Experimental Studies of the Digital Twin of Plant based on Ontologies and Multi-Agent Technologies

PETR SKOBELEV[1], ALEKSEY TABACHINSKIY[1], ANATOLY STRIZHAKOV[1],
EVGENY KUDRYAKOV[1], ELENA SIMONOVA[2]
Samara Federal Research Scientific Center RAS,
3a Studencheskiy Lane, 443001, Samara,
RUSSIA

[2]Institute of Informatics and Cybernetics,
Samara National Research University,
34 Moskovskoye Shosse, 443086, Samara,
RUSSIA

Abstract: - The article discusses the results of research achieved in the field of developing an intelligent digital twin of plants (DTP). An ontological model of the crop production process is proposed, and expanded by including descriptions of physiological and technological factors: predecessors in crop rotation, seed reproduction, and consumption of macro-elements from the soil. The multi-agent DTP model has been modified to account for the morphological and physiological characteristics of crop varieties, as well as parameters for each phenological phase of the plant. A software prototype of the DTP is presented, implementing the developed methods for simulating the production process of crop plants. Experimental cultivation of crops using the DTP was conducted in the 2022/2023 season. The obtained datasets during the experiments will be used to calibrate the model and improve the accuracy of predicting plant parameters at each phenological phase.

Key-Words: - precision agriculture, smart farming, digital twin of plants, crop variety model, multi-agent technology, knowledge base, ontology.

Received: April 27, 2024. Revised: September 18, 2024. Accepted: October 19, 2024. Published: November 22, 2024.

1 Introduction

The transition to the digitalization of all sectors of the economy, including agriculture, is of particular interest to researchers of mathematical models and artificial intelligence methods. The principles of precision farming, whose achievement will significantly increase the efficiency of crop cultivation, are based on a set of digital technologies related to the collection and processing of data, autonomous decision-making for field works, and control of their implementation, [1], [2]. Every year, the use of digital twins in agriculture is expanding, primarily covering systems that simulate specific aspects of the business process of plant cultivation, [3]. Systems for simulation parameters of the production process are also known from scientific sources; however, these solutions are of early technological readiness primarily.

One reason is that the processes involved in plant cultivation are much more complex compared to manufacturing and require the integration of multidisciplinary knowledge in physics and chemistry, biology, agronomy, soil science, and several other fields. Another challenge is adaptive planning and simulation of plant growth based on unpredicted rapidly changing external factors. Additionally, it involves developing precise recommendations that can help farmers and agronomists to timely implement the required field works specifically in the location and time. Finally, the production process of the virtual plant must be synchronized with the growth of real plants through timely diagnosis of crop parameters of the real plants.

In this regard, the task of creating a digital twin of plants (DTP) becomes relevant, allowing to determine the timing and predicted indicators of crop growth under given environmental conditions, which is necessary for precision farming. The concept of the DTP, developed in this article, is based on the application of an ontologically configurable multi-agent system (MAS), [4], [5]. This system allows for real-time planning and simulation of the production process of crops, characterized by dynamically changing compositions and quantities of input data. Some of this data can be expressed through refined expert assessments provided by agronomists.

The article has the following structure. The first chapter discusses the task of digitalization in precision farming. The second chapter provides a general overview of the digital twins for the simulation of plant growth stages. The third chapter gives an overview of existing solutions in the field of using models for the production process of plants and justifies the need for developing new approaches based on interdisciplinary knowledge. The fourth chapter describes variety and resource models within the ontology of plant cultivation. The fifth chapter justifies the development of the multi-agent DTP model by introducing agents of the morphological features of plants. The sixth chapter examines the architecture and functions of the DTP prototype. The seventh chapter describes an experiment on wheat cultivation using the DTP. The eighth chapter discusses the outcomes of the developments and prospects for the further advancement of the DTP.

2 The Concept of the Digital Twin of Plants

The current research on developing digital twins of agricultural crops has been conducted since 2021 in collaboration with several agricultural research institutions. These are utilized in decision support systems for managing resources in agricultural enterprises. The authors define the concept of the "Digital twin of plants" as an intelligent system for planning and simulating the growth and development of plant crops based on environmental data. This system regularly synchronizes with real plants during the production process, [6]. The classes of agents necessary for describing the DT of crops are presented in Table 1.

At the core of DTP implementation lies an ontological approach to represent knowledge in the subject domain, enabling the construction of a knowledge base (KB) of stages of development for various plant varieties in the form of a semantic network of instances of concept classes and relationships. Subsequently, this knowledge can be supplemented and refined from the experience accumulated by specialists during the cultivation of specific crops.

The process of plant development is described through a sequence of successive stages with predetermined rules for determining their duration and calculating indicators of plant development. The rules for calculating the duration of stages and indicators of plant development are based on a simplified mathematical model that sets ranges of environmental parameter values for each stage: under normal plant development trajectories, as well as in the event of hazardous weather phenomena (such as frost, prolonged absence of precipitation, etc.) and exceeding critical boundaries. If the parameter value falls within acceptable limits, a linear law of stage duration change and penalties for monitored plant indicators, such as yield, is applied. When exceeding the permissible boundaries, the maximum possible penalty is assigned. In addition to boundary values for calculation rules, the penalties for exceeding the established boundaries depend on the duration of the parameter exceeding these boundaries.

Table 1. Classes of agents of the DT of plant crops

Agent class	**Functions**
plant agent as a whole	coordinates the work of other agents
stage agents	define the needs of the plant at each stage
agents of resources and growth opportunities	are refined at each stage based on data from sensors, external services, or agronomists
parts of the plant agents	operate within each stage and are responsible for decision-making at their level
agronomist agent	generates context-dependent recommendations for plant cultivation following the evolving situation
environment agent	provides data on weather and environmental conditions from sensors and meteorological services

The effects of different parameters can be combined using various aggregation strategies: sum or multiplication, and selection of the minimum or maximum value. Changes in environmental parameters (such as weather or soil conditions) at any stage should trigger an adaptive recalculation of the duration and indicators of plant development for that stage and subsequent stages.

In the MAS of the DTP, several levels of representation of the production process of plants are developed, but the primary one is the multi-agent network of needs and capabilities (NC-network). It is linked to the stages of plant growth and development, capturing their resource requirements and resource availability. Within this approach, agents operate within an internal virtual market with the capability to buy and sell time slots in the schedule. Agents can identify issues and resolve conflicts by applying negotiation protocols and a compensation method based on individual satisfaction functions (SF), as well as bonuses and penalties, [6].

DTP enables the calculation and prediction of the date and duration of growth and development stages, the length of the vegetation period, and the quantity and quality of the harvest based on weather and soil data. Additionally, it incorporates observations and analyses conducted in both field and laboratory conditions. The forecasting of the harvest and other indicators is performed based on a variety of model constructed in touch with the soil-climatic conditions of the cultivation zone, as well as the biological and morphological characteristics of the crop. The variety model is filled with information in the form of functional dependencies of crop parameters.

The MAS of the DTP is extended to calculate a dynamic set of crop parameters (multi-parameter model) as well as rules for resource replenishment/expenditure in the external environment. This significantly enhances the simulation accuracy when confirmed data on resource consumption and expenditure in the soil are available.

The purpose of this article is to present the results achieved in the development of the DTP and to describe the experimental cultivation of crops using the DTP during the 2022/2023 season.

3 State of the Art

One of the most challenging tasks in implementing DT for plant cultivation is the development of a production model for plant that is dependent on external environmental factors.

Paper [7] explores mathematical models of the growth of agricultural crops based on algebraic or differential equations. They calculate variable rates (photosynthesis, leaf area expansion, etc.) and state variables (crop biomass, yield, etc.) at each stage of plant development throughout the vegetative period based on the crop status, soil conditions, and weather. However, such models often turn out to be complex and are only implementable in relatively simple cases, covering a small portion of the tasks.

Simulation models forecast changes in the state of agricultural crops over time based on exogenous parameters. The AGROTOOL system describes the fundamental processes in the agroecosystem "soil-plant-atmosphere" from sowing to full maturity, [8]. However, even for the initial run, the model must contain data for the past 5–6 years of vegetation. Moreover, simulation models are not directly linked to the real object and are not synchronized with its changes.

Paper [9] proposes a "digital prototype" of a crop to account for individual soil-climatic conditions and plant needs within a comprehensive system for precision agriculture. This system includes digital platforms, artificial intelligence (AI) programs, feedback sensors, and tools for preparing and precisely delivering balanced fertilizers, micronutrients, and plant protection agents at the right time, in the specified location, and in the required quantities.

Paper [10] explores the Digital Twin project Virtual Tomato Crops (VTC), which includes a 3D simulation model predicting tomato yield based on the utilization of nutrients, lighting, and water. The foundation of VTC is a Functional-Structural Plant Model (FSPM) that simulates internal processes in plants, including light capture, photosynthesis in leaves, assimilate distribution, leaf area growth, and stem elongation.

With the transition to Agriculture 4.0, there is an increasing demand for industry-specific solutions to optimize production processes. In this context, digital twins are most widely represented for greenhouse farming, [11], [12]. However, digital twins for open-field plant cultivation are still in the early stages of development, [13], [14].

The review [15] found that digital twin technology is expanding its influence in agriculture. However, future studies should pay much attention to the characteristics of living organisms and their twinning with virtual entities. The authors also state that the architecture of digital twins for crop cultivation should be further enhanced, as should its functionality.

The analysis of research in the field of digital agriculture has revealed that currently there are no solutions that allow for the simulation of the comprehensive state of a crop based on real-time environmental data and provide forecasts of its condition throughout the major vegetative stages until the harvest. Some individual solutions are capable of calculating specific parameters, such as forecasted yield, under limited conditions. The insufficient level of development of digital tools in this field is associated with the complexity of the problem, which requires the simulation of biological systems based on the integration of interdisciplinary knowledge.

4 Ontological Models of the Production Process of Plants

Within the research, an ontological model of the production process was developed, encompassing variety and resource models. This model allows modifications to the plant variety model, including the composition and applicability conditions of growth rules, without reprogramming the DTP. This flexibility is useful for accommodating new agronomic or technological factors and cultures of crops.

Different crops go through various stages of development throughout their life cycle according to the BBCH scale [16], each characterized by specific conditions for transitioning to the next stage. By using a graph depicting the interconnection of parameters between the plant stages, the sequential development of plants during the vegetative period from one stage to the next can be represented. This graph defines which parameters in the next stage are affected by the parameters from the previous stage (Figure 1). Quantity estimation of this correlation is declared in the variety model, which is described later.

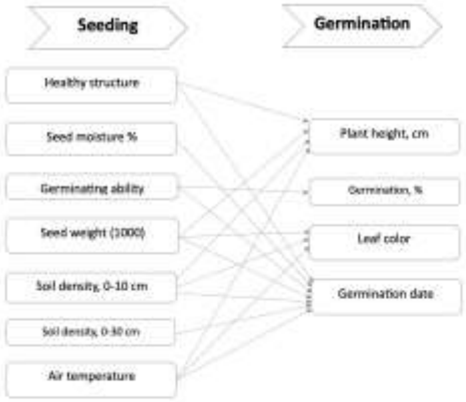

Fig. 1: Fragment of the parameter graph for the growth and development stages of winter wheat

4.1 The Variety Model

The variety model consists of an array of "tubes" for all output parameters applicable at a specific stage. Each "tube" describes the reaction of one output parameter from one input parameter (factor) at a particular stage and its “depth” of plant reaction. The tube of parameters includes critical and optimal ranges for the input parameter, which describe different plant behavior (reaction). DTP estimates the reaction for each input parameter and aggregates them to calculate the value of each affected output parameter of the plant, [6]. The array of input parameter ranges, the depths of variety reaction to each of the factors, and other variety-specific rules together form a variety model. Such rules include the ripening group, the nominal duration of the life cycle, a list of resources, and their influence on the affected parameters of the plant throughout its life cycle.

A fragment of the ontological model of the variety (using winter wheat as an example), including functional dependencies of a series of output parameters on the factor "Soil moisture at the 0-10 cm level," is presented in Table 2.

Table 2. A fragment of the class "Variety model" of the ontology

Soil cont., mm	Critical max	60	Secondary root system	N	Stem length, cm	7	Number of leaves, pcs	5
	Optim.	17		Y		11		8
	Critical min	0		N		8		4

The variety model takes into account the genetic and technological features of the plant production process:

- the influence of predecessors in crop rotation on the duration of growth stages and yield is achieved by imposing penalties on similar characteristics if the predecessor is fallow;
- the impact of seed reproduction on yield is achieved through penalties based on the planned yield, applied to the biological yield rate;
- the influence of environmental factors (such as temperature and air humidity) on the duration of plant development is accounted for by using correction coefficients applied to the calculated deviation value of the plant development stage duration;
- stage-wise extraction of macro-elements (nitrogen, phosphorus, potassium, or NPK) from the soil.

The growth and development of plants occur through the utilization of resources. The duration of a stage is determined by the rate of plant development, which depends on the suitability of external environmental conditions, determined by the plant's satisfaction function with the level of specific resources and the totality of resources.

4.2 The Resource Model

The resource has the following characteristics: initial actual value at the sowing date, expenditure rule, replenishment rule, and current value. The influence of resources on plant parameters at different stages is described in the variety model in the form of:

- resource boundary points (tubes). One tube describes the influence of one resource on one output parameter of the plant: critical minimum, recommended value (optimum), critical maximum;

- values of the affected output parameters at the boundary points;
- expert rules in case the critical minimum is not reached or the critical maximum is exceeded.

At this stage of implementing the DTP, the following resources are taken into account: average daily air temperature, soil moisture at several levels (0-10; 0-30; 0-100 cm depending on the stage of plant development and root system depth), relative humidity, and nutrient reserves in the soil in the form of NPK.

The current resource value is calculated based on the actual resource volume at the initial moment (date of planting) and rules for its expenditure and replenishment. The current value of the resource may be periodically updated based on data provided by the agronomist, which they input during the synchronization mode of the DTP, for instance, after receiving laboratory soil analysis results.

The accounting of resources in the DTP model is based on the actual growth and development strategy of the plant (the crop response to daily changes in external conditions) according to the methodology described in the authors' work, [6]. Specifically, accounting for the influence of the prioritized factor for plant growth, such as air temperature, is carried out using two parameters: the sum of active temperatures and the plant's satisfaction function with temperature. The stage agent calculates the daily value of the plant's SF based on the temperature value depending on which interval of the variety model's tube the temperature value falls into (Figure 2).

Accordingly, the values of the *SF* (Y_T) can range from 0 to 1:

- $T \in [Tmin, Tcr\_min)$, Y_T is calculated according to a rule $Rule_L$, determined by the agronomist, plant death is possible;
- $T \in [Tcr\_min, Trec\_min]$, penalty Y_T is calculated according to the linear dependence;
- $T \in [Trec\_min, Trec\_max]$, $Y_T = 1$, no bonus/penalty is awarded;
- $T \in [Trec\_max, Tcr\_max]$, bonus Y_T is calculated according to the linear dependence;
- $T \in [Tcr\_max, Tmax]$, Y_T is calculated according to a rule $Rule_R$, determined by the agronomist, plant death is possible.

The obtained duration value of the stage and the reason for the deviation (if any) are communicated by the stage agent to the plant agent. As a result, the plant agent receives the calculation of the duration of each stage and deviations in the development of the crop throughout the entire vegetation cycle.

Simultaneously with the duration of stages, the DTP calculates the values of output parameters of the crop (yield, etc.) depending on the available resources.

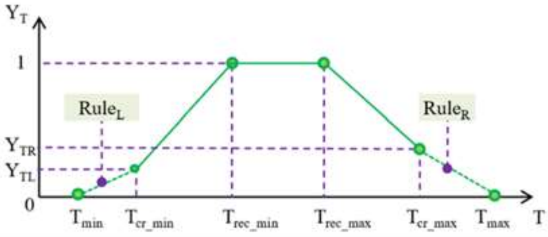

Fig. 2: The form of the satisfaction function of the stage agent in relation to the magnitude of the resource (air temperature)

5 The Development of the Multi-Agent Multi-Parametric Model of the Digital Twin of Plants

The state of the DTP C_{DT} at each stage of growth and development is determined by a combination of three factors:

$$C_{DT} = \{M_O, P, KPI\},$$

where M_O – ontological model of plant, P – the constructed plan of plant growth and development, KPI – the comprehensive indicator of stage progression efficiency.

Let C_R – be the state of a real plant, C_{DT}^k – the state of the DTP. The accuracy of the DTP model will be high if the difference between the states of the real plant and its DTP at each moment in time k is minimal:

$$D\left(C_{DT}^k, C_R^k\right) \to 0,$$

where D – function determining the difference between the indicators of the DT with the parameters of the real plant.

In case of a new event E^k occurring on a real field in the farm, the DTP should move to a new state as quickly as possible by rescheduling the stages affected by the event:

$$C_{DT}^{k+1} = F\left(C_{DT}^k, E^k\right),$$

where F – function adaptively reconfigures the plant growth plan in response to the occurred event.

In this study, the concept of a multi-level multi-agent model of the DTP was developed. This model incorporates both horizontal and vertical interactions among agents, leading to the emergence of a "collective intelligence" of the plant, which has an emergent nature, [17]. The agent world architecture in MAS of DTP includes the following types of agents: fields, plants (crops), stages, and resources, as well as the plant agent as a whole. The MAS is created according to a hierarchical principle, where the top-level agent is the plant agent, and the agents of stages and resources, which are responsible for directly regulating the plant growth process, are located at the lower level. Initially, agents of plant growth stages and resource agents are created. The stage agents start working sequentially. Resource agents correspond to the input parameters of the environment.

In this case, the NC-network of the DTP represents a network of agents of plant growth stages and resource agents, which adaptively recalculate in a chain, and form a "competitive equilibrium" based on data from meteorological stations and results of field inspections by agronomists. The plant agent as a whole, observing the calculation results, can adjust the parameters of the tubes for each stage of plant growth and development, influencing the conservation or, conversely, the expedited utilization of the corresponding resource.

The world of MAS agents is supplemented with agents representing plant morphological characteristics (height, leaf area, root length, and area, stem diameter and height, etc.) and physicochemical parameters of crops (chlorophyll, protein, carbohydrates, water, temperature, macro- and micronutrients N, P, K, Ca, S, Cu, Zn). To implement the level of plant morphological characteristics in the DTP, complementing the simulation of stages, an approach presented in Figure 3 is proposed, where an "organ agent" is introduced – a type of agent representing plant morphological characteristics. The list of specific "organ agents" for each crop is described in the KB using logical rules for the appearance of the organ and a mathematical model of its functioning, represented as functions of its influence on various aspects of the plant's production process. Further introduction to the multiagent world of DTP is provided in [6] and other previous papers of the authors.

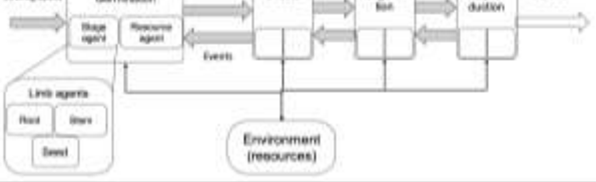

Fig. 3: Decomposition of stage agents in the MAS of DTP

6 Architecture and Functions of the DTP Prototype

The main subsystems of the DTP prototype include an ontology/knowledge base constructor for describing classes of concepts and relationships, as well as domain-specific rules necessary for DTP calculations, and a multi-agent subsystem for planning and simulating plant growth and development. Each of these subsystems contains client and server parts. Additionally, there is a mobile application for phones and tablets running on the Android operating system.

The client part, implemented in JavaScript with the Vue framework, utilizing CSS/HTML markup, enables the DTP user to work through a website accessible from any internet browser. The web application implements functions for creating, modifying, and deleting objects of the following classes: Users, Fields, Crops, Calculation results of crops, Journal entries of crops (synchronization), Virtual crops, and fields.

The software interface of the web application provides functions:

- retrieving a list of fields, as well as a list of crops in the field with the ability to sort by field, crop, variety, and season;
- creating a crop on a field with user-specified planting parameters;
- creating a simulated crop as a virtual copy of the real one;
- building temporal diagrams of external environmental factors based on field environment parameter data;
- constructing a Gantt chart of the growth and development plan of the crop based on DTP calculations;
- creating a journal entry for the crop synchronization function.

The determination of environmental factors and soil indicators is carried out through the interaction of the DTP with the KAIPOS intelligent weather monitoring systems. The data obtained from the weather station is used to create an environmental parameter source, which provides calculations of 5-year averages for each parameter throughout the year. Subsequently, a long-term forecast of parameters is generated, enabling the prediction of the crop conditions for future dates.

The server part, implemented in Java, is intended for conducting calculations and interacting with external services and includes subsystems:

- subsystem of ontology and knowledge base constructor for crops;

- multi-agent subsystem for planning and simulation of plant growth and development, as well as forecasting crop yield and generating recommendations;
- data visualization subsystem;
- data storage subsystem (database);
- subsystem of communication with users;
- subsystem for integration with weather services and other sensors.

The methodological aspects of the organization and algorithm of the DTP prototype's functioning are described in more detail in the authors' previous articles. The growth and development plan of the plant constructed in the DTP represents the sequence and parameters of stages. Changing the value of a parameter on a specific date through synchronization with real crops leads to the recalculation of all related parameters in the growth and development stage scheduler of the DTP's MAS. This, in turn, affects all subsequent stages and may alter the forecast of crop quantity or quality.

7 Experimental Cultivation of Wheat using DTP in the 2022/2023 Season

Crop fields have coordinates, technological maps, crop rotation history, agronomist observation plans, and other data. The experimental validation of the DTP was conducted by comparing the results of DTP calculations with the actual conditions of different wheat varieties and predecessors grown in the Middle Volga region. The diagrams (Figure 4) illustrate deviations in the duration of stages obtained as a result of DTP calculations for various crops. The calculation is based on the environmental and crop data, such as air temperature and humidity, precipitation, available soil moisture (Figure 5) and soil content (NPK), stem height, plant mass throughout the growing season (Figure 6), leaf surface area, and several others.

In particular, significant deviations were recorded in the initial DTP calculations for soft winter wheat varieties. Subsequently, with each subsequent synchronization, the interval decreased. Synchronizations conducted after the earing stage show that the deviation intervals do not exceed 5 days in magnitude. The calculations of the development of hard spring wheat demonstrate a relatively low deviation interval in the negative direction, not exceeding 7 days. A significant (in magnitude) deviation of up to 16 days is observed during synchronization at the flowering stage, caused by a misinterpreted rule for transitioning to the milk ripeness phase, which introduces "chain-by-chain" deviations into the development scenarios of subsequent phases.

Based on the experimental cultivation of the 2022/2023 season using DTP, the following main results were obtained:

1. Based on the discrepancies between planned and actual indicators in the DTP, adjustments to the growth and development rules, as well as variety model values, were made;
2. The average accuracy of predicting the duration of stages for all crops is 93.2% for the entire vegetation period and 99% for the Earing stage;
3. The experimental cultivation methodology for the 2022/2023 season has been refined in terms of specifying parameters of factor satisfaction functions, which will increase the accuracy of DTP forecasting for the data of the 2024 season.

Fig. 4: Difference between the DTP-calculated and actual vegetation duration

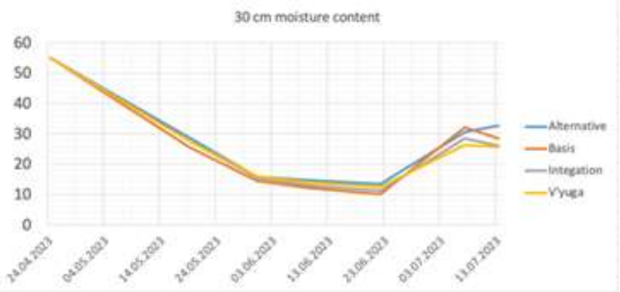

Fig. 5: Diagram of the soil moisture

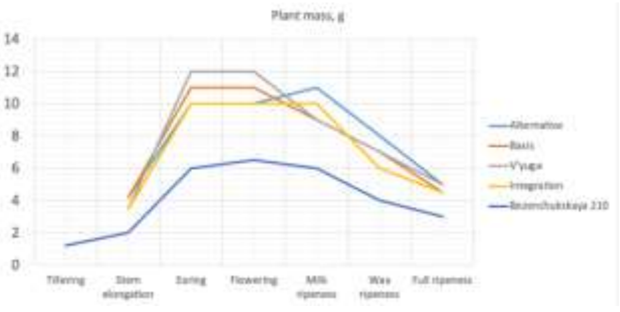

Fig. 6: Diagram of actual plant mass

8 Conclusion

In the presented study, the ontological model of crop production for DTP has been expanded to include crop rotation predecessors, seed reproductions, soil content consumption, and some other environmental factors. The multi-agent model of the production process in DTP has been modified to account for a multitude of input and output parameters of plant crop conditions. For each stage, a resource model has been introduced, allowing for determining the influence of discrepancies between resource requirements and their actual availability on the output parameters of plant conditions. The software implementation of the DTP prototype has been completed.

The experimental research has provided a dataset for calibrating the DTP crop model and improving the accuracy of forecasting plant parameters at each stage. The system functionality will be expanded across various crops for product application (soybeans, corn, potatoes), as well as including a DTP-based subsystem for generating recommendations for agronomists on crop management technologies in different regions.

References:

[1] Kalaiselvy, K., Anand, A. J., Tanwar, P., Raza, H. (eds.), *Advanced Technologies in Smart Agriculture*, NY, River Publishers, 2024, https://doi.org/10.1201/9781032628745.

[2] Zhai. Z., Martínez, J. F., Beltran, V., Martínez, N. L., Decision support systems for agriculture 4.0: survey and challenges, *Comput. Electron. Agric.*, Vol.170, Art.No.105256, 2020, https://doi.org/10.1016/j.compag.2020.105256

[3] Verdouw, C., Tekinerdogan, D., Beulens, A., Wolfe, S., Digital twins in smart farming, *Agric. Syst.*, Vol.189, Art.No.103046, 2021, https://doi.org/10.1016/j.agsy.2020.103046.

[4] Pretel, M. E., Navarro, E., López-Jaquero, V., Moya, A., González, P., Multi-Agent Systems in Support of Digital Twins: A Survey. In Bio-inspired Systems and Applications. Robotics to Ambient Intelligence, *9th Int. Work-Conf. IWINAC 2022*, *Puerto de la Cruz, Tenerife, Spain, May 31-June 3, 2022*, part II, 524-533, 2022, https://doi.org/10.1007/978-3-031-06527-9_52.

[5] Prachi, D., Varsha, M., Madhu, G., Ankita, P., Kadam, S., Pavar, S. S., Overview of Agriculture Domain Ontologies, *International Journal of Recent Advances in Engineering & Technology*, Vol.4, Is.7, 2016, pp. 2347-2354, [Online]. http://www.irdindia.in/journal_ijraet/pdf/vol4_iss7/2.pdf (Accessed Date: July 21, 2024).

[6] Skobelev, P., Mayorov, I., Simonova, E., Goryanin, O., Zhilyaev, A., Tabachinskiy, A., Yalovenko, V., Development of models and methods for creating a digital twin of plant within the cyber-physical system for precision farming management, *J. Phys.: Conf. Ser.*, Vol.1703, Art.No.012022, 2020, DOI: 10.1088/1742-6596/1703/1/012022.

[7] Gowda P. T., Satyareddi, S. A., Manjunath, S. B., Crop Growth Modeling: A Review. *Research and Reviews, Journal of Agriculture and Allied Science*s, Vol.2. No.1, 2013, pp.1-11, [Online]. https://www.researchgate.net/publication/274701819_Crop_Growth_Modeling_A_Review (Accessed Date: July 21, 2024).

[8] Topaj A., Mirschel W., Abnormal shapes of production function: Model interpretations, *Computers and Electronics in Agriculture*, Vol.145, 2018, pp.199-207, https://doi.org/10.1016/j.compag.2017.12.039.

[9] Mikhailov, D., Fedorov, V., Mitrokhin, M., Using artificial intelligence systems for intensive safe cultivation of crops-short communication, *International Journal of Agricultural Technology*, Vol.17, No.3, 2021, pp. 987-990, [Online]. http://www.ijat-aatsea.com (Accessed Date: July 22, 2024).

[10] Ruijs, M., Kootstra, G., Evers, J., van Mourik, S., van de Zedde, R., *The Digital Twin Project Virtual Tomato Crops (VTC), Project Announcement*, [Online]. https://www.wur.nl/en/show/The-Digital-Twin-project-Virtual-Tomato-Crops.htm (Accessed Date: July 25, 2024).

[11] Howard, D. A., Ma, Z., Veje, C., Clausen, A., Aaslyng, J. M., Jørgensen, B. N., Greenhouse industry 4.0 – digital twin technology for commercial greenhouses, *Energy Informatics*, Vol.4, Art.No.37, 2021, https://doi.org/10.1186/s42162-021-00161-9.

[12] De Clercq, M., Vats, A., Biel, A., Agriculture 4.0: The Future of Farming Technology, *World Government Summit*, [Online]. https://www.bollettinoadapt.it/wpcontent/uploads/2019/12/OliverWyman-Report_English-LOW.pdf (Accessed Date: July 21, 2024).

[13] Khatraty, Y. B., Mellouli, N., Diallo, M. T., Nanne, M. F., Smart Digital-Twin hub Concept for Rice yield prediction and monitoring from multivariate time series data,

24th Int. Conf. CSCS 2023, Bucharest, Romania, 24-26 May, 2023, pp. 48-55, https://doi.org/10.1007/978-3-031-06527-9_52.

[14] Madeira, R. N., Santos, P. A., Java, O., Priebe, T., Graca, E., Sarkozi, E., Asprion, B., Gomez, R. P.-B., Towards Digital Twins for Multi-Sensor Land and Plant Monitoring, *Procedia Computer Science*, Vol.210, 2022, pp. 45-52, https://doi.org/10.1016/j.procs.2022.10.118.

[15] Wang, L., Digital Twins in Agriculture: A Review of Recent Progress and Open Issues, *Electronics*, Vol.13, Art.No.2209, 2024, https://doi.org/10.3390/electronics13112209.

[16] Zadoks growth scale, *Agriculture and Food*, [Online]. https://www.agric.wa.gov.au/grains/zadoks-growth-scale (Accessed Date: July 25, 2024).

[17] Mahmoodi, K., Kerick, S. E., Franaszczuk, P. J., Parsons T. D., Gridolini, P., West, B. J., Complexity synchronization in emergent intelligence, *Sci Rep*, Vol.14, Art.No.6758, 2024, https://doi.org/10.1038/s41598-024-57384-5.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Petr Skobelev has proposed the multiagent method to solve the problem and supervised the research. -Aleksey Tabachinskiy has developed the wheat knowledge base and managed the experimental validation.
- Anatoly Strizhakov has provided the agronomical knowledge and conducted the experimental study.
- Evgeny Kudryakov is responsible for DTP interaction and testing, which allowed to provide all DTP calculations.
- Elena Simonova set up state-of-the-art research, analysed the DTP results as compared to the real crops, composed and edited the paper summary.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

This study was funded by the grant of Russian Science Foundation № 22-41-08003, https://rscf.ru/project/22-41-08003/.

Conflict of Interest

The authors have no conflicts of interest to declare.

Creative Commons Attribution License 4.0 (Attribution 4.0 International, CC BY 4.0)