



Improving the Theoretical and Methodological Framework for Implementing Digital Twin Technology in Various Sectors of Agriculture

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Abstract

The aim of this study is to systematize and improve the theoretical and methodological framework for implementing digital twin technology. The study focuses on digital twins in agriculture. This paper is designed to solve the scientific problem associated with the development of a methodological framework for the implementation of digital twins in the work of agricultural organizations. Using methods of analysis of socio-economic phenomena and processes on the basis of a set of scientific approaches, economic-statistical analysis, and others, the study considers the importance of digital twins of agricultural machinery and equipment, identifies trends in agriculture determined by digitalization, and suggests promising areas for digital twins of agricultural machinery and equipment. This paper also examines the theoretical basis for the implementation of digital twin technology in the agricultural sector of production. New research results complement the theoretical provisions on the essence of digital twin technology; develop the methodological provisions of digital twin technology, represented by the study of their significance, principles, and features of operation. The study may be seen as academically novel as it reveals the prerequisites for implementing digital technology in agriculture as well as clarifies and improves the theoretical and methodological provisions of the application of digital twin technology in various sectors of agriculture.

Keywords:

Digital Twin;
Digitalization;
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1- Introduction

The modern development of agricultural production is at a stage of structural and technological transformation. This is caused by global factors, the need to provide food to more and more people and the fight against malnutrition and hunger, as well as by nationally driven factors, the search for new economic and production models for sustainable functioning of the agricultural sector. The basis of the structural and technological shifts is the use of digital technology in various areas of agriculture. At the same time, the use of various digital technologies is not uniform. Therefore, the technology of working with big data is used by more than 20% of agricultural organizations in Russia, and the technology of digital twin only 1.5% [1]. This situation resulted from the lack of a unified scientific, theoretical, and methodological understanding. The implementation of digital twin technologies in the field of agricultural production makes it possible to achieve various economic and technical-technological effects, ensure the growth of labor productivity and profitability of production. They may be used at all stages of the product life cycle.

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The scope of implementing digital twins is determined by the industries of agricultural engineering, production of agricultural raw materials and food, agro-logistics, agro-insurance, and so on. In the scientific community, there is still controversy about what a "digital twin" is. Some scientists and practitioners establish a mandatory requirement to create a digital twin based on three-dimensional models. Another group of researchers created digital twins on the basis of zero- and one-dimensional models. Thus, the scientific problem that the study is aimed at solving is the insufficient level of development of the theoretical and methodological foundations of digital twin technology applications, including in agriculture. The aim of this study is to systematize and improve the theoretical and methodological framework for implementing digital twin technology. This study focuses on digital twins in agriculture.

It may be regarded as academically relevant and novel, as it reveals the prerequisites for implementing digital technology in agriculture based on the analysis of grain crop yields in Russia and the United States, as well as clarifying and improving the theoretical and methodological provisions of the implementation of digital twin technology in various sectors, including agriculture.

The theoretical importance of the study is associated with the clarification of the conceptual apparatus of the theory of implementation of digital twins, a study of their importance in the system of food security. Also, theoretical significance is defined by the development of tasks, principles, stages, and approaches of functioning of digital twins.

The practical relevance of the conducted research is based on the assessment of the level of influence of digital technology on agricultural production and the level of ease of its implementation, as well as the distribution of digital technologies on the groups of generation effects on agriculture.

2- Literature Review

The concept of digital twins is at the formation stage, when the basic theoretical provisions are being scientifically understood. General ideas of digital twin technology undergo a stage of verification and validation as industrial enterprises, primarily aircraft construction, the space industry, etc., conduct their implementation in production processes.

The concept of digital twins is associated with the solution of the NASA spaceflight support and escort team to the task of spacecraft control in conditions of uncertainty in 1970 [2]. At that time, putting the concept of digital twins into practice was a very expensive undertaking that the space agency could afford. The modern stage of digital twin application in production witnesses their intensive use in many areas of the economy. The demand for digital twin technology, both in the global market and in Russia, is present in the aircraft, space, and engineering industries. Four decades preceding the beginning of the 21st century is deemed the preparatory period for the mass introduction of digital twins in the industry. This period is characterized by the creation of digital models at the stage of product development and the absence of the process of their constant updating due to the addition of operating data.

Studies of digital twin technology abroad have recognized that a new stage in the life of digital twin technology began in the early 2000s with the works of M. Grieves [2]. Over the past decades, the understanding of the essence of digital twin technology has changed significantly. It was transformed from the idea of digital modeling at the stage of product design to the idea of the formation of a digital twin at the stages of the life cycle of the product process. The emergence of the modern concept of the digital twin followed the emergence of its interpretations as an intellectual product [3] and an avatar [4]. Both of these substantive positions on the essence of technology raised the question of the mechanism for ensuring that the digital twin is filled with data. Modern ideas about the "*digital twins*" consider them from different perspectives:

- As a multidomain simulation system based on the industrial internet [5, 6];
- As a digital copy [7-10];
- As a product-model system [11, 12];
- As a virtual model [13];
- As a set of approaches and solutions [14];
- As a dynamic virtual representation of a physical object throughout its life cycle [15, 16];
- As integrated multiphysics, multiscale, and probabilistic modeling [17].

General theoretical provisions of the use of digital twin technology in the economic activities of organizations in Russia are considered in the works of Rechkalov et al. [18], Baranovsky & Zaychenko [19], etc. The issues of the development of electric transport based on digital twin technology became the subject of consideration by researchers under the leadership of Borovkov [20–23]. Theoretical and practical issues of computer modeling, which is part of the technological basis of digital twins, were studied by Lysych et al. [24], Prokhorov & Lysachev [2], and others. The use of platform and network approaches to the study of digital twin technology is considered in the works of Shiboldenkov & Kalinina [25], Mucha & Seppälä [26], Matsukawa et al. [27], etc.

As an end-to-end digital technology, digital twins require industry-specific considerations to expand the scope of practical applications. The accuracy of agricultural production depends on the characteristics of agricultural machinery [28]. The improvement of agricultural machines, their working tools, and their production processes is possible based on the basis of digital twin technology. The research of scientists at the Federal Scientific Agro-Engineering Center confirms these prospects. The peculiarities of implementing a digital twin in agricultural engineering were considered through:

- Development of digital systems in agriculture [29, 30];
- Application of digital technologies and robotic technical means for agriculture [31-33];
- Determination of priority directions of scientific and technological development of the tractor industry [34, 35].

The prerequisites of digitalization of the agricultural sector of the economy have formed the conditions for the introduction of digital twin technology. The issues of digitalization of production systems with integrated solutions based on digital twin technology are present in relevant studies:

- In terms of industry [13, 36];
- In terms of the product life cycle [37-41];
- In terms of the functioning of independent and integrated systems [42-44];
- From the perspective of the ecosystem approach [45, 46];
- From a business modeling perspective [47, 48];
- From the perspective of a process approach [49].

State corporations (ROSATOM, ROSCOSMOS, etc.) and agro-industrial holdings (Rusagro, Step, etc.) are active participants in the implementation of digital twins in production processes. State corporations implement the technology of digital twins for modeling large industrial objects. As a rule, creating digital twins of large industrial objects is a demanding process. As a result, a unique digital twin is created, which is almost impossible to repeat. This also stems from the fact that the physical object of industrial type accumulates many scientific and design developments, which will not be repeated when creating the next similar objects, as there is a continuous improvement in technology.

Agricultural holding companies use mainly digital twins of processes and systems in their economic activities, as the results of research in Russia show. The main criterion for the practicality of using digital twins is the level of profitability. Large producers of agricultural raw materials and food are interested in the creation of digital twins of natural systems, allowing forecasting of weather conditions, conditions of the maximization of yield or profit. Rosselmash Group of Companies, Kirov Plant JSC, Chelyabinsk Tractor Plant LLC, and others work on the development of digital twins in the sphere of agricultural machine building.

The development of the theory of digital transformation of the agricultural sector and methods for creating virtual models (digital twins) of biological objects and working elements of agricultural machinery remains a relevant task since about 500 Russian agricultural organizations out of approximately 33 thousand have experience in using digital twin technology. This experience is not uniform because the types of digital twins are different, which does not allow to accumulate the necessary amount of knowledge and skills of practical use of digital twins of a certain type.

The development of digital twins of agricultural machinery and innovative working bodies, taking into account the features of the main technological processes in agriculture, has not yet become a daily practice and requires the development of theoretical provisions, technical documentation, scientific and practical recommendations, etc. Creating digital twins of biobjects, in particular soil, is a condition for developing digital twins of agricultural machinery, equipment, their working bodies. It is necessary for creating a digital polygon, within which experiments will be realized.

Scientifically grounded objective information, in particular on the metallurgy, wear and tear of working tool soil structures, etc., is of great importance in the application of digital twins of agricultural machines and working tool technology. Such scientifically based objective information is the result of many years of scientific research. In view of possessing this resource, important subjects of digital twin-technology development are scientific organizations: the Federal Research Agro-Engineering Center, Research Institute of Integrated Design, etc.

The research problem to solve is the low level of scientific-theoretical and scientific-practical provisions of the implementation of virtual models (digital twins) of biobjects and working bodies of agricultural machinery, which is a factor limiting the digital transformation of the agricultural sector and a threat to the technological sovereignty of domestic agricultural engineering and agriculture.

The review of the scientific literature has shown some inconsistency in the theoretical ideas about digital twins.

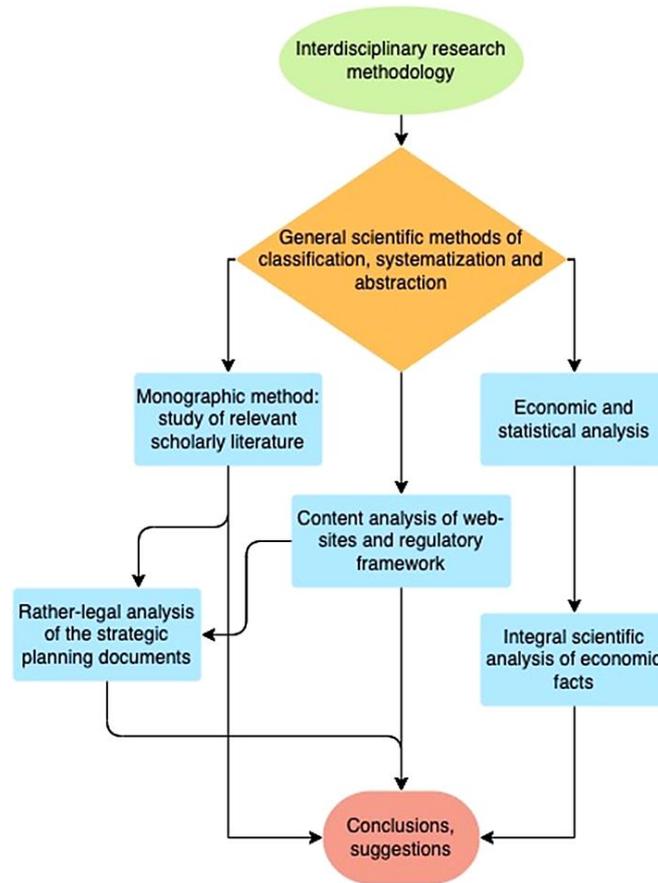


Figure 1. Flowchart of the research methodology

The study relies on general scientific methods: analysis, synthesis, abstract-logical methods, classification, monographic methods, etc. The methodology of the research and the course of its implementation are presented in Table 1.

Table 1. Basic research methods

Methods	Application
Integral scientific analysis of economic facts	A set of scientific approaches allowed to consider the technology of digital twins, their values from the perspective of various general features, which are used to distinguish the approaches
Rather-legal analysis	The legal acts and standards governing the use of digital twin technology were studied, and their content was compared. The study also used documents of strategic development
Economic and statistical analysis	Through the cliometrics approach to the analysis of official statistics on the yield of crops
Secondary interpretation of the research results	Study the results of sociological and statistical research, with the formation of independent conclusions and arguments
Content analysis	Content analysis of reports and conference materials devoted to the creation and implementation of digital twins in agriculture. Also, content analysis was used to study the content of websites of organizations developing digital twins
Monographic method	Study of the content of monographs, scientific articles, and other scholarly works

The study of the prerequisites for implementing digital technologies was conducted through a comparative analysis of the yield indicators of Russia and the United States. Yield is the most objective indicator, reflecting the technological component of production and minimizing the impact of market factors.

The study of the essence of digital twin technology was conducted on the basis of determining its importance for the system of food security. The digital twins of agricultural machinery and equipment were considered because agricultural engineering is one of the two industries providing technological development in agriculture.

3- Results

The study, by using a set of scientific approaches, identified the importance of digital twins of agricultural machinery and equipment in the system of food security (Table 2) [49-55].

Table 2. The importance of digital twins of agricultural machinery and equipment in the system of food security

Approach	Significance Characteristic
Adaptive	A form of adaptation to changes in the technical, technological, and economic environment.
Branch-wise	Contributes to improving the level of high-tech industries in the agricultural sector.
Production	Improves the quality of agricultural work and work in the field of technical maintenance of the agricultural sector.
Project-wise	The number of experiments increased.
Product-wise	Creates a volume of high-tech software products of agricultural specialization. Digital twin is a project product with a wide range of applications within the framework of economic activities of the subjects of the agricultural sector.
Service-wise	The development of technical services and parts of the service of managing innovation, technical, and technological changes.
Standardizing	The modernization of the requirements of general technical standards. The formation of new standards of an interdisciplinary nature.
Technological	Increasing the accuracy of agricultural technology implementation. Improvement of the technology of creation, maintenance, and repair of working bodies of agricultural machinery and equipment; New technology for conducting experiments in the technical field of the agricultural sector.
Economic	Spending on: <ul style="list-style-type: none"> o Conducting experiments; o Design of working bodies, equipment, and their systems; o Development of economic and managerial decisions. Increases the level of competitiveness of the domestic agro-industrial complex in the system of global agrifood markets. Contributes to an increase in the commodity mass of agricultural exports, including high-tech products.
Legal	Development and modernization of agricultural production and infrastructure. Implementation of the state scientific and technical policy. Ensuring the achievement of the national development goal, which is the digital transformation of the agricultural sector.

The data presented in Table 2 suggest the conclusion that the digital twins of agricultural machinery and equipment are relevant to the various structural elements of the system to ensure food security.

It should be separately emphasized that the Russian Federation Food Security Doctrine [51], the national project "*International Cooperation and Export*" [53] set the objectives of increasing the volume of exports of high-tech products, including engineering products. The digital twins under consideration are directly involved in solving these state tasks.

The modern context of food security of the country involves ensuring the technological sovereignty of agricultural production systems, which determines the high importance of digital twins of agricultural machinery and equipment.

State policy in the technical and technological sphere today is largely determined by the task of ensuring food security, the solution of which should not be associated with changes in external and internal conditions, defined as the development of production of material and technical resources for the production of agricultural products, raw materials, and foodstuffs [51].

In agriculture, according to the established provisions of the state agrarian policy in terms of agricultural production and technical and technological sphere of AIC, it is necessary to realize [51, 54]: to increase crop yield; to preserve, restore and improve land fertility; to rationally use agricultural lands; to observe production technologies; to put unused arable lands into turnover; to create new technologies of agricultural production; development of scientific potential of agriculture; optimization of inter-branch economic relations; growth rates of expanded reproduction; attraction of investments and introduction of innovations in agriculture; development and implementation of programs of technical and technological modernization of agriculture; introduction of new machinery and technologies; reduction of dependence of agriculture on import of technologies, machinery and equipment; and ensure creation of new and modernization of existing production capacities: machinery and equipment.

The implementation of the measures outlined in the strategic planning documents requires an analysis of various aspects of increasing crop yields. The study relied on the analysis of grain crop yields.

The dynamics of grain crop yields in Russia are shown in Figure 2*.

Data on grain crop yields in Russia, presented in Figure 2, show that over about four decades, the indicator has increased by 20 dt/ha. The greatest increase in the indicator has been observed in the last decade, which is associated

* Compiled according to the Uniform Interagency Information and Statistical System (<https://fedstat.ru/indicator/31533>); World Bank (<https://tradingeconomics.com/united-states/cereal-yield-kg-per-hectare-wb-data.html>); US Department of Agriculture National Agricultural Statistics Service (https://www.nass.usda.gov/Charts_and_Maps/graphics/cotnyld.pdf).

with the more intense use of domestic developments created on the basis of digital technology in the structure of agricultural production and management. Note that the structural shift, indicated by the increase in the growth rate of the grain crop yield indicator in Russia in Figure 2, is determined by the yield indicator having a value greater than the trend value and began to be implemented in the early 2000s. It stems from the fact that the Russian agricultural sector is accumulating agricultural machinery, equipment, and digital agricultural automated complexes from foreign production. Thus, we may state that the primary digitalization of agriculture in Russia is due to the use of foreign digital technologies integrated into agricultural machinery and equipment.

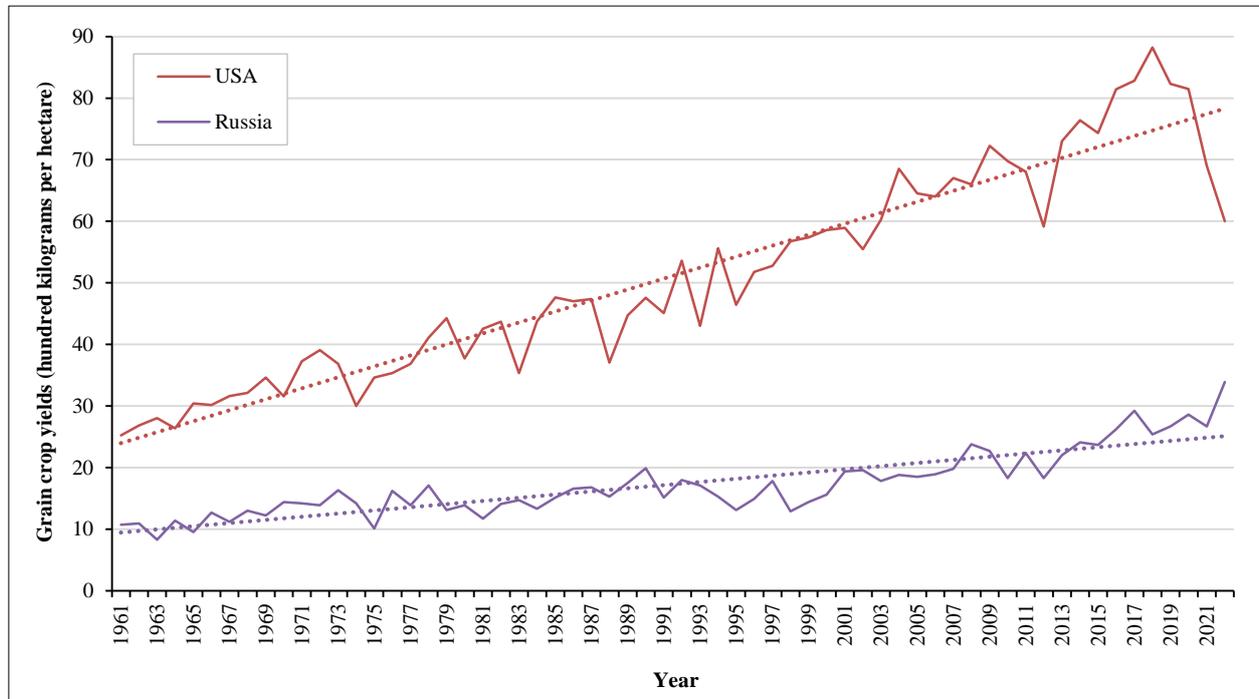


Figure 2. Dynamics of grain crop yields in Russia and the United States from 1961 to 2022 (hundred kilograms per hectare)

Figure 2 also shows the data on grain crop yields in the United States for comparison. This comparative analysis comes from the fact that since the early 1960s, digital automated solutions, which were the result of research in the previous decade, began to be actively implemented in agricultural production in the United States. These early digital solutions were related to management tasks and did not have the primary goal of increasing yields. The increasing digitalization of agriculture in the U.S. has enabled the development of appropriate tools to address technological challenges.

The technology of cereal production largely depends on the quality of the organization of production operations, in particular, the harvesting of the resulting crop. Thus, in the U.S., producers of agricultural raw materials and products implement the principle of prompt harvesting. This implies the implementation of harvesting operations in 2-3 weeks period, which can significantly reduce losses. The scale of the digitalization of agriculture in the U.S. may be estimated through the cost of the U.S. The department of Agriculture to modernize the state agricultural digital platform.

This year, \$1.2 billion has been allocated. The modernization of the digital platform involves upgrading and enhancing technologies for edge computing, remote access, unified communications, collaboration, contact center operations, voice, network operations, as well as cloud technologies and trusted Internet protocol services, etc. This set of technologies indicates that there is, in fact, a digital twin of the industry.

The digitalization of agricultural production is a characteristic process of the leading countries in terms of supplying agricultural products to global markets. It allows for reducing production costs and developing technologies for breeding, genetics, tillage, and the maintenance of farm animals. Today, the quality level of state support for the agro-industrial complex and the level of its digitalization determine its competitive advantages in global agricultural markets. In the context of this study, the analysis of the use of machines and tractor fleets by agricultural organizations is of interest. The analysis is based on the standard norm of providing 1000 hectares of arable land with tractors, the standard value of which is 13,63 units [56].

On the basis of open statistical data on the number of tractor fleets of agricultural organizations, the level of availability of tractors in agriculture in the period from 1950 to 2020 in Russia and the USA was calculated as a percentage of the reference norm (Figure 3) (based on Iovlev et al. [57] and data from official statistical agencies of the Russian Federation and the USA).

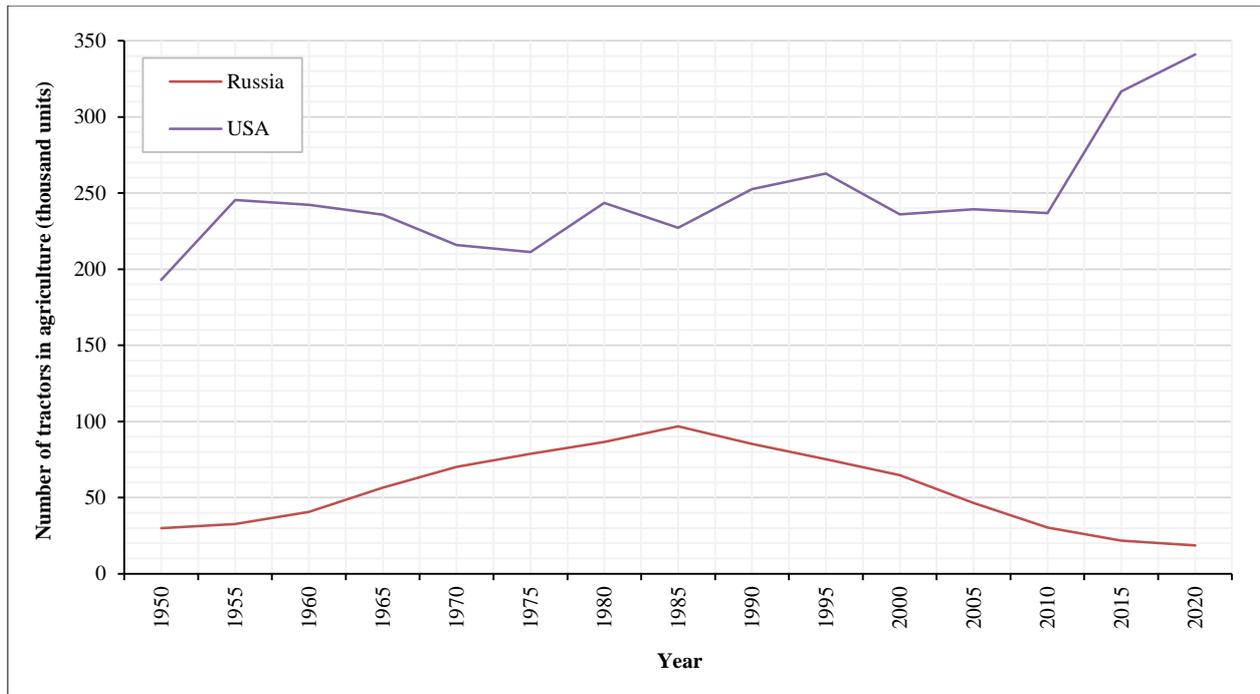


Figure 3. The number of tractors in agriculture in Russia and the USA in 1950-2020 (thousand units)

The data presented in Figure 3 show that the normative provision of Russian agricultural producers was achieved in the mid-1980s and began to decline due to the deterioration of the economic situation and the change in the political and economic regime. The level of availability of tractors in agriculture in the United States, during the period under consideration exceeded the reference norm by more than twice.

The implementation of the principle of the operational harvesting campaign in the U.S. significantly increases the cost of agricultural machinery, which has formed the need to diversify their use. The universalization of the use of tractors and agricultural machinery made it possible to ensure year-round employment of these means of production. The domestic machine-tractor fleet of agricultural organizations, as seen in Figure 4*, has been greatly reduced in quantitative terms in recent decades.

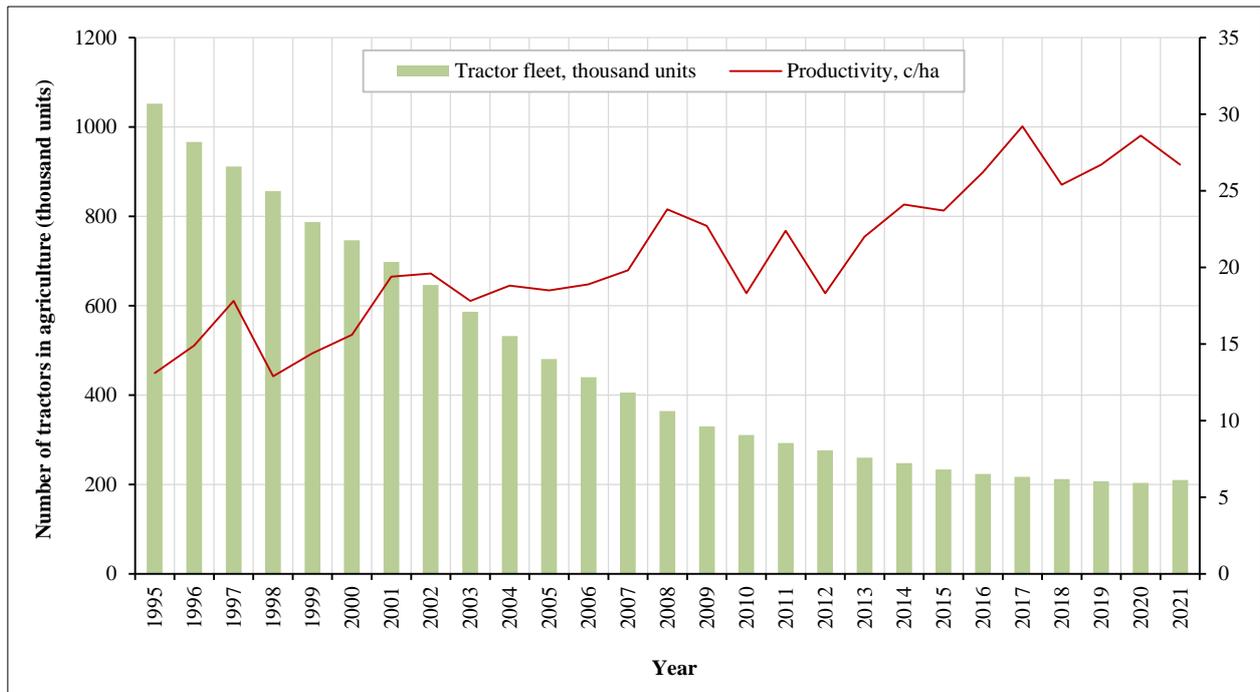


Figure 4. Dynamics of yield indicators and the number of tractors in agriculture in Russia for the period from 1995 to 2021

* Compiled from the Federal State Statistics Service data. <https://eng.rosstat.gov.ru/>.

A comparison of the trend of reducing the number of tractors in agriculture with the trend of increasing grain yields (Figure 4) indicates an increase in the power of self-propelled machinery, which allows you to increase the width of the grip during operation of the unit, the speed of operations, as well as by combining operations.

An important factor explaining the current situation is the increase in the level of precision in agriculture and the use of digital technologies in the production of agricultural machinery and equipment. A confirmation of this conclusion is a sharp increase in the yield index in 2022. According to expert estimates, the yield of grain crops will be 33.8 dt/ha [58]. In 2021, this indicator was 26.7 dt/ha, having decreased by 1.9 compared to 2020 [59]. The increase in grain yields in 2022 may stem from the increase in the share of domestic seeds in the first selection, since the number of machine and tractor fleets of agricultural organizations has not changed significantly. It should also be noted that in 2021, the area of arable land decreased by 40.1 thousand hectares [59]. This trend continued in 2022.

The digitalization of the agricultural sector determines a number of trends in the field of agriculture:

- The forming digital communication environment has significantly transformed the preferences of consumers, whose expectations showed a profound change due to the mass dissemination of marketing information. Within the framework of this trend, attention should be paid to the greening of agricultural production. Consumer preferences shape the increase in demand for vegetarian products and its decrease in protein products;
- Creation of traceability systems for agricultural products and food, which are the result of consumer requests for transparency in the agricultural sector;
- Implementation of the biotechnological revolution related to artificial production and reproduction;
- With the development of digital platforms for economic interaction, sales of products redistribute costs along the production chain of the agro-industrial complex. The marginal profit of agricultural producers is increasing. According to expert estimates, the receipt of about 75% of subsidies by agricultural organizations has been transferred to an electronic form;
- Implementation of elements of project-digital management, involving implementing major digital events and projects. In the medium term, it is planned to develop a digital register of agricultural lands, form an array of data for a breeding and genetic database, etc.

The current state of the use of digital technologies by agricultural organizations in Russia is shown in Figure 5 [1].

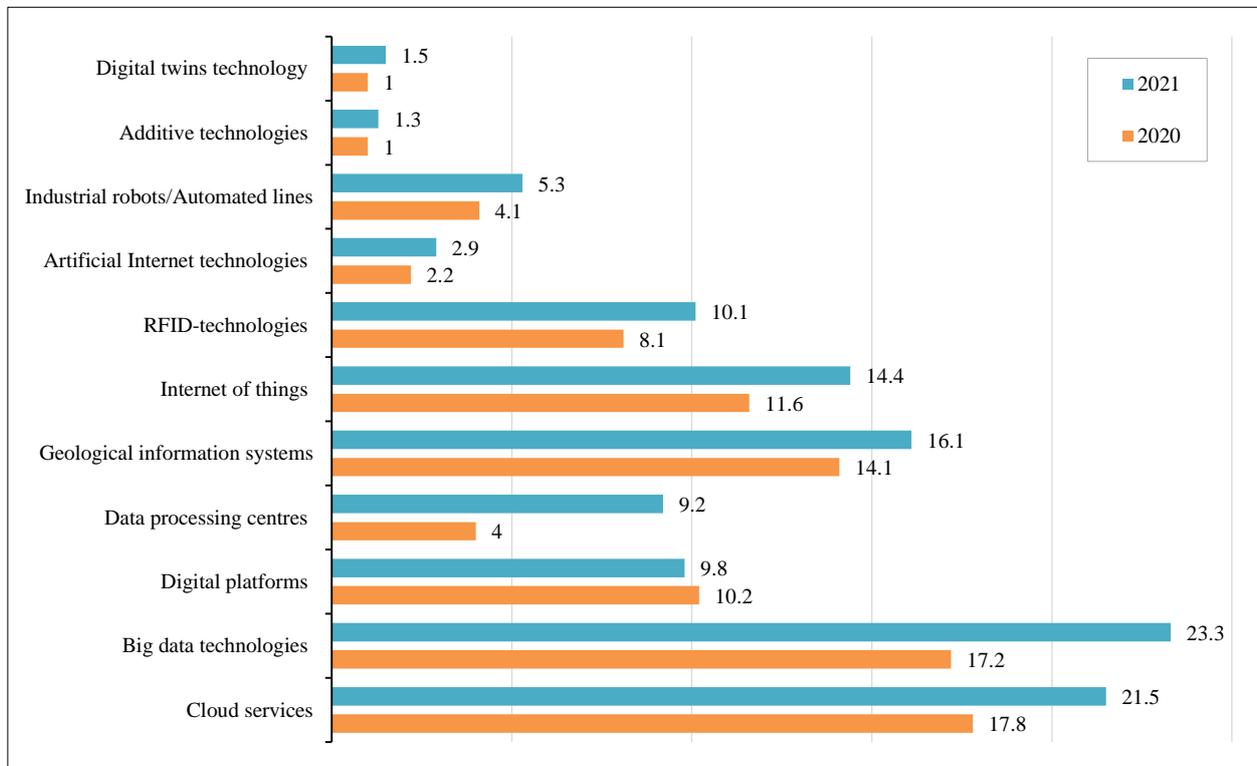


Figure 5. Use of digital technologies in agricultural organizations, %

The analysis of the data shown in Figure 5 suggests that digital technologies and solutions developed on their basis are used in agriculture unevenly. The uneven use of digital technologies in the processes of functioning of agricultural organizations stems primarily from the variety of economic feasibility.

The assessment of economic repercussions and efficiency depends on the impact of digital technology (digital solution) on agricultural production and the level of ease of its implementation. During the study, we assessed the level of impact of digital technology on agricultural output and the level of implementation simplicity (Figure 6).

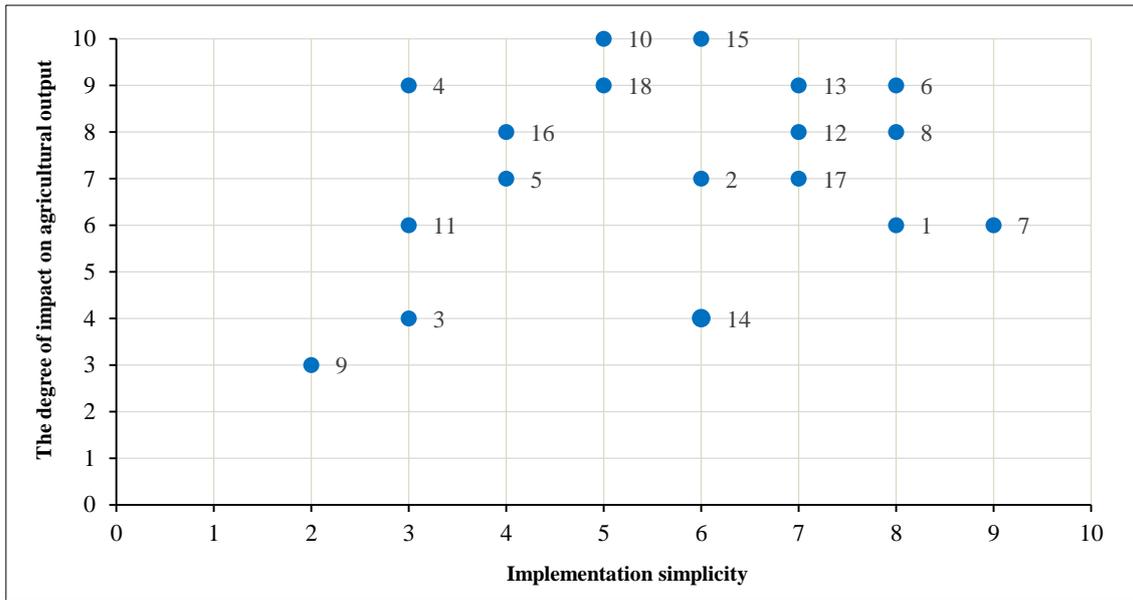


Figure 6. Assessment of the level of impact of digital technology on agricultural production and the level of ease of its implementation (points)

(1) The assessment was made on a ten-point scale, where 0 is the least impact and greatest complexity, and 10 is the highest impact and greatest ease of implementation. (2) The point numbers correspond to the technology numbers presented in Table 3.

Table 3. Distribution of digital technologies by the effect of generation groups for agriculture

No.	Digital Technology	Group
1	Cloud services	High
2	Big data technologies	High
3	Digital platforms	Specialized
4	Data processing centers	Significant
5	Geological information systems	Moderate
6	Internet of things	High
7	RFID-technologies	High
8	Industrial robots/Automated lines	High
9	Additive technologies	Specialized
10	Digital twin technology	High
11	Remote sensing	Significant
12	Agricultural drones	High
13	Global positioning technologies (GPS)	High
14	Yield estimation technologies	High
15	Variable rationing technology	Significant
16	Machine vision	High
17	Artificial Internet technologies	High
18	Industrial Internet	Significant

The results of the study, shown in Figure 5, indicate a generally high level of impact of digital technologies on agricultural output, which results from the increased accuracy of technology implementation and the reduction of various types of losses. The distribution of digital technologies, presented in Figure 6, by groups of effect generation for agriculture is presented in Table 3. A specialized group of digital technologies used in agriculture generates effects at stages not directly related to production processes.

The moderate group includes technologies that function without taking into account industry specifics. A high and significant group consists of technologies that have a high level of influence on agricultural production and differ in technical aspects of simple implementation. A comparison of the data in Figures 5 and 6 shows that digital twin technology is a source of many effects for agriculture, having a high level of influence on technological and production processes as well as an average level of ease of implementation while having a low level of implementation. During the study, the practical significance of digital twins for agriculture was considered in the following areas: technological, industrial, logistical, economic, and organizational. The main effect of the use of digital twin technology in the technological field of agriculture is to increase crop yields and the productivity of farm animals. This effect may be achieved by reducing the human factor during technological operations as well as through the development of digital counterparts of biological objects. This allows you to model the state of the soil and the life cycle of crops.

Digital duplicates of technological processes allow you to control the implementation of all technological operations, setting the best initial requirements. Changing consumer preferences, leading to the transformation of demand, requires a more flexible approach on the part of producers of agricultural raw materials and food, both to meet consumer expectations and to improve the quality of the use of production resources. In this aspect, the technology of digital twins makes it possible to significantly modernize crop rotation, implementing the principles of rational nature management in terms of maximizing profits. A trend in agricultural industries is the requirement of environmental friendliness in manufactured products, which implies a change in technology with a decrease in the use of plant protection products, fertilizers, etc. The consumer's desire to have complete information about the origin of agricultural products and their properties is the motive for the biotechnological revolution. In this aspect, digital twins allow the modeling of biochemical processes in the development of biological objects with specified useful properties. These useful properties are of interest both for the consumer and for reducing the production costs of agricultural organizations.

The biotechnological effects of the digital twin of a biological object are, in particular, the creation of nature-like agricultural production systems that implement the functions of preventing degradation processes in the soil, preserving water resources, and, in general, promoting biocenosis on cultivated agricultural land. The revolutionary nature of the use of digital twins in the technological sphere also lies in deciding on the use of a specific technology based on the history of the field, which includes dynamic data on climate, hydrometeorological conditions, previously used technological techniques and impacts, etc. Agribusiness holding companies, namely the holders of a large bank of land resources, may use the digital twins to monitor, as well as planning the prospective use of part of agricultural land for the implementation of a business project, for example, for cultivating a new type of agricultural crop. An important technological effect of industrial and economic importance is the use of a digital twin to determine the universal parameters of plowing (field preparation) to maximize the possibilities of sowing various crops. Such an opportunity, taking into account production cycles in agriculture, makes it possible for an agricultural organization to make a choice taking into account changes in global and national agricultural markets.

A quantitative assessment of a number of effects from the use of digital twins in the technological field of agriculture is presented in Figure 7.

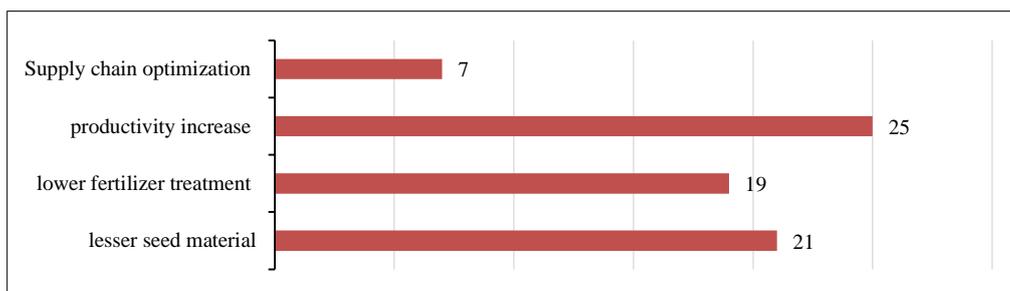


Figure 7. Effects of digital twins in agricultural technology, %

Figure 7 shows the effects of the implementation of digital twins in the technological sphere of agriculture associated with the development of digital twins of biobjects (soil, plants). Digitization of crops in a retrospective of 5-7 years, as part of the digital twin, increases the accuracy of site yield forecasting. The digital twin of fields, crops, and technological processes significantly increases the reliability of analytical data. The sphere of agricultural production witnesses the processes of organization of technological processes. The production of agricultural products during crop production involves several stages: preparatory, sowing, processing, and harvesting. Digital twins of the complete production cycle in agriculture form the most effective use of available resources of the organization. The main effect of the use of digital twins in the production of agricultural products is minimizing the influence of human factors.

Owing to the new design systems, it became possible to design and assemble industrial objects on a large scale, observing all the features of the production process and not violating the strict criteria of industrial safety. These systems make it possible to design a model of a single plant and correctly place all technological and technical components on it. The use of such systems provides a reduction in the number of errors at the stages of both design and operation of all kinds of installations by 50-70%. The effects of using digital twins in the production sphere of agriculture are shown in Figure 8 (based on Hewey [60]).

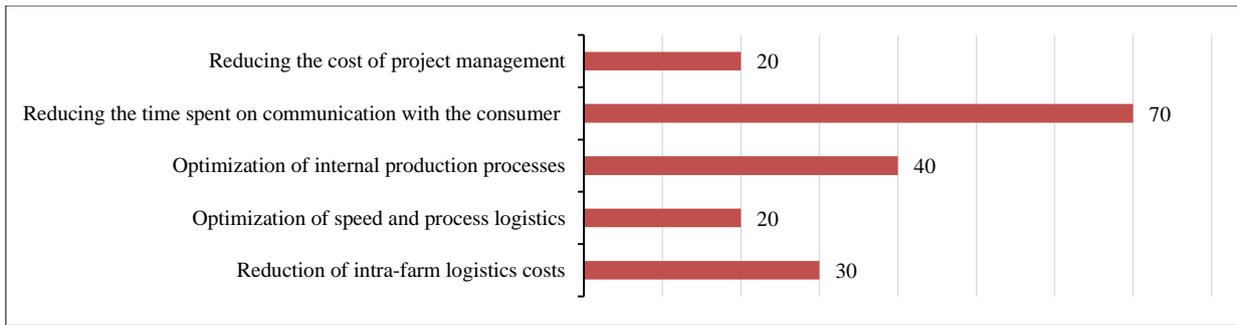


Figure 8. Effects of digital twins in agricultural production, %

The data presented in the figure shows the significant potential of using digital twins in the production process. In particular, the time costs for communication with the consumer are reduced by the objectivization of technical production information. As part of the organizational and production structure of the enterprise, the following positive effects can be carried out [19]: risk prevention, improving the quality of the product, improving enterprise management, etc. Digital twin technology in the technological sphere of agriculture acts as the basis for: training milking robots with human-like models of animal handling; cadastral record keeping; maintaining spatial management; ensuring quality accounting; controlling large-scale and diversified agricultural production; and others. Digital twins of the production processes of agricultural organizations are guaranteed to form an optimal scheme of production logistics in the "garage-field-garage" system. Organizational and technical effects from the application of digital twins in the field of agricultural engineering at the stage of operation are shown in Figure 9.

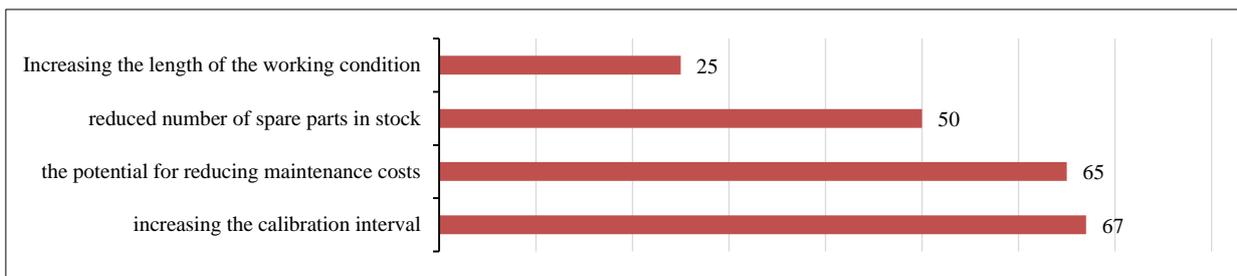


Figure 9. Organizational and technical effects of the implementation of digital twins in the field of agricultural machinery, at the stage of operation, %

The results of the analysis of the data presented in Figure 9 allow us to conclude that digital twins have a high level of influence on the optimization of processes at the stage of operation of agricultural machinery. The socio-economic effects of optimizing maintenance and repair by using digital twin technology are presented in Table 4.

Table 4. Socio-economic effects of maintenance and repair optimization through the application of digital twin technology

Impact	Characteristics
Increased staff culture	Professional development and retraining of employees in the formation of competencies to work with digital technologies. There is an increase in the level of culture of employees, including through the adoption of changes caused by digitalization. Increasing the level of employee awareness of the state of production processes, as well as building high-quality professional communication. Digital twins are a new topic for uniting enthusiasts, innovators, and create / increase the professional interest of the employee. Possessing the competencies of working with digital twins, in general with digital technologies, increases the value of the employee. Employees see the EAM systems as a source of necessary information.
Improved professional discipline	The digital twin requires, already at the design stage, the systematization of information and production processes, which creates an informal regulation in the work team. Regulation of activity increases the level of discipline, creates conditions of ordering of activity and interaction, and increases the quality of EAM-system functioning
Creating conditions for healthy competition in the workforce	The discussion of best practices, modern experience in the field of maintenance and repair of agricultural machinery and its working bodies, etc. provide an opportunity to increase the number of topics for both professional and personal communication between employees. The digital twin helps improve the communication of employees, specialists of various departments of an agricultural organization, First, employees who operate agricultural machinery and equipment and employees who conduct maintenance and repair
Improving the quality of horizontal communications	The development of a digital twin involves taking into account all stages of the life cycle of an object (machine, equipment, unit, product), as well as the features of business processes characteristic of a particular stage. This forms the employees' understanding of the cause-and-effect links between the results of their work and the results of work not only of related structural units, but also of the entire organization. This understanding improves the interaction of the head of a structural subdivision, in general, the managerial staff, with specialists, employees, and labor collective

The socioeconomic effects of the optimization of maintenance and repair through the implementation of digital twin technology highlighted and presented in Table 4 show their impact on the culture of production and workers, which allows the latter to obtain non-material effects.

The economic effects of the application of digital twins both in agriculture and in agricultural engineering depend on the solution of problems of food security in the country, in particular the reduction of various types of costs (material, labor, time, etc.) and the increase in the quality level of realization of economic relations due to the ensuring objectivization of information, the increase in transparency of economic interaction, etc. Building a digital twin of the economic system of an organization allows for the development of projects for management decisions of high quality, as ensured by modeling the set of scenarios for both incoming information and the accounting of the consequences.

The quality of strategic planning and management of the development of an agricultural organization and/or their group is significantly increased on the basis of taking into account a large number of factors. Improving the quality of management is possible based on the basis of building accounting, analysis of big data system of digital twins of objects, processes, and systems in various aspects of the agricultural organization. In the field of management, digital twins can reduce the cost of strategic management by up to 70%. Creating a digital twin of the management process in the agricultural organization allows you to determine the need to use public support measures, their volume and value, subject to the return.

The digital twin of the management system of agricultural organizations stimulates the introduction of automated and robotic systems. An important effect of the application of digital twins in the sphere of management is an increase in the quality of reporting documentation. In addition to increasing the level of reliability, the objectivity of reporting information forms the possibility of making better operational management decisions. Channels of management within an agricultural organization applying a digital twin management system provide access to the necessary operational database through portable devices, as well as regulation and accounting of access by levels of management.

4- Discussion

It was determined that digital twins help conduct an adaptation of agricultural production to technological and economic changes, increase the level of high-tech agro-industrial complexes, and provide a high level of accuracy in the implementation of technological production operations. Digital twins of agricultural machinery and working tools significantly reduce the cost of designing and operating agricultural machinery.

In the context of economic impact, digital twins create an export mass of high-tech products of agrarian profile, improve the quality of service in the agricultural sector, and provide standardization of production operations and manufactured products. The use of digital twins in agriculture allows the formation of competitive advantages for the national agricultural sector and the achievement of national development goals in the field of digitalization of the economy. Latest studies on the content of the concept of "digital twin" confirm the importance of digital twins in agriculture and in the system of food security in the country, as determined on the basis of various scientific approaches.

The digital twin has all the above characteristics. On the basis of what was assessed, the level of impact of digital technology on agricultural production and the level of ease of its application. The results of the assessment, which showed the high importance of digital twin technology for the technological development of the agrarian sector of the economy, confirmed and complemented the provisions of the state agricultural policy of Russia in terms of the digital transformation of the branches of the agricultural sector [61].

Given the prerequisites of the digital transformation of agricultural production, the analysis of grain crop yields and the dynamics of the number of tractor fleets in agriculture in Russia and the United States was carried out. Based on the results of the analysis of statistical data and the results of the study of scientific sources (given above as part of the literature review), the following conclusions were drawn:

- The digitalization of agricultural production at the global level began in the 1960s;
- In Russia, the digitalization of the agro-industrial complex on the basis of its own developments has been carried out since the 2010s;
- The intensity of agricultural production has been increasing over the past decades.

The analysis of grain yield and the dynamics of the number of tractor fleets in agriculture in Russia and the United States caused a discussion, when discussing the results of the study at scientific conferences. Scientists, researchers expressed opinions both in support of this study and with criticism. Criticism was based on the fact that many factors influence the yield, and therefore, it is impossible to link it with the digitalization of production.

Indeed, the yield, particularly of cereals, in addition to the accuracy of the production operations prescribed by the technology of cultivation (which ensures the digitalization of agricultural production), depends on the weather conditions and varietal characteristics. The varieties of cereal crops used are in constant use. Their replacement usually occurs over

an extended period. Weather conditions vary, but they do not affect the technology. Their influence affects the final volume of the crop and its loss. Yield reduction is possible with low-quality seeds and non-observance of cultivation technology. Consequently, yield is a culture objectively showing the level of technological development in agricultural production.

5- Conclusion

The study helped expand the theoretical and methodological framework for implementing digital twin technology in agricultural production sectors by supplementing them with: the definition of the importance of technology to ensure food security; reasoning, through cliometric data on yields, for structural technological shifts in agricultural production; assessment of the level of impact on agricultural production; classification of digital technologies on the basis of the generation of effects; and qualitative and quantitative analysis of the impact of digital technology on agricultural production.

The development of digital twin technology and its theoretical, methodological, scientific, and practical provisions in the near future will be based on: the use of supercomputers, allowing to increase the speed of digital twin creation and increase the number of factors taken into account; the use of neurotechnology, requiring, on the one hand, providing certain food structures and, on the other, forming natural-like production agricultural systems. The study has provided new knowledge necessary for the qualitative design of the initial stages of the digital twin. The results of the study are significant for developing algorithms for creating digital twins of agricultural machinery, technological processes, bio-objects, control systems, and monitoring systems. The implementation of digital twins in the sectors of agriculture makes it possible to build complete life cycle chains of agricultural products, food, and products of related industries.

5-1-Limitations and Study Forward

The presented results of the study of theoretical and methodological provisions for the application of digital twin technology in agriculture reflect the first stage of scientific work. The limitations of the stem from the low level of application of digital twins by agricultural organizations in Russia as well as the fragmentation of research. High time costs have limited the range of researchers and practitioners who develop digital twins of agricultural profiles. Only scarce information on the application of digital twins in agriculture and agricultural engineering is publicly available. The information base was formed by establishing communication with organizations selected based on the assumption of possible implementation of digital twin technology. The next stages of the study will continue to improve the theoretical and methodological provisions of the application of digital twin technology in agriculture and will form a database for developing a digital twin set of working tools for agricultural machinery.

6- Declarations

6-1-Author Contributions

Conceptualization, A.N.S. and M.M.K.; methodology, A.N.S. and M.M.K.; software, D.A.M.; validation, D.A.M., M.M.K., and A.L.Z.; formal analysis, A.L.Z., V.V.I., and D.A.M.; investigation, A.N.S. and M.M.K.; resources, A.N.S., D.A.M. and V.V.I.; data curation, A.N.S. and D.A.M.; writing—original draft preparation, M.M.K.; writing—review and editing, A.N.S. and D.A.M.; visualization, M.M.K.; supervision, A.N.S., A.L.Z., and V.V.I.; project administration, A.N.S. and V.V.I; funding acquisition, A.N.S., A.L.Z., and V.V.I. All authors have read and agreed to the published version of the manuscript.

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6-6-Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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