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Digital twinning in smart agribusiness: Towards a conceptual and methodological framework for organizational digital modelling

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Abstract

At the present stage, the achievement of the set strategic goals of ensuring Russia's economic independence and technological leadership is associated with the development and implementation of domestic information and cognitive technologies. The country's agro-industrial complex, which is undergoing a complex process of digital transformation with the expansion of the use of robotic technology and intelligent systems, plays a special role in solving the basic tasks of maintaining state sovereignty. The development of platform solutions in agricultural production faces serious limitations and constraints on the effective application of the "digital twin" concept, due to unresolved issues regarding the conceptual and institutional justification for their construction for organizational systems. In this regard, the aim of this study is to substantiate proposals for defining the concept of a digital model of an agricultural enterprise and the formation of a possible option for describing the economic system and basic business processes for conducting full-cycle smart agriculture. The application of content and logical analysis methods, and reengineering technology, allowed us to appropriately define a reference digital model of an enterprise in the agricultural sector and present a possible design for a digital model of the economic system of a smart agricultural enterprise. Definitions of the concepts of "digital model" and "digital twin" for organizational systems are proposed, clarifying existing definitions in terms of reflecting the variability of the description of the organization's business model when displaying the entities of "business architecture" and "business processes" as separate structural elements and the contour of subjective perception of information when making decisions. The structure of a digital model of an agricultural enterprise's economic system in a networked precision farming environment is substantiated, taking into account changes in the composition and role of production factors in a data economy. We demonstrate the need to reflect in this model elements and relationships that address the requirements of ensuring environmental neutrality and social responsibility in full-cycle agricultural production. We recommend using the information image of a digital twin of an agricultural enterprise to design the structure and fill the model of the economic system with data based on regulated forms of planning and reporting documentation when building a digital platform to support management decision-making. The digital twin ontology description scheme expands our understanding of the theoretical foundations of the methodology and tools for designing and developing information models of objects and processes for business systems.

Keywords: digital transformation, digital platform, digital standards, digital model, agriculture, smart agricultural enterprise, factors of production, artificial intelligence, robotic devices

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Introduction

Scholarly and public discourse consistently associate the current historical phase with an intensifying transformation of the global order. For Russia, with the expanding spectrum of threats to both scientific and everyday consciousness, the current historical stage is firmly associated with an actively unfolding process of global order transformation. For Russia, the expansion of national security threats amid worsening demographic distress acutely raises the issue of ensuring technological independence and achieving technological leadership.

In addressing fundamental tasks related to strengthening the country's economic sovereignty – while prioritizing population preservation – the agro-industrial complex (AIC) plays a particularly critical role, as it is oriented toward fully satisfying domestic demand for traditional food commodities in the required volume and quality. However, as noted in [1], since 2014 the problem of the Russian economy's dependence on imported technologies – including those needed for the digitalization of the AIC—has intensified: according to estimates by the Russian Ministry of Agriculture for 2014, approximately 95% of specialized agricultural information technologies (IT) were supplied by foreign software developers. Prime Minister Mikhail V. Mishustin's address at the plenary session of the Xth “Digital Industry of Industrial Russia” conference on June 3, 2025, painted a contradictory picture of the current state of software import substitution. He observed that over the past five years, the IT sector's average annual growth has been four times greater than that of the overall GDP. This rapid expansion has occurred alongside a 1.5-fold increase in corporate digitalization spending and a 3.5-fold rise in the purchase of Russian software licenses. Despite these positive trends, the adoption of domestic solutions in the critical area of design and simulation systems remains limited, with their market share barely exceeding 50%. This gap is highlighted by the existence of 412 types of foreign software that still lack Russian-made analogs. The Prime Minister's remarks therefore underscore an urgent need to strengthen the national centers of competence responsible for driving progress in software engineering and digital transformation.

Digital transformation (DT) in the AIC – already underway in agriculture – involves not only the deployment of robotic machinery (RM), artificial intelligence (AI), and information systems (IS), but also the refinement of governance mechanisms for ecologically neutral and socially responsible full-cycle agricultural production. Modernizing the agribusiness model within a data-driven economy necessitates a management system commensurate with the new technological paradigm. Digitalization of technological and managerial processes for economic, social, and regulatory actors within this production system is implemented through the concept of the “digital twin,” which enables the projection of routine and situational decision-making scenarios into a virtual environment via an information model (IM) to support the formulation and adoption of managerial decisions regarding operational and strategic activities. In fact, the approach to developing digital twins has been known since the late twentieth century [2], having already demonstrated significant achievements and secured a reputable position in both research and engineering practice [3]. Nevertheless, substantial barriers impede its broad application in advancing national platform-based solutions within the digital economy. First, there are gaps in the institutional and conceptual foundations for constructing digital twins of organizational systems (OS); second, there is a lag in the development of domestic business modeling software – a domain directly relevant to the task under consideration. These identified gaps hinder the resolution to scientific and practical problems concerning the advancement of methodologies and toolsets for developing and deploying enterprise digital twins aligned with the requirements of the data economy, as well as the creation of domestic digital platforms (DP) for organizational management, including those for smart agricultural enterprises (SAE). This renders it timely to address the problem of refining business modeling methodology and tooling, thereby defining the objective of the present study: to substantiate the proposals for conceptualizing the digital model of an agricultural enterprise and to formulate a potential framework for its representation through the construction of schemas depicting the organization and execution of business processes in smart farming.

1. Theoretical and practical aspects of societal digitalization based on information technologies

Issues concerning the refinement of the normative and theoretical foundations for developing methods and tools of information modeling are extensively addressed in publications by both domestic and international scholars and practitioners, drawing upon the evolution of approaches within computer science disciplines and the implications of legal regulation in the IT domain. Research papers [4, 5] substantiate the importance of scrutinizing platform-based solutions in digital agriculture, emphasizing the necessity of an interdisciplinary approach when implementing projects aimed at creating and deploying intelligent IS in the operational and managerial activities of agricultural enterprises. Typologies of digital products designed for production and management technologies in the agro-industrial complex (AIC) are proposed in publications [6, 7]. The genesis of conceptual frameworks and software tools for designing information systems and sector-specific platform solutions is described in articles [8, 9]. The implementation of artificial intelligence (AI) methods, cognitive modeling, and knowledge management is discussed in research papers [10, 11]. The emergence, evolution, and future prospects of the digital twin concept are characterized in publications [12, 13], while issues related to improving the methodology and toolsets for their construction are addressed in works [14, 15]. Methodological aspects of developing digital twins in the context of economic activity are presented in articles [16, 17]. International experience regarding the application of digital twins in smart agriculture is reviewed in works [18, 19]; a comparative analysis of the effectiveness of digital twin deployment in agribusiness is provided in article [20]; and the design of a precision farming management system for protected cultivation based on digital twins with predictive control modeling support is detailed in publication [21].

Research paper [22] notes that the principle of minimizing labor expenditures required to sustain socio-economic systems of various types constitutes

one of the foundational principles of civilizational development and represents a fundamental condition for the quality of societal progress – a principle that naturally extends to managerial activity as well. Within this context, three revolutionary periods in the development of management theory and practice can be distinguished [23]: the first stage – the organizational revolution of the late 19th to early 20th century – associated with the division and specialization of managerial functions (data accumulation); the second – the computer revolution of the mid-20th century – linked to the automation of management processes (information accumulation); and the third – the cognitive revolution, which emerged in the late 20th century and is currently unfolding – driven by the advancement of intelligent management technologies (knowledge accumulation and utilization).

Any management system employs an informational representation generated by an integrated set of characteristics of the managed object (MO): qualitative and quantitative, structured and unstructured, deterministic and uncertain.

Under conditions enabled by computer technology – based on discrete computational architectures and capabilities for data collection, transmission, and storage – the informational representations of managed and managing subsystems, along with their environment, become digital models (DM) of real-world entities and phenomena.

As is often the case in theoretical inquiry, the original idea for identifying and explaining a given phenomenon typically emerges significantly earlier than the formal adoption of the corresponding term in scholarly literature. This is also true of the concept of the “digital twin”. In substantive terms, the digital twin concept is associated with Michael Grieves, who in 2002 introduced his approach to creating a virtual space in publication [24], inspired by David Gelernter’s 1991 notion of describing physical objects within a “mirror world” of computer-generated and processed informational representations [25]. In the early 1990s, this methodological proposition—promising from the standpoint of informatics theory –

gained recognition among specialists but remained unrealized due to the absence of suitable information technologies and software. With advances in computing and communication technologies, these earlier proposals have since gained renewed momentum, enabling their productive implementation within distributed environments of integrated information systems and universal digital services (DS).

2. Evolution of tools and standards for information system design and modeling

The history of automation began roughly in the mid-twentieth century, when information-based control systems were first actively deployed in defense-related domains and subsequently extended to economic and administrative spheres. During this period, initial attempts were made to develop standardized descriptions of individual entities and phenomena, including those related to design, technological, production, and managerial activities (e.g., CAD/CAE, CAM/DCS, MES/MES, ERP/ERP). Naturally, the first regulatory frameworks for information modeling and design emerged in the leading nations of competing socio-economic systems – the USSR and the USA: GOST 24.104-85 “Unified System of Standards for Automated Control Systems. Automated Control Systems. General Requirements” (implemented in 1987, updating a generation of standards dating back to 1976); and NIST Special Publication 500-167, “Information Management Directions: The Integration Challenge” (issued in 1988). In the former, the architecture of the managed object (MO) was defined by the set of functions providing informational support to the management process [26]. In the latter, a five-level MO model was employed, designed to organize, plan, and construct an integrated set of interrelated and ordered architectures for selective informational descriptions of management layers [27]. Ultimately, both approaches converged on conceptual constructs later identified as belonging to the domain of enterprise business architecture.

The current era of automation in production and management is defined by distributed digital infra-

structures, which emerged around the turn of the millennium. Centered on data storage and processing facilities, these systems are fueled by the exponential growth of global internet traffic and data, driven by a proliferation of connected and autonomous intelligent devices (IDs), especially mobile ones. The first international ISO standards for information modeling of objects from a life-cycle management perspective were adopted somewhat later: for engineering design in 2002 (ISO/IEC 15288 “Systems and software engineering – System life cycle processes”) [28]; for architectural and construction design in 2012 (ISO/TS 12911 “Framework for building information modelling (BIM) guidance”) [29]; and for industrial enterprise information systems design in 2017 (IEC PAS 63088:2017 “Smart manufacturing – Reference architecture model Industry 4.0 (RAMI4.0)”) [30]. A digital model is distinguished from a classical information model by its use of discrete data formats, which allow for the computer-based implementation of functions that describe an entity’s elements, relationships, and representations. Classical information models, by contrast, are confined to the documentary registration of these components through registries and procedural regulations tailored to various organizational forms.

The domain of developing and applying digital models already has institutionalized requirements – based on synthesized conceptual approaches, instrumental capabilities, and practical experience – for digital descriptions of three classes of objects: designed/produced products (items), designed/constructed buildings (facilities), and operating/emerging production enterprises:

- ◆ GOST R 57700.37-2021: “Digital product model – a system comprising mathematical and computer models, along with electronic product documentation, describing the structure, functionality, and behavior of a newly developed or operational product across various stages of its life cycle” [31] (based on ISO 23247-1:2021 [32]);
- ◆ GOST R 58439.1-2019: Information Model (IM) – “a collection of structured and unstructured information containers serving as a single, authorita-

tive source of project (asset) information across all or selected life-cycle stages” [33], i.e., the IM of a project during its construction phase and the IM of an asset during its operational phase (based on ISO 19650-1:2018 [34]);

- ◆ GOST R 59799-2021: reference or reference architecture model – an IM of a physical-world industrial object defining its reference architecture, “represented as a multi-layered (multi-tiered) cube that maps technical objects (assets) as hierarchical levels, enabling their description and traceability throughout their life cycle, accounting for their placement within technical and/or organizational hierarchies” [35] (based on IEC PAS 63088:2017 [30]).

However, as noted by researchers and developers, a fully consolidated and normatively stabilized terminological system for information modeling of real-world entities and processes has not yet been established [36]. An overview of the scope and application of digitalization standards based on the digital twin concept and IoT technologies is provided in the analytical report “Standardization strategy on IoT and Digital Twin – ISO/IEC JTC 1/SC 41” [37].

Turning to the definitions introduced in ISO 23247: “Digital Twin of a Product – a system consisting of a digital product model and bidirectional information links with the product (when the product exists) and/or its components” [32]. It should be noted that this standard includes additional provisions elucidating the conceptual content of the term, leading to the following interpretation: a digital twin is understood as a digital model of “a specific physical element or process, connected to live data streams, which ensures convergence between physical and virtual states at an appropriate synchronization rate” [32].

Considering the general characteristics of the aforementioned concepts and the key features of purposeful activity by agents engaged in social relations, and applying notations and formalization practices established for managing commercial enterprises [38] and information resources [39], we may refine the definitions of “digital model” and “digital twin” as follows:

- ◆ a digital model of an organization is a system comprising mathematical and computational models, analytical and heuristic algorithms, as well as electronic templates and documents, representing – within a computer-based data storage and processing environment – a comprehensive schema of the organization’s structure and operations, grounded in descriptions of its business architecture (assets and resources), business processes (regulations and procedures), and IT infrastructure (software and data);
- ◆ a digital twin of an organization is a system composed of a digital model of the organization and supporting software equipped with functional components designed to accumulate, process, visualize, analyze, monitor, and forecast – over a required and permissible time horizon – the necessary information to generate a sufficient set of performance indicators for characterizing organizational activity and substantiating managerial decisions based on data and knowledge extracted from the organization’s digital environment.

A distinctive feature of the proposed definition of “digital model of an organization,” compared, for instance, with the interpretation used in [39], is the explicit separation of structural components describing the entities “business architecture” and “business processes.” This distinction is significant, as applied digital modeling inherently involves natural variability in representing many-to-many (“m:n”) relationships among entities within the digital model’s construct, depending on the specific business configuration of the organizational system. Similarly, the refined definition of “digital twin,” compared with the generalized formulation presented in [12], shifts emphasis away from modeling automatic interaction and data exchange between physical and virtual environments toward describing the subjective perception of information within the organization’s management subsystem when justifying and making decisions to regulate its operations and development in terms of target and control performance indicators. Given their electronic form and purpose – namely, the management of a specific business system – the concepts of “digital model” and “digital twin” of an organization

must be invariant with respect to the architecture of the existing ensemble of computing, communication, storage, power, and other infrastructure ensuring uninterrupted operation of information systems, and must also align with the catalog of supported information resources and software products. We also note the critical importance of evaluating DT initiatives through the lens of the RAMI 4.0 enterprise reference architecture model [30]. Technological progress is continuous and dynamic; consequently, the normative provisions of IEC PAS 63088:2017 – developed under the “Industry 4.0” paradigm and serving as the basis for the Russian standard GOST R 59799-2021 – can already be considered outdated. Herein lies a fundamental consideration: practical digitalization projects launched under the “Society 4.0” and “Industry 4.0” paradigms are now being implemented amid a transition – from “Society 5.0” (human-centered automation) toward “Society 6.0” (intelligence-driven automation) – in accordance with the logic of continuous innovation. The integration of vast volumes of digital data and knowledge via AI models and methods in Industries 5.0 and 6.0 necessitates an expansion of the conceptual worlds of digital models (DMs). Beyond the representation of the physical world in the information world – alongside the status world, models world, and archive world – a predictive world (or future world) must emerge, integrating forward-looking projections derived from accumulated data and knowledge, as anticipated (predicted by methods embedded within the models world) states of the business system.

The anticipated and empirically assessed effects of digitalization in the national economy – including the agro-industrial complex (AIC) – are linked to the intensification of labor substitution by capital, directed toward acquiring fixed assets such as robotic machinery (RM) and intelligent devices (IDs), as well as intangible assets: databases, knowledge repositories, and digital solutions. Collectively, digital transformation in the AIC will enable timely and targeted adaptation to changing conditions across the full production cycle, effectively neutralizing operational differences between open-field and protected-environment cultivation by accounting for the heterogeneous characteristics of

dispersed agricultural lands and facilities across leading subsectors (crop production, livestock farming, etc.) [40].

3. Conditions and directions for the formation of digital agriculture

The enhancement of agricultural systems is being pursued through the prioritization of digital transformation (DT) in agribusiness, based on the widespread deployment of technical equipment and software solutions aimed at robotizing and intellectualizing production and management technologies within the agro-industrial complex (AIC). The full realization of opportunities and potential inherent in digital innovations is contingent upon the appropriate synchronization of structural and functional transformations in the system and mechanisms governing interactions among economic agents of diverse types (differing legal organizational forms and behavioral models of economic actors within the business environment).

Table 1 characterizes the adaptation of business-system, production, and management models in the AIC under the influence of digital technologies and artificial intelligence (AI) applied to agricultural systems (including both open-field and enclosed production facilities: farmland/fields and agricultural buildings/structures).

The technological dimensions of transforming the economic system (ES) of full-cycle agricultural production under contemporary conditions are defined by the role of key innovation-driven trends in AIC development, implemented on an integrated basis and shaped by advances in information technology (IT):

- 1) production-related (smart production);
- 2) organizational (smart management);
- 3) sector-specific:
 - a) bioengineering – smart genetics;
 - b) agrarian – smart farming;
 - c) environmental – organic and green agriculture.

Table 1.

**Directions for the implementation of the digital transformation project
for an agricultural enterprise and their characteristics**

Areas and directions of digitalization of the agro-industrial complex	Key substantive tasks
Transformation of the agribusiness model (business system)	Innovation focus (market positioning) Social responsibility (political motivation) Environmental neutrality (generational continuity)
Transformation of the agricultural production model	Specialized rationality (product range localization) Technological sufficiency (completeness of operations) Technical autonomy (fleet optimization)
Transformation of the agricultural management model	Dynamic proactivity (market situation assessment) Operational adaptability (condition monitoring) Comprehensive effectiveness (impact assessment)

A pivotal aspect in describing production systems within information modeling standards is the consideration of the entire set of assets belonging to a real economic entity that are engaged in value creation processes. *Figure 1* illustrates a possible scheme for describing the networked operational environment of a smart agricultural enterprise. Here, it is fundamentally important to treat agricultural production within the AIC as an open system embedded in a complex web of external relationships – including regulatory interactions with public authorities at relevant levels – and to reflect the full agricultural cycle, incorporating closing-loop and waste-utilization technologies necessary to meet requirements of ecological neutrality and to harmonize stakeholder relations through the fulfillment of social responsibility commitments within the agribusiness's operational locality, thereby supporting comprehensive regional development and the creation of high-tech, well-paid jobs (including those needed to retain young talent in the AIC).

Digital transformation enables the mechanization and automation of agricultural production to

be addressed at a qualitatively new level, significantly expanding the scope for effective deployment of autonomous robotic machinery and equipment (in both stationary and mobile configurations) and trusted AI (in the development of IS and IT), most rationally achieved through platform-based integration [1]. Contemporary organizational-technical solutions are radically reshaping the model and environment of agribusiness; however, the primary objective lies in ensuring solution flexibility for implementing both universal and specialized agricultural robotic and intelligent devices (IDs) [41], thereby helping overcome budgetary constraints in DT projects through rational and efficient customization aligned with the profile and scale of individual agricultural producers' operations.

It is essential to recognize that historically, information modeling standards were first developed primarily for technical systems (TS). A distinguishing feature of organizational systems (OS) is the active role of subjective factors, which impart flexibility and variability to the mechanisms implementing pur-

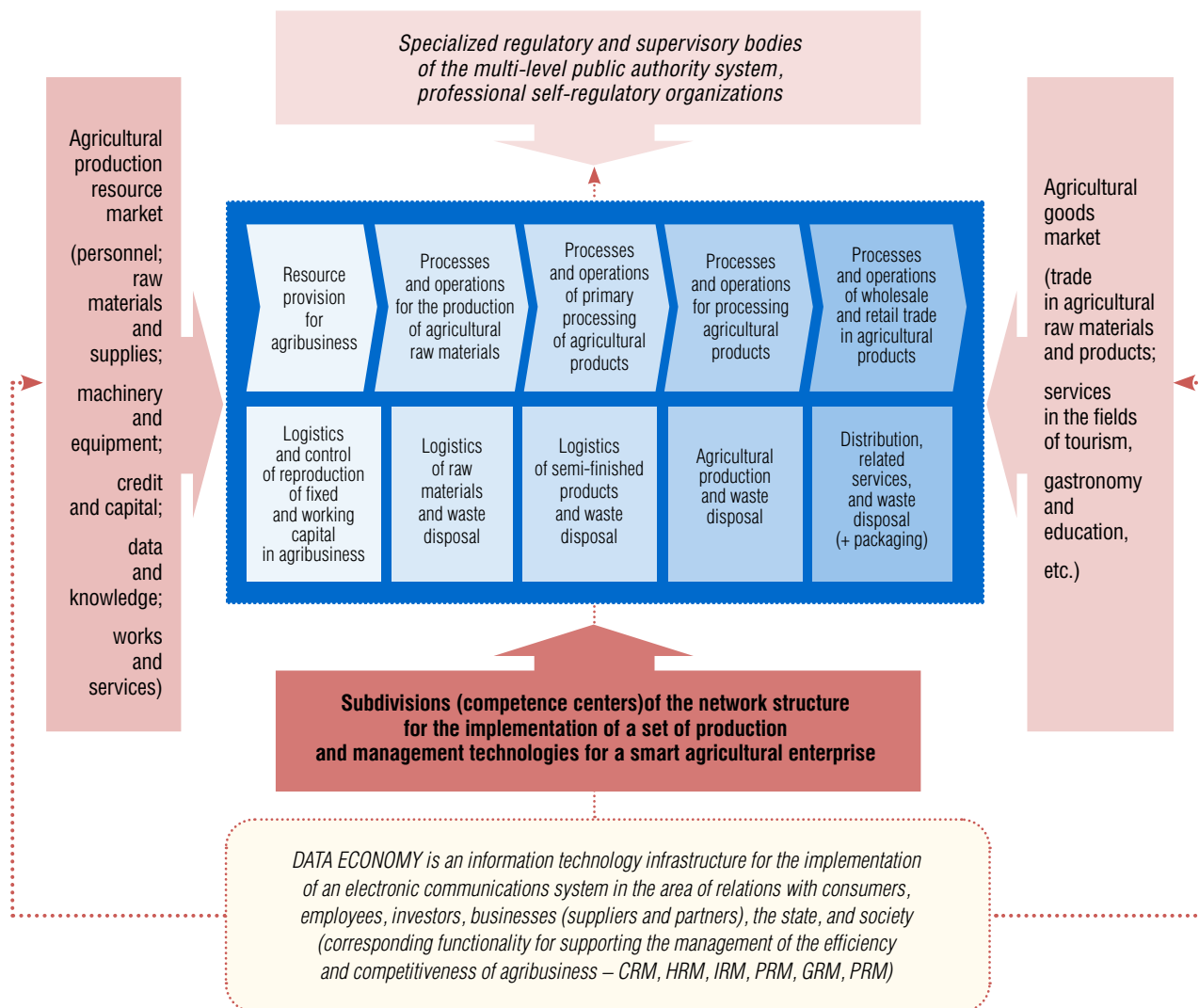


Fig. 1. Diagram of the process of creating added value for a full-cycle agricultural enterprise in a digital environment.

poseful activities – oriented toward an anticipated and necessary outcome of the system’s core functionality, yet permitting both situational adjustments and fundamental shifts in originally planned courses of action. The inherent uncertainty of agricultural conditions necessitates built-in temporal buffers to respond to abrupt impacts from climatic and environmental factors that may devalue outcomes of previously completed seasonal operations and require rapid rescheduling of subsequent technological tasks

on fields that retain productive potential. Accordingly, a digital model, reflecting and accounting for the goals and tasks of the managing subsystem – as the integrative and “animating” component of the OS – must be oriented toward decision support systems (DSS), whose components embody the governance mechanism for OS development within an uncertain socio-relational environment populated by numerous active agents, each possessing distinct motives, orientations, and objectives [42].

Integrating the core characteristics of the concepts discussed above and accounting for the distinctive features of agricultural activity, we propose the following definition: the digital model of the economic system of a smart agricultural enterprise constitutes a unified computerized framework providing an electronic description of its structure and operations across organizational units that jointly participate in the production process – transforming available resources using existing production capacity, including robotic and intelligent systems integrated into economic circulation and data and knowledge activated within the digital environment – into agricultural outputs intended for both production and consumer markets, subsequently sold at quality-adjusted competitive prices sufficient to cover total costs (investment, production, management, and commercial) while achieving an acceptable return on equity for the agribusiness owner.

In our view, when extending the traditional interpretation of the term “economic system” in agriculture – as presented, for example, in publication [5] – it is crucial not only to consider technical and technological aspects of the transition to precision farming but also to explicitly emphasize the role of data and knowledge within the digital environment of an agricultural organization as a factor enhancing the efficiency of both traditional and innovative production inputs. Building upon the refined understanding and attributes of the general concept of DM, the definition proposed above for the DM ES of a smart agricultural enterprise can be regarded as relevant to the realities of conducting agribusiness in a digital environment. This definition adequately captures the role of robotic and intelligent systems as components of fixed assets, and incorporates the maintenance of digital databases and knowledge repositories into the enterprise’s reproduction processes as the foundation for making informed, timely decisions in precision agriculture.

Accordingly, the priority lies not merely in highlighting the absence of information modeling standards for general-purpose organizational systems, but rather to stress the critical need for their adaptation – specifically, the explicit inclusion of digital data and specialized knowledge as production factors integrated

into production and management technologies based on robotic and intelligent systems. From a theoretical standpoint, and adhering to the four-level notation of managerial aspects outlined in GOST R IEC 62264-1-2014 “Enterprise Control System Integration” [43], a holistic DM construct must encompass the next hierarchical level of OS description detail. Beyond specifying core parameters such as production scheduling, material usage, transportation, delivery logistics, inventory levels, and operational production control, it is also necessary to define characteristics of tactical management mechanisms (pertaining to corporate market positioning, Level 5.1, rhythm: annual and shorter) and strategic management mechanisms (pertaining to regulating the company’s investment cycle, Level 5.2, rhythm: annual and longer).

Within the scope of this study, the structured electronic description of an agricultural enterprise focuses specifically on DM ES – conceived as a theoretical representation of a real production (economic) entity whose objective function is to deliver market-demanded products in a manner and volume that yield stakeholders an acceptable financial return. Moreover, given contemporary trends toward multifunctional rural development models [44, 45], a crucial dimension of information modeling involves examining the full agricultural production cycle under conditions of robotic and intelligent device deployment, while adhering to norms and regulations concerning ecological neutrality and social responsibility within the agribusiness’s operational area. We now proceed to elaborate on the challenge of constructing a digital model of the economic system of a smart agricultural enterprise, with a specific orientation toward the adoption of profitable closing-loop technologies in agribusiness.

4. Constructing the digital model of the economic system of a smart agro-enterprise

Among the principal drivers transforming the economic sphere of society is the activation of new elements within the composition of production factors:

incorporating information and knowledge as digital components in the description of a firm's capital and resources enables a precise specification and differentiation of the roles played by traditional and innovative production factors under conditions of digital transformation. In the data/knowledge economy, intellectual capital within the digital space of business interactions contributes to the generation of additional value by the enterprise's aggregate capital, which is engaged in a new mechanism of information exchange with business partners.

The generation and utilization of data and knowledge in the digital environment entail substantial capital and operational expenditures. Moreover, projects integrating these assets into organizational and technological-administrative processes exhibit diverse financing models for developing the requisite corporate IT infrastructure. The degree of integration among the processes of creating, accumulating, and consuming digital informational and knowledge-based assets may vary significantly – from full self-provisioning to complete outsourcing. Specifically, an economic agent may: (1) independently develop and expand the digital infrastructure of smart agricultural production while accumulating necessary data for its databases and knowledge repositories; (2) partially utilize only selected external services for data and knowledge provision, along with processing and integration services, embedding them into internal agricultural business processes based on robotic and intelligent technologies.

Digital standards and formats for describing data and knowledge define – within the category of intangible assets – both general/global and specific/local resources supporting production activities, conceptualized as labor-associated components of an organization's intellectual capital (i.e., employees as competent bearers and skilled users of digital production factors in the knowledge economy). *Figure 2* presents a generalized schematic of the agricultural enterprise's economic system (ES), highlighting the regeneration mechanism for information and knowledge as intellectual production factors.

Figure 2 illustrates the expansion of material, energy, financial, and informational flows through cognitive linkages along the business value-creation chain.

The schematic employs the following notations:

$I&K$ denotes the agricultural enterprise's data and knowledge repository;

$X_{I&K}$ represents consumed informational resources from the business environment ($X_{I&K} = P(I&K)$);

$Y_{I&K}$ denotes produced informational outputs ($Y_{I&K} = S(I&K)$).

The traditional "black box" model of an ES – describing a production entity through input-output transformation and feedback-based regulation – has been extended by explicitly including data and knowledge on precision farming among input resources and by reflecting their use in formulating managerial interventions (decisions) to sustain the effectiveness of agribusiness digital transformation.

Figure 3 presents a scheme that characterizes the composition and interconnections of core and supporting business processes within a smart agriculture system. It should be noted that in the digital economy, data and knowledge as commodities possess two key properties:

- 1) non-depletability in production,
- 2) non-rivalry in consumption.

Consequently, in the value-creation chain depicted in *Fig. 3*, the output of the ES – measured in terms of agricultural output volume and associated service delivery – includes an increment in the overall utility derived from financial investments in the reproduction of information and knowledge.

The widely accepted approach to business process reengineering allows the value-creation process within an agricultural enterprise (as shown in *Fig. 3*) to be elaborated in detail, using crop production as an illustrative example. The interrelationships among all types of business processes depicted in the sche-

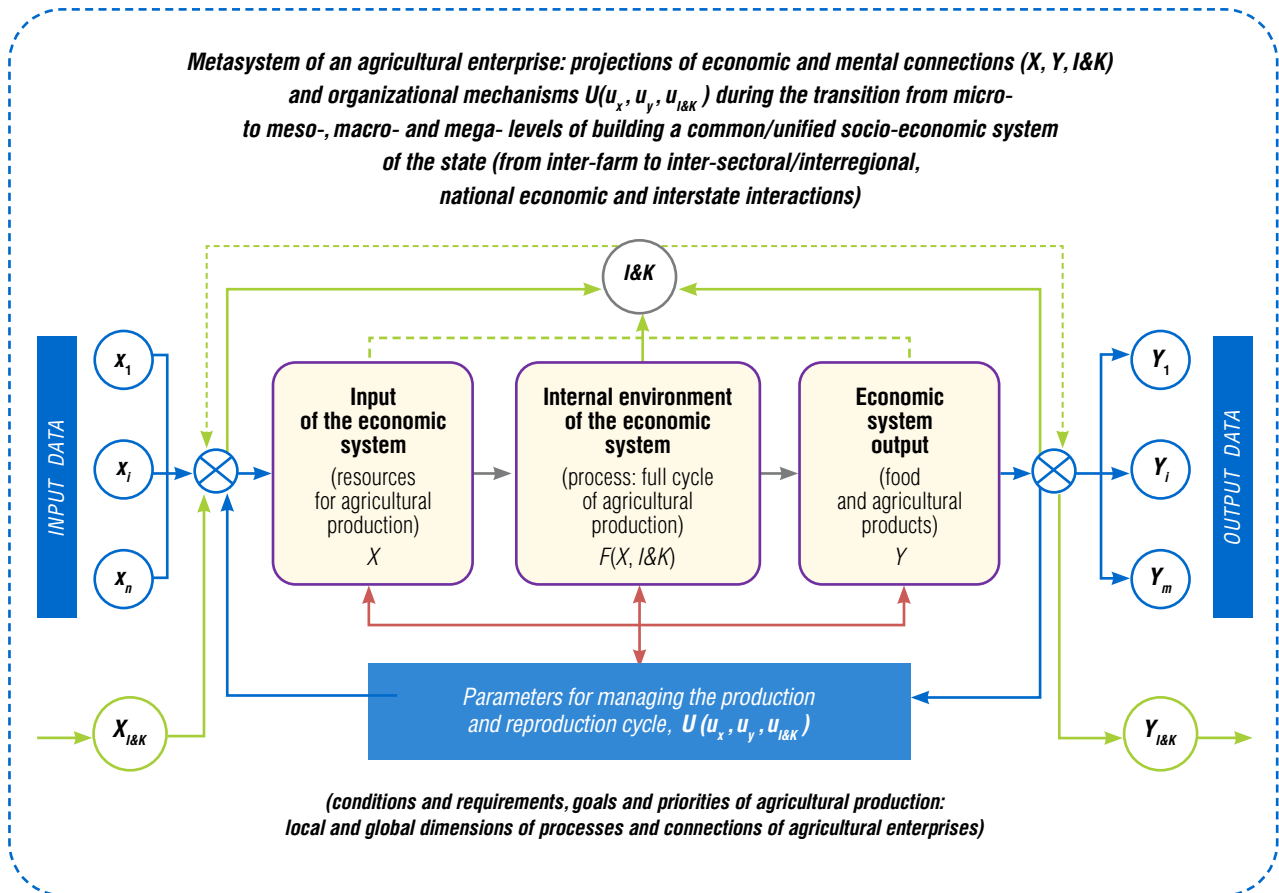


Fig. 2. Schematic description of the economic system of a smart agricultural enterprise: a cybernetic approach in the context of digital transformation.

matic reflect the overarching logic of executing full-cycle agricultural operations, including waste utilization across stages of agro-raw material processing into agricultural products. Notably, the requirement of ecological neutrality extends to wholesale and retail distribution channels, particularly within the enterprise’s own trading network, where traceability of digitally tagged packaged/batched shipments facilitates waste management in commerce.

The development of a digital model of the economic system is conceptually and functionally tied to defining the business model of a smart agricultural enterprise – specifically, its business architecture and business processes – which serves as the foundation

for subsequent construction of a digital platform supporting production and management technologies.

The architecture of the DM ES is directly dependent on the adopted management model governing the SAE’s operations and development. Therefore, the DM of any organizational system, including those in the AIC, is determined by the set of managerial tasks addressed across management functions, as well as by the procedures governing decision formulation and implementation. Unlike RAMI 4.0 – which focuses primarily on production – the upper-level DP management functionality supports the formation of ensembles and cascades of decisions for organizing and regulating the full spectrum of business processes:

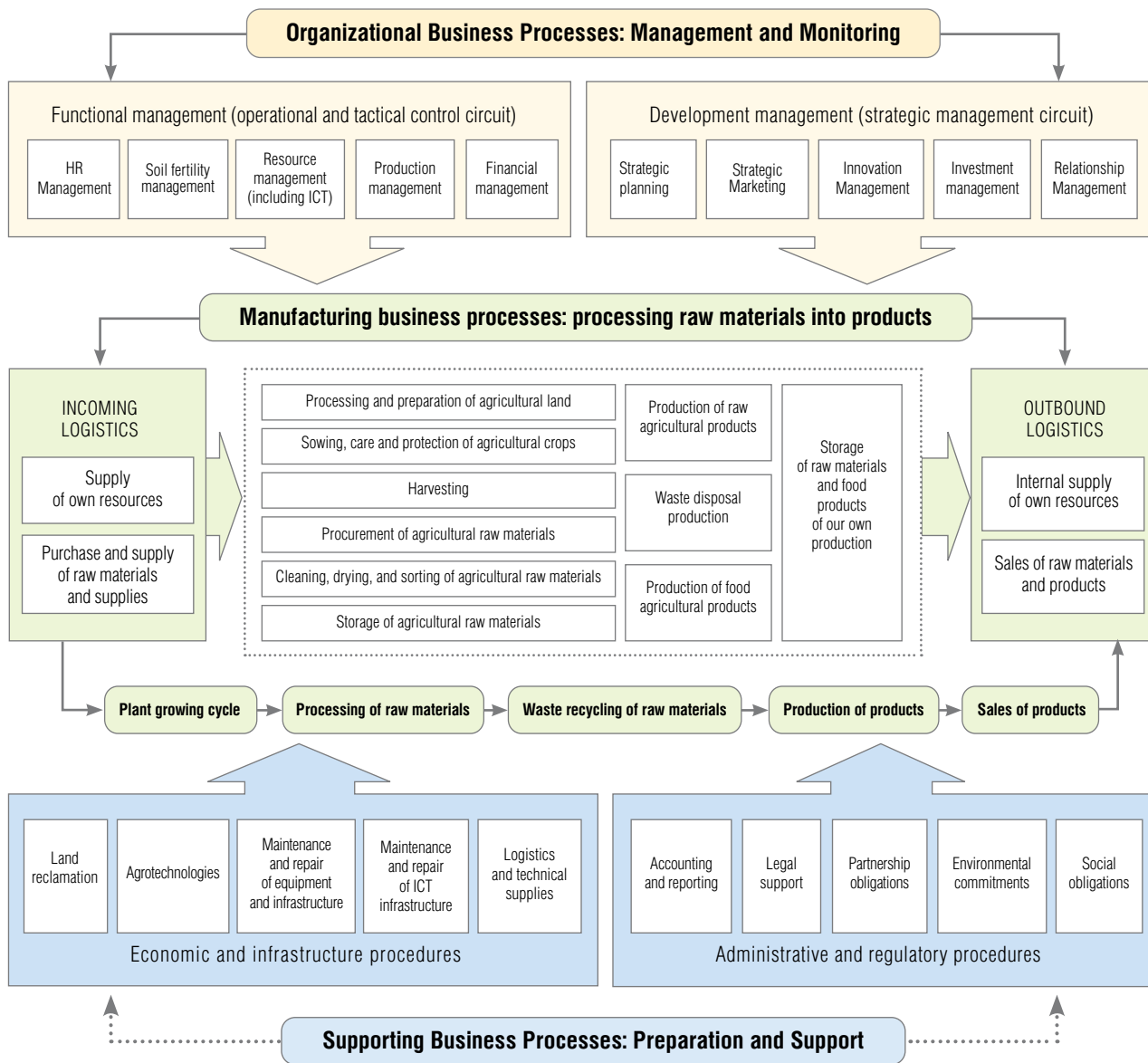


Fig. 3. Composition and relationships of the main business processes of a multi-agricultural enterprise at the stages of the full cycle of agricultural production.

technological, operational, enabling, auxiliary, administrative, and others. The content and parameters of managerial tasks predetermine the composition of methods and models embedded in the DP's knowledge base for designing decision-making solutions across strategic, tactical, and operational planning horizons of agribusiness activity.

Figure 4 presents a characterization of the informational-algorithmic support structure for the DM ES of an agricultural enterprise, implemented within the periodic procedure of ex post and ex ante evaluation of agribusiness performance, based on an electronic representation of the ES framed in terms of key financial planning and reporting documents.

A high-level representation of the functional blocks of the DM ES of an SAE enables a comprehensive overview of the entire spectrum of full-cycle agricultural management tasks but does not reveal the nature of entities and relationships within individual structural components. For instance, it is crucial to emphasize that, given the distributed interaction mechanisms among owners of electronic data – from soil sensors to remote sensing systems for farmland, as well as their processing centers (see the “Data import” block in *Fig. 4*) – the use of the DM ES as the basis for constructing an SAE DP necessitates adherence to a multi-domain organization of digital services supporting a federated data storage and computational governance infrastructure. Analysis of the proposed architectural concept for the ES and DP of an SAE demonstrates that the platform solution for smart farming must be developed primarily with consideration for the heterogeneous nature of data and algorithms employed in the agribusiness management system within the digital environment. Therefore, while adhering to traditional IS design principles – modularity, adaptability, and scalability – it is essential to incorporate the requirement of multimodal activation regimes for the DM ES within the SAE DP, implying domain-oriented, decentralized ownership of services, data, and knowledge.

The developed DM ES and the prototype SAE DP can be regarded as the foundation for constructing a modeling complex serving as the analytical component of the knowledge base for a digital platform supporting AIC production and management technologies under conditions of ecological neutrality and social responsibility throughout the full agricultural cycle. The primary objectives of creating a full-cycle digital model of agricultural production include:

- ◆ formulating and evaluating alternative agricultural production plans based on forecasts of weather-climatic and financial-economic conditions affecting the execution of seasonal operations and agribusiness activities;
- ◆ analyzing, forecasting, and planning agribusiness operations and development in light of local and global market dynamics and agricultural commodity trends;

- ◆ analyzing, optimizing, and adapting digital transformation project/program designs for the agricultural enterprise in alignment with target and contextual characteristics of agribusiness development during DP deployment within the regional AIC ecosystem.

The core tasks addressed through the DM ES of an SAE within the agribusiness development management framework reflect the functional dimensions of leveraging the productive potential of accumulated data and structured knowledge regarding the preparation and execution of seasonal field operations, with optimization of procurement and sales activities. Knowledge extraction will be more complete and more accurate when based on updated and verified indicator values derived from successive generations of digital datasets capturing the full production cycle. A critical element here is the formulation of a coherent set of requirements for information-technological and information-analytical support tailored to the diverse user base of an integrated agricultural enterprise information system (agroholding/agrocluster), including channels for external informational and cognitive communication. When constructing an effective multimodal and multi-modular upper-level SAE DP within a networked business environment, the primary requirement is the establishment of an integration mechanism for functions and data originating from external platforms [38]. Within the paradigm of DT project implementation, it is imperative to follow the logical progression from service integration to platform integration – a shift that aligns with the objective of distributing responsibility for high-quality digital resources among multiple owners, grounded in the federated principle of domain-based DP IS infrastructure design.

Conclusion

The strategic guidelines and priorities of national development render it timely to assess the current state of the conceptual and institutional foundations of business-system information modeling in Russia.

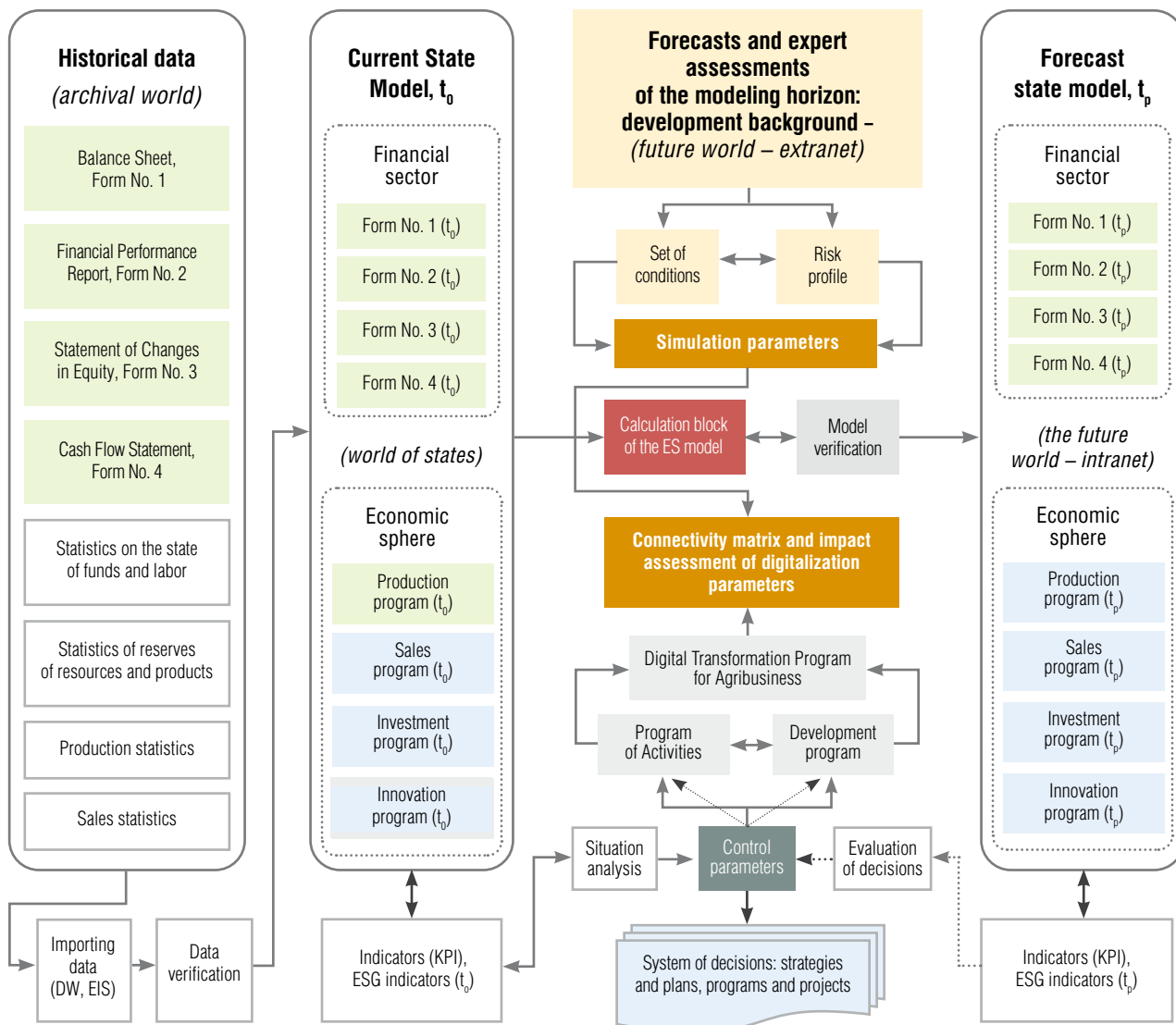


Fig. 4. Scheme of information and algorithmic support of the digital model of the economic system of a smart agricultural enterprise in the projection of the description of the architecture of the digital platform for supporting production and management technologies.

Analysis of existing challenges has revealed that high-technology sectors of the economy consistently outpace the prevailing frameworks of regulatory standardization, as innovative solutions frequently emerge outside the boundaries of established norms – including in critically important sectors of the national economy such as agriculture. Modernization of the

domestic agro-industrial complex through contemporary information technologies and digital platforms is hindered by the lag in mechanisms for unification and standardization of integrated information systems designed to support precision farming technologies, thereby complicating efforts to ensure national food security and technological sovereignty.

Within the scope of this research, a series of interrelated tasks was formulated and addressed in the following domains:

- 1) identification of distinctive features and definition of parameters for standardizing the development of digital twins for organizational-type economic systems;
- 2) determination and justification of the structure of the digital model of an agro-industrial complex enterprise;
- 3) specification of the process model for organizing smart agricultural operations under conditions of digital transformation;
- 4) formulation and substantiation of recommendations for utilizing the digital model of the economic system of a smart agricultural enterprise in construct-

ing a digital platform for managing the full cycle of agricultural production to support core decision-making functions.

The findings of this study may inform the development of provisions for a national standard or regulatory framework governing the creation of digital twins for agro-industrial complex enterprises and organizations, thereby extending the scope of standardization beyond information modeling of technical systems to encompass the construction of digital models of general-purpose organizational systems. ■

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