication interface module connected to a number of information sources (inputs) representing technical and software information processing tools, an automatic design system for entering data and queries, an electronic archive module and an information model of an agricultural technology (Figure 2).

2. A system for constructing a unified information space, containing a communication interface module connected to a number of information sources (inputs) representing technical and software information processing tools, an automatic design system for entering data and queries, an electronic archive module and an information model of an agricultural technology or product.

3. The system is characterized by adaptive digital environment depending on the technology or product, it is possible to create a set of target indicators.

4. The system contains an updating function designed to collect and update measurement information regarding a set of target indicators, formalize initial data and knowledge about the state and monitor these states.

5. The system contains a metadata conversion block and a virtual data integration block connected to each other and to the specified information environment, a unit of services for a single information space and a data exchange module.

6. The system contains of control centers for data and knowledge processing are designed to store data and knowledge, various product life cycles and the system also includes tools for processing analytical reporting and tools for generating recommendations for decision-making.

7. The information system contains a geoinformation module for storing and processing geophysical information of target territories (territories where the technology will be implemented), including cartographic and reference information,

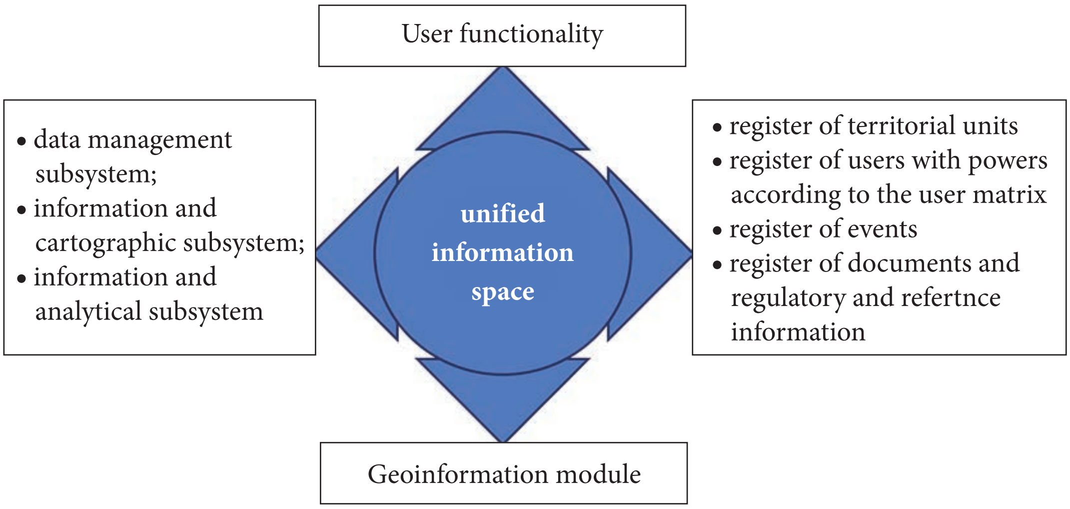

Fig. 2. Unified information space for innovation tech development
Source: author`s idea.

a means of constantly entering and replenishing geophysical information and a system for administering user accounts.

8. The module contains the ability to connect digital video data of a territory with the ability to link a three-dimensional image to the current time and transfer it to a server, which is designed with the ability to permanently store retrospective and prospective maps. For this purpose, it is possible to enter into the database an image of the area, its coordinates and the time the video image was recorded and with the ability to enter time and coordinates.

9. The geoinformation module is distinguished by the fact that it is designed to transmit information online.

10. The geoinformation module is distinguished by the fact that it is designed with the ability to transmit retrospective information to the user (researcher, technician worker).

11. The geoinformation module is distinguished by the fact that it is designed with the ability to predict events in the time of future information.

12. The geoinformation module is distinguished by the fact that it is designed to determine the coordinates of an object on the plan, taking into account the specified time.

Organizational interfaces of digital convergence of agriculture and Industry 4.0

Emphasizing the significance of innovation revitalizing of agricultural businesses' business models, it is vital to draw attention to the primary factors that need to be considered when formulating framework for digital convergence of agriculture and Industry 4.0:

- focusing on regional development priorities, especially the agriculture sector; establishing public-private partnerships and encouraging private investment in the agricultural sector (Omelianenko O., Omelyanenko V., Pidorycheva, 2025; Pidorycheva, Bash, 2024);
- allocation of funds from local and regional budgets to initiatives that are strategically important for the area, guaranteeing food and environmental security;
- activation of communication and informational efforts, with the aim of presenting a favorable picture of the area to a prospective investor and giving him the most comprehensive information regarding investment offers and the benefits of funding the agriculture industry.

Unlike traditional ones, the mechanism for managing the agro-industrial complex's sustainable development based on the concept of a business model proposed in the study is regarded as a system of network business interaction of enterprises in the agro-industrial complex. It reveals the key components of the value chain of enterprises in the agro-industrial complex, implies that an agro-industrial complex enterprise chooses the best kind of innovative business model and enables the determination of strategic directions for achieving the region's sustainable development goals.

ISSN 1562-109X Econ. promisl. 2025. № 3 (111)

The following justifies the speed with which a business model concept can be selected for the establishment of an integration mechanism for the sustainable growth of agricultural enterprises:

• considering the growing popularity of the sharing economy (economy of joint use) theories, business networks of agricultural firms function as organizational innovations. Long-term megatrends, primarily brought about by technological advancements, resource scarcity and social changes, come together to form the economy of shared consumption;

• business models explain how enterprises interact with one another in networks and they can also be a source of competition between players (the interaction of stakeholders in the network occurs on a competitive market basis);

• agro-industrial complex's business networks are based on both formal and for the most part, informal groups of businesses that interact with one another. This calls for knowledge integration and exchange. By addressing social and cognitive issues, business modeling seeks to improve enterprise group interaction and foster the creative potential of each employee in the business network.

Within the framework of smart specialization and organization of interaction between technology transfer participants, it is proposed to create a *technology transfer center*, the purpose of which will be the development and implementation of a system of commercialization and technology transfer in the region's agriculture, the transfer of scientific results, new technologies from their developer to a new owner.

The tasks of this center can include: preparation and organization of events to identify promising scientific developments aimed at further commercialization and technology transfer; search for partners for the commercialization of developments; organization and holding of advertising activities, exhibitions, seminars, symposia and conferences focused on the commercialization of R&D results; information support for the process of commercialization and transfer of developments; assessment of costs associated with the acquisition of technologies; conclusion of an agreement and transfer of technology.

As a result of the study, the network and cluster form of organization of agricultural production was identified as the most acceptable for the implementation of the relationship between science and production. In world practice, a cluster approach is used in the implementation of innovation policy, according to which a cluster is understood as a network of independent production and service firms, including suppliers, creators of technologies and know-how, connecting market institutions and consumers interacting with each other within a single value chain.

A feature of a cluster is the emphasis on the links between industries, enterprises and organizations that contribute to: the development of production and competition; simplified access to the latest technologies; risk distribution in various types of joint activities; organization of joint scientific research and the process of training and retraining of specialists; reduction of transaction costs, etc.

The creation of an agro-technological cluster in terms of technological development will allow:

• to identify problems and determine the current state of the technical and technological sphere of the region;

• to assess the resource potential;

• to determine the mechanisms for regulating technological development;

• to assess the expected socio-economic results from the activities carried out.

An agro-technological cluster is understood as a system of interconnected organizations integrated with the aim of simultaneous and interconnected solution of agricultural production problems based on effective technologies.

The fundamental difference of the proposed cluster model is its construction based on technology transfer. The cluster boundaries will cover several industries, as it develops, the depth of secondary raw material processing will increase and the supplier and consumer bases will expand. Resource-saving technologies will form the basis of the agro-technological cluster.

In the cluster structure, a large role is given to scientific institutions, since these institutions act as a system for promoting knowledge and technology, in addition, inventions are transformed into innovations in them.

Thanks to information and consulting services, participants in the cluster formation receive competitive advantages from innovations.

The implementation of the cluster strategy will require attracting large investment resources. The enterprises themselves should act as the main investors, which is unlikely at present. Therefore, additional scientific research is required, significant amendments to a number of laws and regulations on agro-industrial formations of the holding and cluster type.

The productivity of organizations, supported by the technological connectivity of the cluster value chain, provides its critical mass and the basis for further innovations. Based on this, it should be noted that the interaction of participants in the sphere of the innovation process has a number of characteristic features expressed in the specifics of the industry and the innovation cycle itself. Analysis of experience in the creation of innovation structures provides broad opportunities in choosing a model of innovative development, the main result of innovation activity is the transfer and commercialization of technologies. Technological development in the institutional sphere provides for developments related to the creation of forms and mechanisms for connecting science and production — this is the central link in the implementation of integration processes, intensification of science and production, acceleration of the pace of scientific and technological progress. To solve this problem in agriculture, research, creation and operation of multi-level scientific organizations within the framework of cluster policy are necessary.

Following the example of developed countries, it is advisable to involve a third party in the transfer of material technologies and innovative services, whose task is to provide information support for this process. Such mediation will be carried out through the information provider system. The function of providers is also to mediate between manufacturers and the financial sector.

The development of an information provider network is possible only in the structure of an effective technology transfer system, functioning in the form of a branched network and providing for the coordination of all transfer participants from a single center. Examples of such networks are European Entrepreneurship Network, American Technology Transfer Center, which have a complex multi-level hierarchical structure of regional centers and representative offices. At the same time, the commercialization of technology, as well as ensuring the purchase of innovation on the most favorable terms, are usually carried out with the mediation of their participants.

There are two large networks in Ukraine (Ukrainian Technology Transfer Network with a coordination center in Academy of Technical Sciences and National Technology Transfer Network), as well as several transfer centers, business incubators, technology parks, operating independently of each other. Unlike foreign practice, the domestic technology transfer sector is characterized by significant fragmentation. This is due to the fact that the specified non-integrated technology transfer networks perform almost the same functions. In addition, none of the domestic networks is a participant in foreign technology transfer platforms, which not only significantly complicates access to foreign databases, but also makes it impossible for providers and manufacturers from other countries to access data on domestic achievements in science and technology. From the above, we can conclude that it is necessary to create a single centralized domestic technology transfer network.

Technology transfer services within the framework of agricultural production should cover:

1) legal support for the development commercialization process;

2) patenting and licensing;

3) creation and maintenance of an information support platform for the innovation process;

4) economic assessment of the prospects of innovations, their effectiveness;

5) marketing services for technology transfer, in particular, promotion of technologies, search for the necessary innovations for specific buyers.

It is advisable to integrate personnel for servicing technology transfer in agriculture on the basis of agricultural and natural science universities. This is explained by the availability of specialists with the necessary qualifications, in particular, practicing legal scholars, economists who are specialists in the fields of investment, innovation management, intellectual property, finance, marketing, etc., IT specialists who are capable of not only servicing but also creating information systems. Scientific institutions in such a system will play, first of all, the role of technology developers, the commercialization of which will be carried out by transfer specialists

It is advisable to create the following divisions in the structure of Center for Technology Transfer in Agriculture:

1) technology department (technological audit of technology and the enterprise — the customer of the innovation; development of accompanying technical documentation, etc.);

2) marketing department (research of the market situation for innovations in agriculture, in particular, supply and demand; organization of participation in conferences, exhibitions);

3) financial and economic department (assessment of socio-economic and environmental efficiency of an idea, development; preparation of business plans and innovation and investment projects; establishment of contacts with budget financing bodies, optimization of financing sources and innovation portfolio);

4) patent service (preparation and support of patent applications, protection of intellectual property);

5) legal service (legal support for registration of license agreements, loan agreements, agreements with contractors, consulting in case of violation of intellectual property rights);

6) information support department (creation and maintenance of information support of the technology transfer center; ensuring two-way communication of the center's information system with the information platform of the national technology transfer network).

Conclusions

High-tech agriculture represents a paradigm shift in how food is produced, managed and delivered in the 21st century. It merges traditional farming with cutting-edge technologies from across the industrial spectrum, transforming agriculture into a knowledge-intensive, data-driven and innovation-oriented sector. The integration of IoT, AI, robotics, biotechnology and renewable energy into agricultural systems fosters not only higher productivity and resource efficiency but also greater sustainability and adaptability to climate and market uncertainties. As shown by international experiences, especially in technologically advanced countries, the implementation of smart agricultural technologies results in measurable improvements in yield, energy use and water efficiency. However, realizing similar outcomes in developing and transitioning economies, such as Ukraine, requires a focused effort in strategic planning, capacity building and technology transfer. The institutional environment, research support and international cooperation play decisive roles in this transformation. By positioning high-tech agriculture within the broader context of Industry 4.0 and innovation ecosystems, this study confirms that the sector can act as a catalyst for inclusive economic growth and regional development.

The transition to concurrent engineering in agriculture marks a paradigm shift in how modern agri-technologies are developed, tested and deployed. By replacing linear development models with synchronized, collaborative processes, this methodology addresses the pressing need for faster, more sustainable and context-adapted innovations in a rapidly evolving sector. The integration of ICT tools and digital infrastructures facilitates the coordination of multidisciplinary teams, supports knowledge-driven decision-making and ensures early problem detection. Moreover, the inclusion of sustainability indicators during the design phase, supported by methods such as QFD and the «sustainability house», strengthens alignment with environmental and socio-economic goals. As high-tech agriculture continues to evolve within complex innovation ecosystems, the adoption of concurrent engineering provides a robust foundation for systemic, scalable and inclusive technological advancement. The proposed approach not only enhances product and process innovation but also supports the resilience and competitiveness of agriculture in the face of global challenges.

The effective transfer of agricultural technologies requires not only scientific excellence but also well-structured, digitally enabled systems that can bridge the gap between research and practice. This study proposes a comprehensive model of a concurrent engineering-based information and analytical system that facilitates the co-creation, adaptation and dissemination of innovations within the agri-food sector. By integrating data-driven modules, geospatial tools and decision support functionalities into a unified platform, the system empowers stakeholders to reduce development time, manage risk and increase the efficiency of technology adoption in diverse territorial contexts.

The formation of agro-technological clusters and technology transfer centers is central to operationalizing this model, fostering collaboration among universities, startups, producers and policymakers. These clusters provide a functional environment for the coordinated development of sustainable and locally adapted technologies, while the digital architecture ensures transparency, knowledge continuity and stakeholder accountability. Furthermore, the institutionalization of transfer services is essential for scaling innovations and creating robust, investor-ready ecosystems.

Given the fragmentation of the current technology transfer landscape in Ukraine, the paper underscores the need for a centralized, integrated national network that connects domestic innovation actors with international platforms. Such an approach not only enhances global competitiveness but also aligns agricultural innovation with national goals for food security, environmental sustainability and regional development. The proposed model demonstrates that digital infrastructure, organizational integration and smart specialization can collectively transform technology transfer into a dynamic engine of agricultural modernization.

Prospects for further studies

Future research will focus on expanding the functionality of the proposed system through the integration of real-time data analytics, which can further automate scenario generation and decision-making processes. Another important direction includes testing the tool in specific sectors, such as green infrastructure, high-tech agriculture and urban mobility, to tailor the models to sector-specific needs. There is also significant potential for international collaboration, particularly within the framework of EU digital and innovation ecosystems, to adapt the tool for cross-border infrastructure projects. Furthermore, researchers aim to investigate the role of local innovation communities in optimizing the interaction between technological systems and human decision-makers. These steps will contribute to refining the system's responsiveness and scalability across various environments and use cases.

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Надійшла до редакції 11.07.2025 р.
Прийнята до друку 29.07.2025 р.

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Received: 11.07.2025
Accepted: 29.07.2025

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ЦИФРОВА КОНВЕРГЕНЦІЯ СІЛЬСЬКОГО ГОСПОДАРСТВА ТА ІНДУСТРІЇ 4.0: МОЖЛИВОСТІ ТА ОРГАНІЗАЦІЙНІ ІНТЕРФЕЙСИ

Агропромисловий комплекс зазнає глибокої трансформації, зумовленої нагальною потребою в подоланні таких глобальних викликів, як продовольча небезпека, зміна клімату, демографічні зрушення та дефіцит ресурсів. Проаналізовано роль високотехнологічного сільського господарства як ключового рушія інновацій і стійкості в агропромисловому комплексі. Наголошено на основних технологічних тенденціях Індустрії 4.0, зокрема інтеграції Інтернету речей (IoT), робототехніки, точного землеробства, біотехнологій і відновлюваної енергетики, які в сукупності переосмислюють сільськогосподарські практики та тісно пов'язують агросектор із сучасними галузями промисловості. Особлива увага приділяється стратегічній важливості трансферу технологій, плануванню на основі форсайту та заснованих на даних рішенням для підвищення продуктивності, зниження екологічного навантаження та посилення стійкості. Взаємозв'язок між сільським господарством та іншими секторами («зелена» енергетика, ІКТ) представлений через системний погляд на інновації, що підкреслює зростаючу конвергенцію галузей. Висновки підтверджують ідею, що високотехнологічне сільське господарство є не ізольованим, а становить складову цифровізованої промислової економіки. Сформовано системно орієнтований підхід до трансферу та комерціалізації аграрних технологій, що передбачає використання цифрових технологій і ґрунтується на принципах паралельної інженерії та теорії інноваційних мереж. Паралельна інженерія широко застосовується в передових галузях промисловості та пропонує трансформаційну альтернативу традиційним послідовним моделям розроблення, забезпечуючи колаборацію та паралельне проєктування. Підкреслено критичну роль етапу проєктування в життєвому циклі агротехнологій. Розглянуто, як паралельна інженерія підвищує ефективність, стійкість та адаптивність в інноваційних мережах сільського господарства. Із використанням цифрових інструментів, інтегрованих систем знань і платформ ІКТ-співпраці такий підхід передбачає узгодження інженерного проєктування з цілями сталого розвитку, забезпечуючи раннє виявлення ризиків, гнучке прототипування та залучення зацікавлених сторін із різних секторів. Запропоновано структуру ІКТ-підтримки інноваційних мереж. Наголошено на необхідності включення міждисциплінарних і географічно розподілених команд у цикл розроблення для забезпечення релевантності, стійкості та створення довгострокової цінності в секторі аграрних технологій. Запропонована організаційна модель трансферу технологій інтегрує підсистеми управління даними, геоінформаційного аналізу та прийняття рішень на основі знань для підтримки життєвого циклу аграрних інновацій. Основну увагу приділено зближенню сільського господарства та Індустрії 4.0 через регіональну смарт-спеціалізацію, публічно-приватне партнерство та формування агротехнологічних кластерів. Висвітлено організаційні та інфраструктурні вимоги до побудови мережі трансферу технологій з фокусом на важливості маркетингових сервісів й інтегрованих високоефективних екосистем трансферу. Завдяки поєднанню інституційного проєктування з цифровою інфраструктурою модель забезпечує ефективніше, масштабоване та стійке впровадження агротехнологічних інновацій у регіонах.

***Ключові слова*:** сільське господарство, трансфер технологій, інформаційно-комунікаційні технології, інноваційна мережа, агротехнологічні інновації.