CHAPTER 4

R&D process management in the context of digitalization

Nataliia Sysolina
Iryna Sysolina
Volodymyr Amosov
Sergiy Nisfoyan
Olga Chumachenko
Ruslan Kisilov

Abstract

The article is devoted to a comprehensive study of the theoretical, methodological, and applied aspects of process management in the context of the Fourth Industrial Revolution. The focus is on the transformation of the new product development system, moving from purely mechanical improvements toward the creation of intelligent robotic systems based on the concept of "disruptive innovations".

The first section systematizes the conceptual foundations of innovation cycle management and defines the role of R&D within the Agriculture 4.0 value chain. The study substantiates a multi-factor functional dependence of management effectiveness on intellectual capital, strategic positioning, time parameters, and the level of uncertainty. The process architecture is based on the implementation of the Stage-Gate model, which serves as a risk filter and a decision-making tool at the early stages of the innovation lifecycle.

The second section presents the results of economic and mathematical modeling for the development of an intelligent "Smart" type coulter. The study demonstrates the critical role of the intellectual component (software and AI algorithms), which accounts for approximately 50% of the total development budget. The investment project parameters are calculated for an agricultural machinery enterprise (the full payback period for the developer is 1.66 years).

An analysis of the implementation efficiency from the perspective of the end-user (small agricultural enterprise) was conducted, establishing that the payback period of the implemented innovation is 2.4 years, which renders digitalization

 DOI: 10.21303/000-0000-0000-0-0.ch4

a justified investment in the medium term. The research confirms that within the Agriculture 4.0 framework, strategic advantage is attained through the capitalization of intellectual capital and the rigorous filtering of innovation projects during the early stages of development.

The findings of this study can be utilized by machinery manufacturing enterprises to justify R&D budgets, by scholars to examine the patterns of digital transformation in the agricultural sector, and by investors for the assessment of AgTech startups. The article is addressed to scientists, educators, students of economic and engineering disciplines, agribusiness managers, and innovation management specialists.

Keywords

Management of innovation development, R&D, Stage-Gate model, digital transformation, agricultural machinery company, Agriculture 4.0, intellectual capital, disruptive innovations, econometric modeling.

4.1 Introduction

In contemporary conditions, influenced by globalization, digitalization, and the concept of open innovation, both the directions of research and the theoretical-methodological basis for managing Research and Development processes are undergoing a fundamental transformation. This requires enterprises to utilize a comprehensive set of tools that combine classical management approaches with dynamic models of strategic networking.

In this regard, significant shifts are occurring globally. A primary trend of the decade has been the rapid growth of Asia, which now accounts for approximately 45% of total global innovation spending. China has seen a sharp increase in R&D intensity, rising from 1.96% of GDP in 2014 to 2.58% in 2023. Notably, in 2024, China surpassed the United States in total R&D expenditures for the first time (785,9 billion USD vs. 781,8 billion USD, respectively). The United States maintains steady leadership growth, from 2.7% of GDP in 2014 to 3.45% in 2024, with R&D predominantly driven by the private sector (Big Tech). Japan, with expenditures of 186 billion USD (3.44% of GDP in 2024), is experiencing stagnation, as its share in global R&D has contracted by 7.2 percentage points since 2000. South Korea, spending approximately 140 billion USD in 2024 (4.96% of GDP), holds the highest innovation intensity in the world. The EU–27, with total expenditures of 542,0 billion USD (2022) and an R&D intensity of 2.11% (2024), shows moderate growth, where Germany leads (3.13%) and Romania records the lowest indicators (0.46%). Israel remains the leader in terms of R&D share relative to economy size at 6.35% of GDP (2024).

Ukraine, at 0.14% of GDP (2024) due to full-scale military actions, is undergoing a militarization of its R&D sector. An analysis of R&D trends across various countries from 2014 to 2024 reveals that following the "boom" of 2021–2022, global R&D growth slowed to 4.4% in 2023, a trend projected to persist due to the complex geopolitical situation [1–4].

Thus, the study of innovation development management R&D process management is of paramount relevance.

This article is devoted to the theoretical justification and development of applied tools for R&D process management amidst the digital transformation of the agricultural sector, aimed at increasing the efficiency of innovation development and implementation.

To achieve the research objective, the following scientific hypotheses were formulated:

H1: Innovation is not a random spark of genius but a structured business process that can be modeled and managed.

H2: In the modern economy, knowledge and creative labor hold greater weight in product value creation than physical assets.

H3: The effectiveness of an innovative solution is based on optimizing the ratio between functional utility and implementation costs.

H4: Agricultural development is inevitably transitioning to the Agriculture 4.0 stage, where robotic systems and AI play a pivotal role.

H5: High uncertainty in R&D is not an insurmountable obstacle if flexible financial planning tools and stage-by-stage controls are utilized.

The methodological framework of the study is built on a systemic approach using the following methods:

1. Analysis and synthesis: applied to decompose the complex R&D process into distinct stages and subsequently integrate technical and economic factors into a cohesive management model.

2. Functional-value analysis (FVA): used as a core tool to optimize the ratio between the consumer properties of the coulter (seeding precision, moisture measurement) and the costs associated with its development and production.

3. Econometric modeling: to formalize R&D process management into an integral functional relationship.

4. Comparative analysis: to contrast traditional mechanical sowing approaches with modern (robotic) ones, revealing the significant advantages of the latter.

5. The real options method: for evaluating and making decisions, under conditions of high uncertainty, regarding innovative projects at each stage of the Stage-Gate model.

6. Statistical and dynamic analysis: to study global trends in R&D funding over the past 10 years.

7. The scenario and forecasting method for planning the market launch of an innovative product and developing a commercialization strategy.

The combination of these methods ensured that the conclusions regarding the viability of the business model were well-founded.

4.2 Theoretical and methodological foundations and tools for managing the research and development process

The modern paradigm of research and development (R&D) management is based on the understanding of innovations as significant modifications of technological processes and products that possess scientific and technical novelty, as well as socio-economic effectiveness. Management of innovative development requires a comprehensive set of tools covering the entire innovation cycle (from fundamental research to industrial implementation and diffusion)

Modern R&D management has evolved from a linear internal function of a company into an open, complex, digital ecosystem.

R&D-related activities are a strategically important component of a company's operations, aimed at generating new knowledge and applying it in practice to create new products or processes or improve existing ones.

R&D is no longer viewed simply as an "expense item" but as an investment in intellectual capital. Managing the innovation process requires a balance between the creative freedom of scientists and engineers and strict business metrics (deadlines, budgets).

Contemporary R&D management is not solely about technological oversight; it represents a complex architecture of capital management and organizational behavior, which must account for:

– the role of intellectual capital and "innovation ambidexterity": the enterprise's capacity to simultaneously refine existing technological solutions and generate radically new products [5];

– the problem of "myopic management": the risk that short-term financial incentives for top management (e.g., stock options) may negatively impact long-term strategic investment in development [6];

– the balance of knowledge sources: the integration of internal research with external expertise (Open Innovation), which determines the firm's overall absorptive capacity [7].

Furthermore, innovations within the R&D system should be interpreted as substantial modifications in products and technological processes that fundamentally alter their parameters, functional properties, and cost structures. Such innovations must be strictly differentiated from routine technical modifications or simple product line extensions aimed merely at satisfying current market demand.

The selection of management methods directly depends on identifying the type of innovation based on several key characteristics:

– by typology: product, process, marketing, and organizational innovations;

– by degree of novelty: incremental – small-scale improvements; radical (breakthrough) – implementing revolutionary scientific ideas and creating new industries; modified – aimed at improving specific parameters of existing machinery; disruptive (per C. Christensen [8]) – simpler and more affordable solutions that progressively capture the markets of large corporations;

– by source of planning: centralized, local, and spontaneous;

– by nature of knowledge: innovations based on fundamental scientific discoveries versus those based on new combinations of existing technologies;

– by scope: point (local), systemic, and strategic;

– by source of origin: closed (internal) and open (the result of collaboration between various companies and institutions).

The transition toward open innovation is a hallmark of the modern globalized economy. The innovation process within the R&D framework is viewed as a sequential system of activities, where an idea undergoes a transformation into a specific technology or product. Management efficiency at each stage – from conceptualization to market launch – determines the ultimate success of the entire project.

The core phases of R&D are as follows:

– fundamental research: theoretical or experimental study of natural patterns without a direct goal of practical application;

– exploratory and applied research: development of innovative ways to increase efficiency and solve specific practical tasks;

– design and development: creation of project-engineering documentation, blueprints, diagrams, and mock-ups;

– experimental testing: testing the first technical prototype in an experimental production environment to verify compliance with technical standards and sanitary norms;

– industrial implementation: transition to a large-scale manufacturing process and serial production.

To optimize development and minimize risks, modern corporations utilize specialized methods and models (**Table 4.1**).

Table 4.1 Modern models of R&D process management

Model category	Tools / Authors	Essence and management mechanism
Conceptual model	Innovation funnel	Illustrates how a large number of raw ideas are progressively filtered until only the most viable projects remain. Permeable boundaries allow ideas to enter from the outside or reach the market through other companies (licensing, startups)
Operational model	Stage-gate model (R. Cooper)	Transforms the complex R&D process into a series of clear steps (Stages) and decision checkpoints (Gates) to ensure disciplined project execution
Strategic models	Strategic networking model	A non-linear integrated model where R&D is performed through information systems that ensure strategic links with partners, allowing for risk-sharing through cooperation
	Technological S-curve model	Based on the existence of a "natural limit" for each technology, allowing for an assessment of the feasibility of further investments in its improvement
	Real options method	Allows for structuring a sequence of investment decisions to increase project value and adequately evaluate intellectual property
Specialized models	Herpott model	Assists in selecting the localization system for R&D units of international corporations depending on technology attractiveness and risk levels
	Pearson-Brockhoff-Boehmer model	Utilizes a modified "Porter's Diamond" to evaluate human resources and supporting technologies at the locations of development centers

Source: compiled by the authors based on [9–11]

The innovation funnel serves as a dynamic selection tool encompassing three key phases:

– generation (ideation phase): the systematic gathering of ideas from all possible sources-ranging from marketing departments and R&D engineers to direct customer feedback. At this stage, the priority is the maximum quantity and diversity of concepts;

– selection (screening phase): the critical evaluation of ideas for alignment with the company's strategic goals, technical feasibility, and potential economic profitability;

– realization (execution phase): the final transformation of the selected idea into a prototype, followed by testing and full-scale market launch.

The absence of a structured "funnel" creates the risk of resource dissipation across an excessive number of weak and unprofitable projects simultaneously.

The stage-gate model functions as a phased control mechanism. Each Stage involves intensive information gathering and steps to reduce uncertainty (market analysis, engineering design, field trials). Notably, the cost of each subsequent stage increases progressively.

Gates serve as critical quality control filters where management evaluates the results of the previous stage and makes one of four strategic decisions:

Go: the project receives funding and approval for the next stage.

Kill: immediate termination of the project. Timely cancellation of a weak project is considered a management success, as it saves millions in future investment.

Hold: temporary suspension of the project until more favorable market or technological conditions arise.

Recycle: returning to the previous stage to address identified deficiencies.

The primary advantages of the Stage-Gate model include the radical reduction of the risk of "costly mistakes" in late development stages, acceleration of time-to-market, and the focused allocation of limited resources toward the most profitable innovations.

Functional-value analysis (FVA) within the R&D system is regarded as a methodological foundation for optimizing the ratio between the functional utility (properties) of a future innovative product and the costs of its development and manufacturing. This is critically important, as innovations must not only be scientifically and technically novel but also economically viable for production and capable of generating profit.

Integrating FVA into the innovation cycle facilitates informed management decisions based on the following principles:

Interdisciplinary development: during the design and development stage, technologists, engineers, and economists collaborate on cost estimation and pricing, comparing various technical solutions based on their effectiveness and ability to achieve superior quality parameters.

Consumer-centric evaluation: technological efficiency is assessed by contrasting the primary functional parameter of interest to the consumer (e.g., seeding precision) with the costs of its implementation. This distinguishes substantial innovations from insignificant modifications that lack a noticeable impact on properties or value.

Value management via real options: the application of FVA is closely linked to the real options method, which allows for the structuring of sequential investment decisions to increase project value and adequately evaluate intellectual property components.

Technological limit analysis: utilizing the Technological S-curve model helps determine the point of diminishing returns, where further investment in improving specific functions becomes excessively capital-intensive due to approaching the natural frontier of the current technology.

Within the R&D framework, innovation success is evaluated through factor-based assessment, where functional-value parameters play a pivotal role:

– consumer criteria: the ultimate result of innovative activity is assessed directly during operation based on quality, price, and energy efficiency indicators;

– strategic network integration: the utilization of information systems (strategic networking model) enables enterprises to optimize the development process by synchronizing the activities of suppliers, developers, and end-users;

– preventive FVA: conducting functional-value analysis during the experimental testing phase allows for the refinement of technological process parameters and the elimination of critical defects before the capital-intensive launch of industrial production.

Risk management in innovation projects is complicated by high uncertainty regarding outcomes in the initial phases. Although risk in the R&D sector is probabilistic, it is predictable at every stage-from conceptual design to serial production. To ensure informed management, a factor-based assessment is applied, characterizing the complexity, uncertainty, and dynamics of the processes. The classification of risks by source and corresponding management models is presented in **Table 4.2**.

Table 4.2 Matrix of risks and strategic choice in R&D management

Risk category	Manifestation within the R&D process	Assessment instrumentation (model)
Technological risk	The technology approaching its "natural limit," where minimal parameter improvements require colossal investments	Technological S-curve model
Strategic risk	Selection of a flawed innovation policy: aggressive strategy despite a weak position or ignoring technologies that threaten current business	Herpott model
Resource risk	Insufficient personnel qualification or inefficient localization of R&D centers	Pearson-Brockhoff-Boehmer model
Intellectual property risk	Loss of rights to the creative product, lack of copyright protection, or ineffective patent searches	Intellectual property management (IPM)
Market risk	Mismatch between the development's features and actual market demand or consumer needs	Innovation cycle market research

Source: systematized based on [11]

To reduce the likelihood of financial losses, the innovation process is structured in stages, each of which acts as a "filter" for risks.

Fundamental and exploratory research allows for the early elimination of ideas that are clearly unviable.

Experimental testing allows for the identification and elimination of technical, sanitary, and environmental shortcomings (potential) before expensive industrial production is launched.

The use of digital technologies – computer modeling and 3D printing – significantly simplifies and accelerates testing, allowing for iterative refinement of the design at minimal cost.

The primary driver of firms' innovation performance is digital transformation, which creates new

Digital transformation is not merely a tool, but a comprehensive environment for research and development. The implementation of digital twins and the integration of the real economy and the digital economy help companies overcome the "innovation dilemma" while simultaneously reducing time to market [14]. Digitalization also helps resolve such "innovation dilemmas" as the more efficient allocation of resources within enterprises [15].

The practical implementation of digitalization in research and development management faces certain organizational challenges (barriers): the "cultural gap" between digital operational logic and traditional scientific thinking; the need for significant professional development of personnel in the field of research and development; and the obsolescence of research infrastructure, which makes it difficult to integrate with digitalization mechanisms [16].

During digital transformation, large organizations face structural dilemmas such as: preserving expertise versus reconfiguring resources; quality versus speed; decentralization versus centralization of innovation management; and standardization versus adaptation of research and development processes [17].

A phased approach to digital transformation is a mechanism for tackling these challenges, prioritizing strategic processes with the highest readiness for change. Agile methodologies and iterative development cycles enable organizations to innovate, experiment, and adapt much faster than in traditional linear R&D management structures [18].

Artificial intelligence is becoming a "co-researcher". Generative models automate routine stages of R&D, ranging from patent searches to predictive modeling of the properties of new materials, which is radically changing the role of scientists and engineers [19].

In agriculture, AI-based innovations are becoming critical for energy efficiency and sustainable development – for example, in greenhouses – demonstrating the sector-specific nature of modern R&D [20].

Synergy across different fields of knowledge drives successful innovation, including science, technology, marketing, and the arts.

"Green innovations" given the social demand for environmental sustainability, have become a mandatory standard. The development of renewable energy and industrial robots is a strategy aimed at addressing the problem of environmental degradation [21]. Technological innovations help mitigate environmental degradation in developing countries.

Consequently, the results of research and development are often evaluated using environmental, social, and governance indicators [22, 23].

Company boundaries are becoming permeable. Successful developments are based on the synergy between external knowledge sources and internal research [24]. Collaboration with universities and startups, along with the use of digital financial instruments, creates a steady flow of innovation. Digital financing and ecological decentralization stimulate the development of green technologies [25].

Effective R&D management requires moving away from a short-sighted focus on quarterly reports. Long-term success depends on the development of intellectual capital and dynamic capabilities that allow a firm to adapt to challenges in the global economy.

In the context of global competition, innovation cycles are constantly shortening, requiring R&D management to demonstrate exceptional flexibility and speed in decision-making.

The effectiveness of R&D process management today depends on the synergy of the intellectual work of scientists, engineers, marketers, and lawyers, as well as management's willingness to take calculated risks in the face of uncertain outcomes. The management of the R&D process ($M_{R\&D}$) can thus be represented as an integral model, functioning as a derivative of key influencing factors

$$M_{R\&D}=f\left(IC,S_{tech},R_{res},\tau,U\right),$$

where IC (intellectual capital) – the results of the collective intellectual labor of all involved specialists, including scientists, engineers and software developers; S_{tech} (strategic position) – the technological standing of the enterprise and the inherent attractiveness of the selected technology; R_{res} (resources) – the aggregate of constrained resources, encompassing financial, material, and informational assets; τ (time/dynamics) – the temporal factor, accounting for the continuous shortening of innovation cycles in the contemporary economy; U (uncertainty) – the level of inherent uncertainty and risk, which is a critical determinant for innovation projects.

This function possesses several distinctive characteristics:

1. Factor-based management efficiency: management effectiveness is contingent upon the ability to apply factor-based assessments that characterize the

complexity and scientific rigor of the development, its dynamism (speed of change), and its practicality (feasibility of implementation).

2. Phase-dependent dynamics: the management function undergoes transformations depending on the specific phase of the innovation cycle. For instance, at the stage of fundamental research, scientific novelty and rigor predominate; conversely, during experimental testing, the focus shifts toward practicality, scalability, and compliance with safety standards.

3. Non-linear network integration: modern corporations utilize a non-linear integrated model (strategic networking model). This implies that R&D management is not merely a linear sequence of steps but a complex network interaction. In this paradigm, research and development activities are performed in parallel with marketing analysis and the active utilization of information systems.

The essence of R&D management today is inextricably linked to the creation of added value through intellectual property. This paradigm shift permeates every facet of project management, from quality assurance systems to talent acquisition strategies. Thus, R&D management can be defined as the function of converting intellectual potential into commercial value under conditions of temporal constraints and high uncertainty.

The transition from radical to incremental (modification) innovations entails a significant restructuring of the R&D management framework. The relative "weight" of individual factors within the functional dependency ($M_{R\&D}$) adapts accordingly, reflecting the varying nature, novelty, and risk profiles of these innovations.

Radical (disruptive) innovations represent fundamental shifts that either establish entirely new industries or revolutionize existing productive forces. The impact of key factors is analyzed as follows:

– Intellectual capital (IC): this factor carries maximum weight. The process is anchored in fundamental scientific research and requires a high density of creative intellectual labor. It necessitates human capital with unique, specialized competencies that form the "creative engine" of the project team.

– Uncertainty and risk (U): reaches extreme levels. This volatility is driven by the inherent unpredictability of outcomes during the early development stages. Organizations consciously embrace higher risk to secure substantial expected returns and drive qualitative breakthroughs.

– Strategic technological position (S_{tech}): characterized by an aggressive posture. The high appeal and potential of breakthrough technologies demand substantial resource allocation to maintain leadership in global innovation races and implement capital-intensive projects.

Incremental (modifying) Innovations represent smaller-scale enhancements aimed at optimizing specific parameters of existing products or technologies while preserving the core underlying principles. The impact of management factors in this context is as follows:

– Intellectual capital (*IC*): the impact is moderate. Management is based on existing scientific knowledge and new combinations of established technologies. The primary focus is on the labor of engineers and technologists regarding modernization, adaptation, and refinement.

– Uncertainty and risk (*U*): significantly lower. Such innovations are subjects of routine and strategic planning, where outcomes are more predictable. Risk is minimized through incremental improvements and the gradual diffusion of the innovation.

– Strategic technological position (S_{tech}): oriented toward stabilization. This approach is used to extend the product lifecycle during the market saturation stage. The policy is typically less aggressive and often oriented toward international cooperation and standardization.

The differences in factor impacts are systematized in the comparative matrix below (**Table 4.3**).

Table 4.3 Comparative matrix of factor impact in R&D management

Management factor	Radical innovations	Incremental (modifying) innovations
Intellectual labor (*IC*)	Dominant (scientists, creators, visionaries)	Technical (engineers, technologists, analysts)
Risk level (*U*)	Maximum (high uncertainty, breakthrough)	Minimum (predictability, planned cycles)
Technological goal (S_{tech})	Creation of a new, fundamental element/industry	Quantitative optimization of existing parameters
Investment strategy	Capital-intensive, aggressive, high-stakes	Efficiency-oriented, stable, conservative

Source: developed by the authors

In summary, managing disruptive (radical) innovation is fundamentally about the management of uncertainty and talent, whereas managing incremental (modifying) innovation centers on the management of processes and operational efficiency.

4.3 Applied aspects of R&D process management

Applied aspects of R&D management encompass specific mechanisms and tools that ensure the effective functioning of research and development processes within a digitalized environment. The primary task of applied management is the transformation of theoretical models and strategic concepts into the daily operational practices of enterprises.

Contemporary R&D management practice demonstrates that the implementation of digital technologies significantly impacts all key performance indicators of research activities. Research by T. Pu [26] confirms that digital transformation accelerates corporate innovation and strengthens competitive advantages by enhancing decision-making processes based on Big Data, Cloud Computing, and Artificial Intelligence (AI). Specifically, Big Data provides more accurate market forecasts, enabling companies to select priority areas for innovative development more purposefully, while digital platforms accelerate resource integration and rapid response to market fluctuations.

R&D directions are shifting in alignment with modern innovative advancements, a trend most vividly observed in the agricultural sector (**Table 4.4**). The transition to Agriculture 4.0 is predicated on the implementation of digitalization, automation, robotics, precision farming, and AI for agricultural production management. This paradigm involves the integration of GPS, IoT (Internet of Things), drones, and Big Data analytics to enhance the efficiency, precision, and sustainability of agricultural enterprises.

Table 4.4 Comparative characteristics of R&D directions in agricultural engineering

Feature	Traditional Approach (Agriculture 2.0/3.0)	Modern Robotic Approach (Agriculture 4.0)
Drive system	Mechanical (utilizing shafts, gears, and chain drives)	Electric (individual electric drive for each row unit)
Control system	Manual adjustment and periodic monitoring by the operator	Automated control based on sensor networks and AI algorithms
Seeding depth	Static: mechanically preset as an average parameter for the entire field	Adaptive: dynamically adjusted based on real-time soil moisture in specific field segments
Grain losses	Identified post-harvest; difficult to rectify during the operation	Minimized in real-time through computer vision (monitoring cameras) and flow sensors

Source: compiled by the authors based on [27–29]

These technologies (**Table 4.4**) are integral to the Agriculture 4.0 concept, where mechanical hardware serves merely as the executor of commands issued by digital intelligence. Precision agriculture (PA), as a philosophy, dictates that the "right" operation must occur in the "right" place, at the "right" time, and with the "right" intensity.

In technical terms, "Precision Agriculture in hardware" represents the transformation of mechanical machine units into intelligent executive organs.

Consequently, the modern agricultural machine is evolving into a mobile computing center, where mechanical components are subordinated to artificial intelligence algorithms. The primary objective of R&D in this field is to develop machinery that maximizes yields while minimizing the consumption of fuel, fertilizers, and manual labor.

It is possible to focus on the management of modifying innovations within the agricultural sector, specifically examining seeding operations. The fundamental shift in seeding is the transition from massive, uniform implements to "smart" seeding modules, where every individual seed is monitored independently.

It is possible to consider autonomous seeding robots: each row unit is equipped with a sensor (e.g., SmartFirmer) that measures moisture, temperature, and organic matter content in the furrow in real-time. The robot can automatically adjust the seeding depth if the soil is too dry at the preset level. To develop such a smart-type coulter, it is possible to apply a combination of the stage-gate model and the functional-value analysis approach.

Gate 1. Preliminary Screening.

The initial selection of ideas was based on the following criteria: Does the idea align with the "Precision Agriculture" concept? Are there viable technical solutions to integrate moisture and organic sensors into the metallic structure of the coulter?

Notably, the SmartFirmer (developed by Precision Planting, USA) represents a radical innovation. As a seed-firmer sensor, it measures the exact amount of moisture available to the seed, facilitating precise depth regulation and ensuring consistent crop yields. This technology replaces traditional manual spot-checks (digging up seeds), which fail to provide a comprehensive overview of seeding depth accuracy across an entire field.

SmartFirmer measures the furrow while simultaneously pressing each seed into the bottom of the furrow, ensuring optimal seed-to-soil contact. It provides deep insights into the seedbed environment and the condition of the placed seeds, while also identifying various types of field variability.

As a soil-sensing module installed on each row unit immediately behind the seed openers, SmartFirmer is a unique development that enables real-time data collection on soil temperature, moisture, organic matter (OM) content, furrow uniformity, and residue presence. This data can be utilized both during and after planting; the system can automatically perform variable rate seeding in areas with differing humus content, as well as adjust application rates for starter fertilizers, nitrogen, and insecticides.

A stable environment is essential for uniform seed germination and plant growth. SmartFirmer identifies any irregularities along the furrow, such as soil clods, air pockets, or dry soil falling from the surface. This provides the necessary insights to adjust row-unit performance and address yield-robbing issues, including over-compaction and fluctuations in organic matter content.

Crop residues within the furrow negatively impact seed germination and growth. SmartFirmer enables the measurement of residue levels in the furrow and the subsequent adjustment of row cleaners, ensuring that residues do not impede moisture absorption or transmit pathogens to the seeds. It facilitates on-the-go variable rate seeding and fertilization without the necessity of pre-generated prescription maps or prior field surveys, thereby significantly reducing operational costs.

SmartFirmer grants farmers comprehensive control over the seeding process, enhancing yield and efficiency through precise real-time soil monitoring. Functioning as a "mini-station" integrated directly onto the seeder, it allows for remote monitoring via smartphones, tablets, or laptops when paired with modules like FieldView.

While precision planting equipment is versatile and compatible with both mechanical and pneumatic seeders from major American manufacturers (e.g., AGCO, John Deere, Kinze, Case IH, Great Plains), structural differences in the row units of European manufacturers often limit direct compatibility.

Technologies like precision planting represent a strategic solution for "retrofitting" older machinery, essentially revitalizing legacy equipment and allowing it to perform at the level of the latest high-end models. Therefore, the primary objective of this R&D initiative is the development of a Smart-type coulter integrated with modified sensors-inspired by the SmartFirmer concept-specifically engineered for compatibility with alternative seeder platforms (including European and domestic models).

This phase concludes with the approval of the "Smart Depth" concept, augmented by a device for real-time seeding precision monitoring.

Stage 1. Scoping the scoping phase consists of:

– technical analysis: evaluating existing SmartFirmer patents and analyzing the feasibility of developing an in-house sensor versus licensing existing technology;

– market analysis: conducting rapid surveys of agro-holdings to assess their willingness to pay for "automatic depth control" and high-precision seeding. As a result, a preliminary technical description (product concept) is established.

Stage 2. Building the business case at this stage, functional-value analysis (FVA) is primarily applied to calculate the manufacturing cost of the sensors versus the economic gain derived from uniform seedling emergence.

The FVA implementation during the design phase of innovative robotic systems-such as coulters with integrated SmartFirmer-type sensors and seeding precision trackers-facilitates the optimization of the balance between advanced technological features and economic viability. Given that scientific and technical developments are intermediate results, their successful transformation into a market-ready innovation requires a rigorous justification of their socio-economic efficiency.

The functional-value analysis algorithm for an intelligent opener at the design stage consists of 5 Stages:

FVA Stage 1. Functional decomposition and identification of needs (**Table 4.5**).

Table 4.5 Technical specifications and promotion strategy for the intelligent seeding system

Strategic direction	Factors / parameters	Essence and content of activities
Product description	Innovation type	A product-based, modifying scientific and technical innovation integrating sensor technologies and robotic actuators
	Key characteristics	Real-time measurement of furrow parameters (moisture, temperature, organic matter); automated adjustment of seeding depth and precision
	Criteria	Scientific novelty, manufacturability for high-tech production, and high socio-economic efficiency
Market analysis	Industry trends	Researching global technological trends within Agriculture 4.0 and precision farming systems
	Consumer needs	Identifying the demands of agro-holdings regarding resource saving (seed/fuel economy) and yield maximization
	Competitive analysis	Benchmarking existing analogs (e.g., SmartFirmer) to highlight the technological advantages of the proprietary product
Market Entry strategy	Segmentation	Identifying priority regions based on the level of digital economy development in agriculture
	Branding & USP	Developing a Unique Selling Proposition that emphasizes the materialization of human potential in a high-tech product
	communication policy	Formulating a promotional plan involving professional agri-networks and high-tech trade fairs
IP management	Technology transfer	Designing licensing schemes and know-how sales models within the "Open Innovation" framework
	Information security	Implementing trade secret protections and patenting key engineering solutions during the promotion stage
Expected KPIs	Market position	Achieving the planned market share in the innovative seeding equipment segment
	Economic effect	Ensuring manufacturer profitability and positive ROI for consumers (higher yields, resource efficiency)
	Innovation diffusion	Large-scale replication and identification of new application areas for the developed sensor technology
Coordination	Cross-functional links	Ensuring close collaboration between marketers, design engineers, and financiers to refine product parameters based on early adopter feedback

Source: developed by the authors

During the applied research and technical specification stage, the product is decomposed into primary and secondary functions:

Measuring function: Real-time monitoring of soil moisture, temperature in the seeding zone, organic matter content, and seeding precision.

Executive (actuation) function: Automated adjustment of the coulter's depth via robotic systems and servo actuators.

Target function: Ensuring optimal agronomic conditions for seed germination and achieving the maximum socio-economic effect (yield maximization coupled with cost reduction).

FVA Stage 2. Resource cost calculation and pricing.

The economic component of R&D management involves allocating costs to each specific function. This methodology enables the identification of "excess cost" zones and optimizes the value proposition (**Table 4.6**)

Table 4.6 Costs for main components of a smart-type coulter

Components	Functional purpose	Cost, UAH
Sensor Integration Kit (SmartFirmer cable to 20/20 Gen 3 controller, fasteners, mounting adapters, protective caps/gaskets)	Enables real-time soil condition data transmission; ensures compatibility with various seeder models and sensor durability	46,630
Calibration sensor	Ensures the precision of moisture, temperature, and organic matter measurements	
Keeton seed firmer	Ensures precise seed placement and seed-to-soil contact; minimizes resistance and sticking in the furrow	3,641
Seeding accuracy sensor (John Deere type)	Monitors seed placement precision and detects skips or doubles	2,520
TOTAL per row unit		52,791

Source: compiled by the authors based on commercial offers [30]

The aforementioned components (**Table 4.6**) ensure the reliable operation of the Smart-type coulter, enabling the effective utilization of its capabilities for precise real-time control and soil condition monitoring during seeding.

Technical specifications for the project define the following measurement accuracy targets (soil moisture: ±1%; soil temperature: ±0.5°C).

The R&D plan at this stage focuses on estimating the development time for specialized software required to operate the robotic downforce/depth actuator.

Gate 3 (go to development) is centered on the strategic question: "Is the budget allocation for full-scale prototyping justified?" to address this, a Scorecard is utilized to verify whether the development represents a "substantial modification" capable of delivering real market value and if it warrants the investment of the primary R&D budget into experimental units. The structure of the scoring matrix is presented in **Table 4.7**.

Table 4.7 Scorecard for Gate 3: strategic investment decision

Assessment category	Key factors	Factor essence	Weight, w	Score, s	Result, w · s
Strategic fit	Strategy alignment	Alignment with the company's "Precision Agriculture" vector	0.05	4	0.2
	Project priority	Strategic importance compared to other R&D initiatives	0.05	5	0.25
Product advantage	Novelty level	Presence of "substantial modification" in seeding parameters	0.10	7	0.7
	Value for money	Incremental yield vs. affordable price point for farmers	0.07	8	0.56
	Eco-efficiency	Fuel and resource saving via optimized depth control	0.06	7	0.42
Market attractiveness	Market demand	Validated customer demand for automated seeding depth	0.08	9	0.72
	Competitive landscape	Barriers to entry (difficulty for rivals to replicate)	0.10	7	0.7
Technical feasibility	Supporting tech	Accessibility of hardware (sensors, MCUs) and software	0.08	9	0.72
	Staff competence	Engineering expertise in mechatronics and digital systems	0.06	8	0.48
	Durability	Electronics protection in harsh soil environments	0.05	7	0/35
Financial reward vs. risk	Expected NPV	Forecasted profit margin vs. development costs	0.10	10	1
	Payback period	Return on investment within 2–3 seeding seasons	0.10	10	1
	Uncertainty level (U)	System reliability and resilience to field failures	0.10	9	0.9
Total score			1.0	–	8

Source: developed by the authors.
*Note: each criterion in the scorecard (**Table 4.7**) is evaluated on a scale of 1 to 10. The final decision regarding the project's progression is based on the aggregate score:*
8–10 points (Go): immediate commencement of Stage 3 – development of full engineering design documentation and the creation of Alpha–prototypes (initial functional units).
6–7.9 points (Hold/Recycle): returning the project to Stage 2 for business case refinement, seeking alternative component suppliers, or optimizing technical solutions to enhance cost-efficiency.
Below 6 points (Kill): final termination of the project. Resources (financial, temporal and intellectual) are strategically reallocated toward more promising R&D initiatives within the portfolio

At this stage, it is critically important for an agricultural machinery company to assess technical feasibility in synergy with market demand (**Table 4.8**). Even a scientifically flawless "Smart-depth" technology may be terminated at Gate 3 if its implementation costs prove prohibitive for the average farming enterprise.

Stage 3. Development encompasses the following key areas:

– engineering design: designing the coulter body with dedicated niches for integrated electronics. The structure must ensure robust protection for sensor units against high vibration, dust, and moisture, adhering to the rigorous IP69K standard (protection against high-pressure water jets and high temperatures);

– software engineering: developing a control algorithm based on adaptive response logic. A simplified iteration of the logic follows the principle: "If soil moisture $< X$, then seeding depth is adjusted by +Y mm";

– alpha-testing: conducting initial laboratory trials of sensors and actuators within artificial soil boxes to calibrate measurement precision in a controlled environment.

Table 4.8 R&D budget and break-even analysis for the intelligent Coulter

Total costs	Expenditure components & deliverables	Estimated cost, USD
Cost of the intelligent component	Sensors, microprocessors, controllers (test batch of 10–15 units)	25,000
	Embedded AI, signal processing algorithms, UI/UX, programming labor	180,000
	3D modeling, stress analysis, CAD documentation	45,000
Production costs	Wear-resistant alloys, composites for electronics protection (IP69K)	15,000
	Manufacturing of molds, soil box testing facility construction	85,000
Intellectual property (IP)	Patenting (PCT international application) and know-how acquisition	30,000
Total R&D investment (FC)	Total fixed costs for the R&D stage	380,000
Break-even point (BEP)	$BEP = FC/(P - VC)$, where *FC* – fixed costs; *VC* – variable costs, 1,200 USD; *P* – price, 2100 USD	423 units

Source: compiled and calculated by the authors according to ***Table 4.6***

The project demonstrates high investment attractiveness, as the break-even point (423 units) is low relative to the potential market capacity of Ukraine and the EU. The financial efficiency of the R&D project has been calculated based on a three-year planning horizon and a 10% discount rate (**Table 4.9**).

Table 4.9 Financial efficiency indicators of the R&D project

Indicator	Year 0 (investment)	Year 1	Year 2	Year 3
Sales volume (units)	0	160	400	800
Cash flow (CF), USD	–380,000 USD	+144,000 USD	+360,000 USD	+720,000 USD
Cumulative CF, USD	–380,000 USD	–236,000 USD	+124,000 USD	+844,000 USD
Discount factor ($r = 10\%$)	1.000	0.909	0.826	0.751
Discounted cash flow (DCF), USD	–380,000 USD	+130,909 USD	+297,521 USD	+540,947 USD
Cumulative DCF (NPV)	–380,000 USD	–249,091 USD	+48,430 USD	+589,377 USD

Source: calculated by the authors based on data from ***Table 4.8***

The project exhibits exceptional investment appeal: Payback Period is less than 2 years, and for every 1 USD invested, the company generates 2.55 USD in return (profitability index, $PI = 2.55$). A positive net present value (NPV) of nearly 0,6 million USD facilitates the acquisition of external financing on favorable terms. The accumulated profit of 844,000 USD – more than double the initial investment – enables the firm to fully repay investors, establish an internal R&D fund for future initiatives, and expand into new markets without additional debt.

FVA Stage 3. Innovation and market alignment assessment.

The innovation value is validated through comparative analysis: the integration of the Keeton Seed Firmer yields an average corn increase of 0.18 t/ha, resulting in an additional 12.61 USD/ha in profit. The technology reaches its break-even point within 16–24 hectares of operation [30]. At this stage, the technology S-curve is analyzed to determine the limits of current efficiency, and real options analysis (ROA) is applied to manage investment decisions dynamically.

FVA Stage 4. Experimental testing and optimization.

A critical phase where applied research results are verified against quality and safety criteria. Laboratory and pilot studies test sensor precision, while digital modeling accelerates the design phase and minimizes engineering errors.

FVA Stage 5. Final adjustment and implementation.

Refining the technological process and eliminating defects prior to mass production. A successful FVA result is a coulter design where every implemented function (e.g., the organic matter sensor) generates manufacturer profit while satisfying consumer needs at an optimal cost point.

To evaluate the socio-economic impact of the innovation, a calculation was performed for a model farm of 100 hectares utilizing an 8-row seeder (**Table 4.10**).

This demonstrates the technology's viability for the small and medium-sized enterprise (SME) segment in agriculture.

Table 4.10 Economic efficiency of smart-coulter implementation agricultural enterprises (per 100 ha)

Indicator	Value, USD	Calculation formula
Annual variable costs	40,000	100 ha × 400 USD / ha (seeds and fertilizers)
Predicted savings (5%)	2,000	40,000 USD × 0.05 (seeding optimization via moisture control)
Annual software Fee	1,000	10 USD / ha × 100 ha (cloud services and AI subscription)
Additional income (3%)	6,000	100 ha × 10 t/ ha (yield) × 200 USD/t (price) × 0.03 (increase)
Net annual effect	7,000	(2,000 USD savings + 6,000 USD yield) – 1,000 USD software fee
Payback period	~2.4 years	16,800 USD (cost for 8 rows) / 7,000 YSD

Source: calculated by the authors based on the Smart Agriculture implementation financial model

Economic analysis for small-scale farms confirms that the system cost for an 8-row seeder (16,800 USD) reaches its payback point within 2.4 years. The primary efficiency driver is the incremental yield income (6,000 USD), which exceeds the annual software maintenance fees sixfold.

Stage 4. Testing & Validation.

This phase represents the transition from controlled laboratory settings to real-world operations:

Field trials: testing the coulter's durability at varying speeds, in soils with stony inclusions, and under extreme moisture conditions.

User validation through interface testing in the tractor cab. Answering the question: Does the operator understand what the coulter is doing?

Gate 5 (Go to launch): reviewing test results. Did the coulter withstand 1,000 hectares of operation without breaking down?

Stage 5. Launch.

The company launches a production line.

From a marketing perspective, it is advisable to hold presentations at agricultural exhibitions, train service dealers, and configure sensors.

Post-Launch Review – collect feedback from farmers after the first planting season to inform future modifications.

Using the Stage-Gate process prevents situations where a sensor is developed but the team forgets that it might break in the field. At Gate 2 or Gate 3, such risks are eliminated, thereby protecting the company's budget.

4.4 Conclusions

Summarizing the study conducted, and taking the hypotheses into account, it is possible to arrive at the following conclusions:

1. Restructuring the management model and assessing probable risks. The stage-gate model, proposed as the foundation for managing the R&D process, is also defined as a strategic system for transitioning from linear development to a multi-level selection of ideas. This corresponds to H1: the use of evaluation Scorecard allows for structuring "innovation chaos" in the early stages and minimizing budget losses, as well as abandoning economically inefficient capital investments before the start of the production phase.

2. Intellectual capital is a priority in the structure of added value. It has been shown that, in the context of digitalization, intellectual assets dominate over tangible ones. This confirms H2: the share of expenses for the intellectual component in the budget for developing a smart plow (software and AI algorithms) is approximately 50% (180,000 USD). It is precisely this high concentration of intellectual capital that ensures premium profitability (900 USD per unit), which is unattainable for traditional mechanical components.

3. Consumer-driven optimization of business decisions through FVA. The H3 is confirmed by functional-value analysis (FVA): for an agricultural enterprise, it is a rational move to invest in high-tech equipment when a function – such as moisture measurement – generates a benefit that is many times greater than the cost of its implementation. The technology is feasible even for small farms, as the project's effect for 100 hectares will amount to 7,000 USD, and the payback period will be 2.4 years.

4. The limits of technological feasibility and the transition to Agriculture 4.0. The H4 has been confirmed by research: the efficiency limits of traditional mechanical control systems have been reached, and further increases in crop yields are possible, particularly through the transition to robotic systems. A comparative analysis of traditional and innovative approaches revealed that the adaptive depth adjustment of a coulter equipped with sensors is a "disruptive innovation" that replaces manual adjustment with autonomous AI control and, in this way, transforms the agricultural production system.

5. Investment attractiveness and financial stability. The H5 is confirmed by econometric modeling of discounted cash flows: the project exhibits a high level of risk resilience. A positive NPV of 589,377 USD and a PI of 2.55 reflect the potential for the high level of initial uncertainty (*U*) to be fully offset by potential profitability. The financial stability of the company's innovation strategy is ensured, as sensitivity analysis has shown that the break-even point will be reached as early as the second year of implementation.

Thus, the confirmed hypotheses, through their synergy, demonstrate that effective R&D management is fundamental to a company's survival in the global value chain, where strategic advantages are determined by the speed of capitalizing on intellectual solutions rather than the scale of production.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

Funding

The study was performed without financial support.

Data availability

The data that support the findings of this study will be made available by the authors on reasonable request.

Use of artificial intelligence statement

The authors have used artificial intelligence technologies solely to verify the correctness and consistency of the English translation of the manuscript in an academic style. In particular, the authors used the generative language model ChatGPT (OpenAI, GPT-5.1 Thinking) for language checking and minor stylistic refinement.

The authors bear full responsibility for the content of the final manuscript; the AI tool is not credited as an author and is not responsible for the reported results.

Acknowledgments

The authors received no specific support from individuals or organizations that should be acknowledged beyond their institutional affiliations stated in the manuscript.

Authors' contributions

Nataliia Sysolina: Conceptualization, Methodology, Project Administration, Visualization, Writing – review & editing.

Iryna Sysolina: Theoretical Framework, Formal Analysis, Data Curation, Writing – original draft, review & editing.

Volodymyr Amosov: Methodology, Domain Expertise (agroengineering), Investigation, Integration of Results, Writing – review & editing.

Sergiy Nisfoyan: Conceptualization, Data Analysis, Validation, Literature Review, Writing – review & editing.

Olga Chumachenko: Supervision, Investigation, Data Analysis, Interpretation of Results, Writing – review & editing.

Ruslan Kisilov: Data Curation, Validation, Formal Analysis, Writing – review & editing.

All authors contributed equally to the scientific content of this chapter, jointly developed the conceptual idea of the work, and approved the final version of the manuscript.

References

1. Global Innovation Index 2025 (2025). World Intellectual Property Organization. Available at: https://www.wipo.int/web-publications/global-innovation-index-2025/en/index.html
2. Main Science and Technology Indicators (MSTI) 2025 (2025). OECD. Available at: https://www.oecd.org/en/data/datasets/main-science-and-technology-indicators.html

3. R&D expenditure statistics (2024–2026) (2024). Eurostat. Available at: https://ec.europa.eu/eurostat/rd-expenditure
4. Derzhavnyi biudzhet-2026. Kabinetu Ministriv Ukrainy. Available at: https://kmu.gov.ua/news/derzhbiudzhet-2026-nauka
5. Farzaneh, M., Wilden, R., Afshari, L., Mehralian, G. (2022). Dynamic capabilities and innovation ambidexterity: The roles of intellectual capital and innovation orientation. Journal of Business Research, 148, 47–59. https://doi.org/10.1016/j.jbusres.2022.04.030
6. Wang, X. (2024). Too much incentive to innovate? CEO stock option exercise and myopic R&D management. Journal of Product Innovation Management, 41 (6), 1141–1164. https://doi.org/10.1111/jpim.12731
7. Audretsch, D. B., Belitski, M. (2022). Evaluating internal and external knowledge sources in firm innovation and productivity: an industry perspective. R&D Management, 53 (1), 168–192. https://doi.org/10.1111/radm.12556
8. Christensen, C. M., McDonald, R., Altman, E. J., Palmer, J. E. (2018). Disruptive Innovation: An Intellectual History and Directions for Future Research. Journal of Management Studies, 55 (7), 1043–1078. https://doi.org/10.1111/joms.12349
9. Cooper, R. G. (2022). The 5-th Generation Stage-Gate Idea-to-Launch Process. IEEE Engineering Management Review, 50 (4), 43–55. https://doi.org/10.1109/emr.2022.3222937
10. Chesbrough, H. W. (2003). Open innovation: The new imperative for creating and profiting from technology. Harvard Business School Press.
11. Petrova, I. L., Shpylova, T. I., Sysolina, N. P.; Petrova, I. L. (Ed.) (2010). Innovatsiina diialnist: stymuly ta pereshkody. Kyiv: Dorado, 296. Available at: https://library.krok.edu.ua/media/library/category/monografiji/petrova_0002.pdf
12. Li, S., Gao, L., Han, C., Gupta, B., Alhalabi, W., Almakdi, S. (2023). Exploring the effect of digital transformation on Firms' innovation performance. Journal of Innovation & Knowledge, 8 (1), 100317. https://doi.org/10.1016/j.jik.2023.100317
13. Dąbrowska, J., Almpanopoulou, A., Brem, A., Chesbrough, H., Cucino, V., Di Minin, A. et al. (2022). Digital transformation, for better or worse: a critical multi-level research agenda. R&D Management, 52 (5), 930–954. https://doi.org/10.1111/radm.12531
14. Sun, G., Fang, J., Li, J., Wang, X. (2024). Research on the impact of the integration of digital economy and real economy on enterprise green innovation. Technological Forecasting and Social Change, 200, 123097. https://doi.org/10.1016/j.techfore.2023.123097
15. Zhuo, C., Chen, J. (2023). Can digital transformation overcome the enterprise innovation dilemma: Effect, mechanism and effective boundary. Technological

Forecasting and Social Change, 190, 122378. https://doi.org/10.1016/j.techfore.2023.122378
16. El Samra, A., James, A., Malik, K. (2023). Disrupt through digital: a study on the challenges faced when digitalizing R&D. R&D Management, 54 (4), 713–723. https://doi.org/10.1111/radm.12637
17. Kulichyova, A., Kazantsev, N., White, L., Islam, N. (2025). Digital transformation in large established organisations: Four restructuring dilemmas based on dynamic capabilities. International Journal of Management Reviews, 27 (3), 420–450. https://doi.org/10.1111/ijmr.12395
18. Omol, E. J. (2023). Organizational digital transformation: from evolution to future trends. Digital Transformation and Society, 3 (3), 240–256. https://doi.org/10.1108/dts-08-2023-0061
19. Mariani, M., Dwivedi, Y. K. (2024). Generative artificial intelligence in innovation management: A preview of future research developments. Journal of Business Research, 175, 114542. https://doi.org/10.1016/j.jbusres.2024.114542
20. Hoseinzadeh, S., Astiaso Garcia, D. (2024). Ai-driven innovations in greenhouse agriculture: Reanalysis of sustainability and energy efficiency impacts. Energy Conversion and Management: X, 24, 100701. https://doi.org/10.1016/j.ecmx.2024.100701
21. Lee, C.-C., Qin, S., Li, Y. (2022). Does industrial robot application promote green technology innovation in the manufacturing industry? Technological Forecasting and Social Change, 183, 121893. https://doi.org/10.1016/j.techfore.2022.121893
22. Ahmad, N., Youjin, L., Žiković, S., Belyaeva, Z. (2023). The effects of technological innovation on sustainable development and environmental degradation: Evidence from China. Technology in Society, 72, 102184. https://doi.org/10.1016/j.techsoc.2022.102184
23. Wang, R., Usman, M., Radulescu, M., Cifuentes-Faura, J., Balsalobre-Lorente, D. (2023). Achieving ecological sustainability through technological innovations, financial development, foreign direct investment, and energy consumption in developing European countries. Gondwana Research, 119, 138–152. https://doi.org/10.1016/j.gr.2023.02.023
24. Zheng, J., Zhang, J. Z., Kamal, M. M., Wang, H., Yang, Y., Dey, B., Apostolidis, C. (2025). Empowering Radical Innovation: How Digital Technologies Drive Knowledge Transfer and Co-Creation in Innovation Ecosystems. R&D Management, 55 (5), 1444–1458. https://doi.org/10.1111/radm.12764
25. Feng, S., Zhang, R., Li, G. (2022). Environmental decentralization, digital finance and green technology innovation. Structural Change and Economic Dynamics, 61, 70–83. https://doi.org/10.1016/j.strueco.2022.02.008

26. Pu, T. (2025). How Digital Transformation Shapes Corporate R&D Expenditure: An Exploration of Multidimensional Perspectives and Innovation Consequences. Sage Open, 15 (3). https://doi.org/10.1177/21582440251349263
27. SmartFirmer. Precision Planting. Available at: https://www.precisionplanting.com/products/smartfirmer
28. Planters & Planting Equipment. John Deere. Available at: https://www.deere.com/planters
29. Zhai, Z., Martínez, J. F., Beltran, V., Martínez, N. L. (2020). Decision support systems for agriculture 4.0: Survey and challenges. Computers and Electronics in Agriculture, 170, 105256. https://doi.org/10.1016/j.compag.2020.105256
30. ARK Group. Available at: https://arkgroupp.com.ua