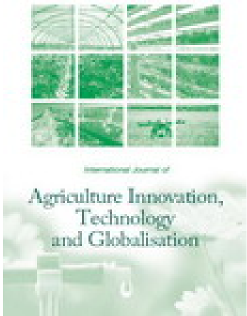

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Towards national-size digital platform and ecosystem of smart services for precision farming

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Abstract: The paper describes problem statement and developed prototype of smart farming solution, which is designed as an open digital platform and ecosystem (system of systems) of smart agricultural services. Each service is implemented as an autonomous artificial intelligence system for decision-making support. The paper describes the functionality of the created prototypes of services within the smart farming solution for precision farming and the possibilities of their use for a wider range of consumers, including state authorities, universities, suppliers of fertilisers and plant protection products, technology companies, startups and end users. A distinctive feature of the considered system is the use of knowledge bases and multi-agent technologies in order to support collective decision-making processes regarding allocation, planning, optimisation and control of resources of farms in real time. Furthermore, the paper discusses results of development and first applications, as well as directions for further development of the proposed system.

Keywords: Industry 5.0; Society 5.0; precision farming; digital ecosystem; multi-agent technologies; knowledge base; decision making; resource management; digital twin of plant.

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1 Introduction

Agriculture is a complex area in which production processes has a high level of uncertainty and turbulent dynamics, as they depend on poorly predicted environment conditions, such as weather, diseases, soil condition, seasonality and climate (Trienekens et al., 2014). In addition, farmers have to take into account requirements of consumers and society regarding food safety, sustainable development and public health.

In this regard, farms must not only be economically efficient, but they also have to meet high standards of quality and environmental friendliness, and must also adapt to constantly changing market conditions. All of these factors impose heavy demands on the management tasks of farmers (Fountas et al., 2013; Tang and Zhao, 2019). They constantly have to revise production strategies and reschedule agrotechnological measures based on timely monitoring of economic activity and crops development in order to achieve profitability.

Driven by the rapid pace of technology development, such as cloud computing, Internet of Things, big data, machine learning, augmented reality and robotics (Janssen et al., 2017; Tzounis et al., 2017; Wolfert et al., 2017; Kamilaris and Prenafeta-Boldú, 2018; Zhai et al., 2020), agricultural production is increasingly transitioning to smart agriculture. It can be considered as the next stage of precision farming, in which management tasks are based not only on accurate data on the location of machinery and plants, but also on situational awareness, simulations and event triggers (Wolfer et al., 2017; Balafoutis et al., 2017).

The paper presents the development of an intelligent cloud-based precision farming management system called smart farming. It is designed to automate decision-making processes for management of crop production enterprises using precision farming technologies. The system includes a number of smart services that make it possible to automate collective decision-making processes in farms, primarily in terms of continuous monitoring of crops and operational management of certified workers and expensive precise farming machines and equipment, as well as calculating economical aspects in real time. During development, the system is designed not as a one monolithic solution, but as an open multi-agent platform and an ecosystem of smart services employing models and methods of collective decision making based on formalisation of domain knowledge for agriculture.

In this regard, the paper highlights new interesting opportunities that can help transform the proposed system into a national digital multi-agent platform and an ecosystem of smart services suitable for a wider range of consumers, including state authorities, universities, suppliers of fertilisers and plant protection products, technology companies, startups and end users.

This approach corresponds to the emerging new trend of Industry 5.0 and Society 5.0, which is continuously replace Industry 4.0. In works (Kagermann, 2015; Industry 4.0: Building the Digital Enterprise, 2016), Industry 4.0 is defines as “an umbrella term used to describe a group of connected technological advances that provide a foundation for increased digitisation of the business environment”. This point is consistent with McKinsey, which describes Industry 4.0 as “the next phase in the digitisation of the manufacturing sector, driven by four disruptions: the astonishing rise in data volumes, computational power, and connectivity, especially new low-power wide-area networks; the emergence of analytics and business-intelligence capabilities; new forms of human-machine interaction such as touch interfaces and augmented-reality systems; and improvements in transferring digital instructions to the physical world, such as advanced robotics and 3-D printing” (McKinsey, 2015).

New concept of Industry 5.0/Society 5.0 means AI-technologies to penetrate everyday life and their symbiosis to widen the human possibilities. Unlike to Industry 4.0, Society 5.0 is not limited with industrial sector, but also solves social impacts by integration of physical and digital realities. Actually, Society 5.0 is a society, which intakes information technologies, internet of things, robotics, AI, VR/AR in industrial, healthcare and other fields to increase life quality and progress. Society 5.0

focuses heavily on the public impact of technology and on the need to create a better society (Deguchi et al., 2020; MachineDesign, 2022).

The concept of Society 5.0 through the use of methods and means of domain knowledge formalisation and collective artificial intelligence, accelerates the transition from centralised to distributed network structures, from multi-level hierarchies to self-organisation, from top-down orders to coordinated decision–making, from fixed payments to result-based payments, etc. Besides, the motivation and full use of talents, knowledge and skills of people is also very important in this system (Skobelev and Borovik, 2017).

The paper has the following organisation. The introduction substantiates the relevance of development of a smart cloud-based system for management of precision farming. The second section sets the task of developing a multi-agent platform for automating decision-making processes in farms. The third section provides an overview of smart precision farming products available on the market. The fourth section describes the functions and architecture of the smart farming solution, as well as the services implemented in it. The fifth section presents a virtual 'round table' of agents of smart ecosystem services for making coordinated decisions in the field of precision agriculture. The sixth section substantiates the need to use the domain ontology-driven knowledge base for decision making support (intellectualisation) of plant management farms. The seventh section describes the development and application of a smart digital twin of plants for predicting crop yield. The eighth section suggests possible ways of developing the smart farming cloud-based precision farming management system into an ecosystem of smart services on a national scale. The ninth section discusses advantages of using the smart farming system as compared to the existing systems. Tenth section focuses directions for its further development.

2 Problem statement

Currently, the classical farming traditions are facing new challanges due to the following reasons:

- global climate changes and the resulting lack of moisture, soil erosion, insect migration, etc.
- outdated knowledge and appearing new equipment and technologies
- increasing uncertainty and turbulence of supply and demand in the market
- fewer land areas suitable for crop production
- decreasing number of labour resources in agriculture
- growing requirements for environmental friendliness of products, reduction of carbon emissions, etc.

Under these conditions, agriculture needs to become smarter and more accurate and precise, adaptive to climate change, cost-efficient, reliable and environmentally friendly.

For effective management of farms, it is necessary to take into account the following factors:

1 Plant cultivation is an *adaptive process* that requires smart, fast and flexible response to unforeseen events in real time. At the same time, strategic and tactical work plans of the farm can change many times during the season based on available capacities (financial resources, machinery fleet, workers' qualifications, etc.).

2 Technology is a set of standard, proven *knowledge-based operations* that have developed from experience, expert knowledge, scientific research, etc. Technology also includes recommended ways of responding to unforeseen events. Knowledge about the effectiveness of operations is constantly modified, replenished and accumulated. It is necessary to collect and formalise new knowledge and react promptly to a particular situation, therefore, rigid programming of actions based on even the most advanced technology is not practical, because in case of possible changes, it will lose its relevance for farms situations.

3 The main *limiting factors* in crop development and application of technologies in different regions are moisture, minerals (soil composition), crop variety, varieties of precursor crops, and weather conditions. Users can set up an initial profile for certain crops and then form a refined one. The system must prompt which components and in what quantity are required, as well as how the crops will develop in different conditions.

4 For each specific field, it is important to have *as much information as possible* about the chemical balance of soil, which shows how many elements were obtained by the culture (moisture, minerals – from fertilisers) and how much was spent. Then a soil model can be built based on such data.

5 An important goal of any precision farming management system is not only to collect a sufficient sample of data but to provide analytics to further understand and draw conclusions about why the expected result was not obtained, or what measures have led to a better result than expected: the timing of their implementation, effect, or context (weather, culture, variety in relation to the stage of plant development). The most important thing is to ensure the process of *collective and coordinated decision making* on farm resource management in a team of managers, agronomists, machine operators, economists and other specialists.

6 It is necessary to compare the technologies used for different fields in order to understand their distinctive features, analyse the reaction to emerging events and the final result. Accumulation of such information about processes and facts of activity is necessary to perform analytics and build *a knowledge base*, which is very important for all farms.

7 It is necessary to automate the process of managing the work of machine operators in agriculture so that the *system can make plans for the use of workers and machinery*, visualise and monitor the results of each team of machine operators. At the same time, it is necessary not only to take into account the movements and location of the machinery, but also to fix the duration and many parameters of separate stages of operations.

8 Based on the collected information, it is possible to see deviations from the average values, taking into account the types of work and field areas, and evaluate positive results *to motivate employees* to increase labour productivity and business efficiency.

Planning in crop production has a number of specific features, since it is necessary to fully take into account the following factors:

- Biological – biological cycles of production, protection of flora, quarantine rules, agro-climatic conditions, requirements for different species and varieties, etc.
- Technological – in agriculture, technologies are extremely differentiated and diversified. They depend on natural and economic conditions, technical infrastructure of production, financial capabilities of the manufacturer. Technology options require thorough expertise and analysis of their economic efficiency. Technological maps and resource consumption standards developed on their basis are a reliable tool for such an assessment.
- Technical, due to the need for a wide range of technical means in agriculture. Most of them are used for a limited period of time. Technical means are often not unified. Moreover, operational, consumable and expendable materials, as well as spare parts are not interchangeable. Therefore, the cost of machinery is relatively high.
- Ecological – the environment is an integral component of agricultural production, therefore compliance with environmental safety rules is mandatory. Production processes cannot jeopardise environmental safety of a region, area, or specific landscape.
- Economic – economic efficiency of agricultural production in the world is lower than in other industries, and it is subsidised. Achieving the result is time-consuming and has a high level of risk.

Thus, plant cultivation should be methodically considered as a process of managing complex adaptive systems (Pinedo, 2016), requiring decision-making among all participants in a balance of interests (or consensus) that takes into account characteristics of soil, weather, plant varieties, availability of resources and numerous other factors.

To automate decision-making processes in farms, especially in terms of continuous monitoring of field crops and operational management of machinery, it is necessary to develop a digital cloud Internet platform that has the possibility of building up smart services to support coordinated decision making, which in turn requires methods and means of formalising knowledge about precision farming.

3 Review of smart products for precision farming

Currently, the market offers a wide range of computer systems designed to solve various tasks of precision farming.

The Canadian company Farm-At-Hand provides control systems for sowing, fertilisation and plant protection products, harvesting and other agrotechnical activities. Information about the available agricultural machinery (model, serial number, purchase price, service) is stored in the smartphone. The system provides an assessment of the current state of machine park and control of all purchases (Farm at Hand, 2022).

Nevertheless system is not conceptualised as a digital platform, which could be filled with autonomous and integrated services, and does not provide decision-making for a user.

The Android application MachineryGuide, developed by the Hungarian company Afflield Ltd., is a navigation software for uniform and precise sowing or application of plant protection products in the fields. Hardware and software solutions of MachineryGuide can operate autonomously and with wireless connection (Bluetooth/WiFi), which is user-friendly and flexible (MachineryGuide, 2022).

However, this application does not include a computational model to simulate plant growth and development, and the result of this application'' calculation is not synchronised with real crop on the field, which could cause irrelevant results and forecast and could predict wrong agricultural measures.

The British company Hands Free Hectare has implemented full automation of all processes of crop cultivation: from sowing to harvesting. Machinery is controlled by technical personnel from the control room. The system also uses drones with onboard multispectral sensors (Hands Free Hectare, 2022).

In the system, crop and machinery monitoring is executed, but integration with extra services for data acquisition and analysis from UAV, field sensors, stations, hardware buses is not considered.

Online farm management system by the US company ExactFarming implements the following functions: recording the history of field cultivation and monitoring their condition (field map, vegetation index and NDVI maps, monitoring the situation in real time), as well as the main accounting functions that control the costs of agricultural operations. The system is a dictionary of pests and diseases, and intakes a feature to predict abnormal weed development in the field. System is based on big data, collected from various field sensors, meteorological stations, remote sensing, UAVs within a first-party digital platform. Data collection implies computer vision, neural networks for analysis and prediction. As a result, user gets a simple and wide solution to manage agricultural measures within the fields and crop rotation (ExactFarming, 2022).

The problem is that the collected data, which includes crop state, soil and yield model is not synchronised with real crop in the field, and model of real crop is taken out of consideration. Thus, models and datasets of this system apply a so called 'digital shadow', which is suitable for crop management, but unavailable for crop state prediction and forecast.

The A-FARM solution is a universal platform consisting of a set of microservices implemented on the ATLAS framework. It is designed to deploy precision farming systems and data management within complex agricultural production systems. Based on annual statistics, report and dashboards regarding the crop cultivation are created: cultivated area, yield quality and quantity, purchases for the next season and so on (Antonopoulos et al., 2019).

However, its significant drawbacks are the platform's versatility and the lack of a knowledge base and a decision support module.

According to this brief review, all these systems collect large amounts of data and help farmers take into account and visualise the situation in the fields. However, none of these systems is focused on digitising knowledge and automating collective decision making in precision farming by experts and farmers.

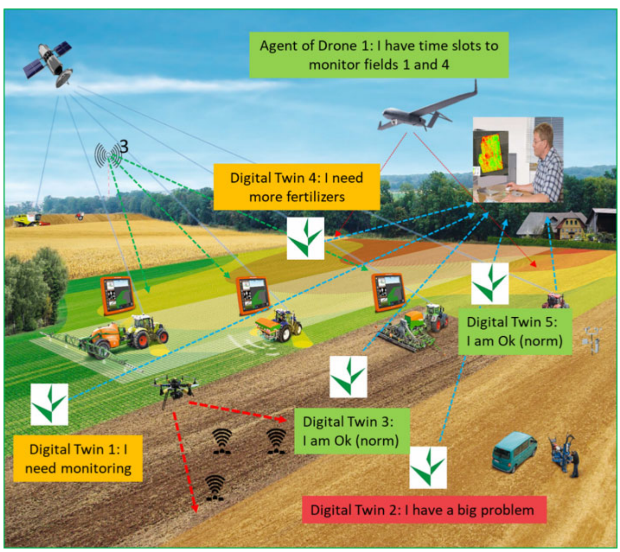
A number of new studies aimed at using ontologies and multi-agent technologies in agriculture have appeared lately (Bei et al., 2011; Pudumalar et al., 2017; Muangprathub et al., 2019). These developments represent the first prototypes designed mainly for research purposes. Basically, these systems provide recommendations regarding agricultural operations. However, none of them performs adaptive planning based on domain specific knowledge base on agriculture.

In any case, even these first prototypes demonstrate the emerging new trend of intellectualisation for decision-making processes in precision farming management.

4 Functions of the smart farming system for managing a precision farming enterprise

The developed smart farming system uses an ontology-based knowledge base for digitisation and formalisation of domain-oriented knowledge, and methods and means of automatic collective decision making based on a multi-agent technology to manage a crop production enterprise (Budaev et al., 2018). The general vision of the smart farming multi-agent system is presented in Figure 1, where software agents are responsible for every crop, every field, every piece of equipment, including a tractor or drone, fertilisers and plant protection products, etc. (Budaev et al., 2018).

Figure 1 The concept of smart farming for precision farming (see online version for colours)



The new version of the smart farming system develops results of the work (Budaev et al., 2018). Its key element is a smart digital twin of each crop, developing synchronously with the real crops in each field and able to order monitoring tools to clarify its condition and processing with machines.

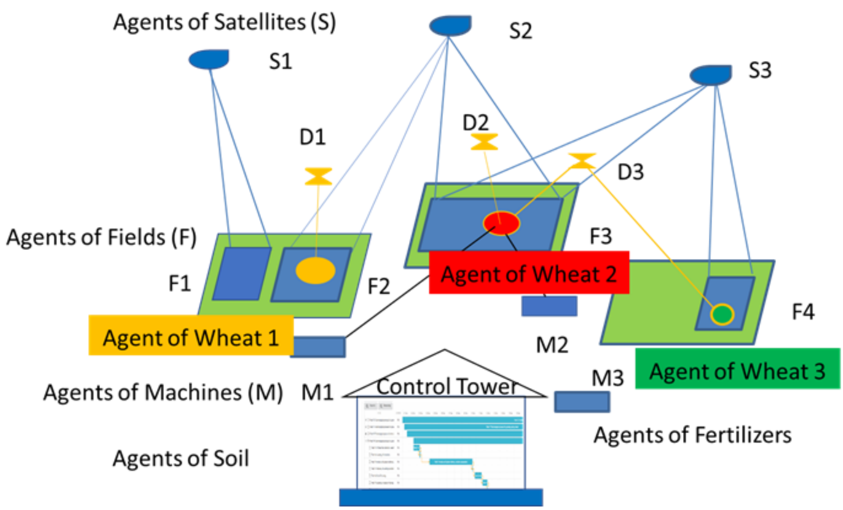
At the same time, the multi-agent platform provides a basis for interaction of smart precision farming services in each field of each enterprise. A software agent (Rzevski and Skobelev, 2014) is a small autonomous software system which relies on a knowledge base on crop production and operates in the interests and on behalf of its owner (fields, crops, machinery and equipment, employees, fertilisers, plant protection products, etc.).

Figure 2 shows a more detailed example of using multi-element technology in precision farming, explaining the concept of agent interaction.

The general logic of the system can be the following. The agent of satellite S2 recognises a problem situation event 1 (highlighted in red) in the field F3. The agent of the F3 field clarifies the information about the problem with the wheat agent (A2). The F3 Agent negotiates with the D3 drone agent. In response, the D3 Agent requests a detailed check of the situation on the F3 field. As a result of the inspection, agents of M1 and M2 machines are identified, and precision farming operations on F3 are planned for them. For example, application of more fertilisers and pesticides. Each agent is a representative of its own software service, and these services may belong to different suppliers who can compete and cooperate in the virtual market of an agricultural enterprise, differing in the quality of services, availability intervals, prices, etc.

The proposed smart farming concept corresponds to the following definition of digital ecosystems: “A digital ecosystem is a distributed, adaptive, open sociotechnical system with the properties of self-organisation, scalability and sustainability inspired by natural ecosystems… Digital ecosystem models are based on knowledge about natural ecosystems, especially with regard to aspects related to competition and cooperation between different actors” (Digital Ecosystem, 2022).

Figure 2 The concept of multi-agent precision farming (see online version for colours)



The architecture of the smart farming ecosystem includes the following basic components, which in this work are expanded via the smart digital twin of plants, compared to the paper (Skobelev et al., 2019):

1 A digital multi-agent platform is a cloud-based software environment in which software services are represented as agents – autonomous software objects capable of responding to events, planning and monitoring implementation of plans, as well as coordinating decisions based on negotiation protocols. This requires a big data warehouse for real-time analytics and forecasting, support for negotiations between agents based on the enterprise service bus, etc.

2 Ontology-driven knowledge base on precision farming – contains useful information about modern precision farming technologies, specific features of soil, crop types, necessary machinery, fertilisers, insects, diseases and treatment methods, pesticides, etc. Knowledge about the subject area is formalised using agricultural ontologies based on semantic networks (Skobelev, 2012) to automate decision-making processes among software agents and farmers, which can help identify the problem and find balanced solutions for farmers.

3 Intelligent services 'smart field', 'smart crop', 'smart fertilisers', 'smart soil', 'smart pesticides', etc. are a set of autonomous software agents representing smart services in the general semantic space of the enterprise, which will monitor the condition of their owners, make plans, form recommendations and coordinate results with other services and users.

4 The 'round table' service for agents of specialists and farmers is designed for conflict resolution – agents of smart services are organised into a virtual 'round table' for coordinated decision-making support and consulting of farmers. Agents involved in the situation that has arisen as a result of an unforeseen event must come to a new consensus, developing new solutions and rebalancing their plans, consulting with the knowledge base on precision farming. Service agents can compete and collaborate by offering different responses to the use of biotechnologies, fertilisers, pesticides, etc.

5 The smart digital twin of plant (SDTP) is an intelligent computer system that includes its own knowledge base and methods of reasoning or decision making. SDTP is also developed for online management and simulation of plant behaviour synchronously with development of a real plant.

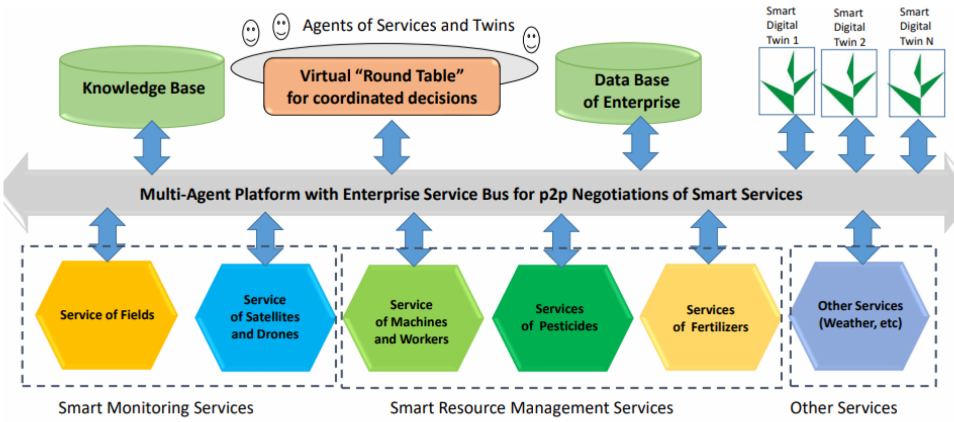
6 Smart agent of the enterprise (farmer) is responsible for the interests of an enterprise as a whole (or of the farmer). Via a tablet or mobile phone, it helps users to adequately respond to events, plan and adaptively reschedule agricultural operations, and reminds them about important stages of crop cultivation.

The purpose of the digital platform and the ecosystem of smart services is to accelerate introduction of precision farming technologies and increase the productivity of farmers' activities through timely recognition of problem situations and adaptive management of enterprise resources in close connection with plant growth and development.

Figure 3 shows the main services of the smart farming ecosystem.

The main functions of the system allow users to quickly respond to unforeseen external events, adaptively plan and replan the work of the enterprise and monitor the use of resources in real time: online knowledge base on crop production includes important information about plant crops, soils, plant protection products and fertilisers, machinery and equipment, seeds, etc. It contains proven precision farming techniques adapted to the region. This knowledge is formalised for computer processing and is used by agents to develop solutions. The information is available to users in the visual form of Wikipedia of the subject area, suitable for hypertext navigation and information search.

Figure 3 The main services of the smart farming ecosystem (see online version for colours)



Smart strategic planning of crop rotation provides adaptive strategic planning of crop rotation for the new season, creation of an end-to-end enterprise plan for the whole year, analysis of available resources in departments and risk assessment: from planning the purchase of fertilisers and repairs of machinery – to harvesting, conservation and selling of crops:

1 Smart monitoring – agents of each field not just plan and provide an image of the field for analysing the course of plant growth and development (before and after the onset of each important stage) or monitoring the results of each important operation, but also automatically identify and classify problem situations in the field and send a notification to the agronomist's cell phone about the possible type of detected problem, for example, pest attacks, sparse crops, soil compaction or excessive moisture from rains, etc. And the agronomist does not need to personally look through images of dozens of fields.

2 Smart operational planner – provides adaptive resource allocation, planning, optimisation and control in real time, including machines and workers, mobile teams of agronomists and trucks, pesticides and fertilisers.

3 Smart employees – each employee of the enterprise has an agent which builds operational plans (shift-daily tasks) for the day and adaptively changes them in accordance with unforeseen events. If necessary, tasks are rescheduled for other days, taking into account the situation.

4 Smart machinery – every important event (from pest detection to rain forecast for the next day) causes adaptive rescheduling of routes and schedules of machinery with simultaneous control of the plan compared to the real current situation for each machine in real time. Foremen and machine operators do not need to manually rearrange plans and form shift-daily tasks for each day. Moreover, the tasks themselves can change during the day in accordance with the work performed in the fields.

5 Smart finance – the agent of financial expert assesses the possible costs and revenues for each field and for each crop, identifies possible problems and suggests solutions, and further rebuilds financial profit forecasts in real time.

6 Smart maintenance – planning the repairs for machinery.

The prototype of the developed system has a web service architecture and works in all the main browsers such as Internet Explorer, Google Chrome and others. It also can be integrated via API and data transfer with other existing systems.

5 Virtual round table of agents representing smart ecosystem services

Emerging conflicts are resolved by software agents at the permanent virtual round table, exactly the way the company's specialists usually do it, seeking coordinated decisions made by consensus of all participants, taking into account their individual preferences and limitations. The virtual round table is a set of rules for coordinated decision making by service agents in case of problem situations simulating the work of specialists of a plant-growing enterprise.

The main principles of agent design are the following:

1 Each service agent is considered as a state machine. This means that the agent, as well as the multi-agent system as a whole, operates in a cycle of autonomous functioning, reacts to events, makes decisions, coordinates these decisions with other agents and achieves their implementation. Using external commands, users can initialise any service agent, request and check its status, ask it to shut down, etc.

2 The software agent is built on the basis of a generalised design setup that receives information about events from the outside world, develops solutions and coordinates these solutions with other agents.

3 The basic agent is a software object that includes a basic control unit that does not depend on the subject area, and a specialised unit for the subject area, which allows users to quickly configure the agent for any subject area, embedding meaningful models, methods and algorithms into it.

4 Each of the agents appears at the request of a new user, or of other agents of incoming tasks or other services, as well as enterprise resources. To implement the task requirements, the agent remains active until all its functions are executed. It also has internal activity, constantly strives to achieve its goal and performs all the required current tasks until the result is obtained.

As a result of the research, the following basic classes of agents have been proposed for management of a crop production enterprise (Budaev et al., 2018; Skobelev et al., 2019) (Table 1).

Table 1 Agent classes

Agent type	*Functions and goals*
Field agent	Determines the choice of the most appropriate crop for achieving field efficiency, taking into account preceding crops, soil types, relief and other factors
Crop agent	Determines the choice of the most appropriate field for the plant variety and then - the order of operations for cultivation and control of process technical maps. The crop agent also generates tasks for agents of machinery, brigades, and monitoring
Plant protection product (PPP) agent	Determines the type of plant protection products to be applied in the field. Plans technological operations for PPP application. Minimises the amount of applied pesticides
Fertiliser agent	Plans tasks from agronomist by types, order and timing of fertiliser application. Minimises the amount of applied fertiliser in accordance with the technical process
Monitoring agent	Determines the choice of satellites or drones for processing requests and possible delivery times for images, provides data on field surveys, determines field indices, identifies inhomogeneities in the fields
Agent of pests (insects) or diseases	Based on the identified inhomogeneities in the fields and related parameters (weather conditions, calendar of disease development, proximity to a forest area, etc.), the agent tries to determine the most likely pests or possible plant diseases, determines the possible PPP type for treatment or insect control
Agronomist agent	Plans crop rotation and determines crops for sowing in fields, controls the state of fields, determines technological operations for each field and plant
Team agent	Forms, coordinates and monitors plan implementation for crop processing (plan for shift-daily tasks)
Machinery agent	Generates the field processing plan, sets maintenance requirements, selects machine operators and machinery by specialisation type, minimises downtime
Machine operator agent	Plans working hours, and employment calendar as agreed with the Agronomist Agent
Staff agent (moderator)	Moderates the ‘round table’, controls indicators set by the agronomist and supports the process of plan coordination by agents

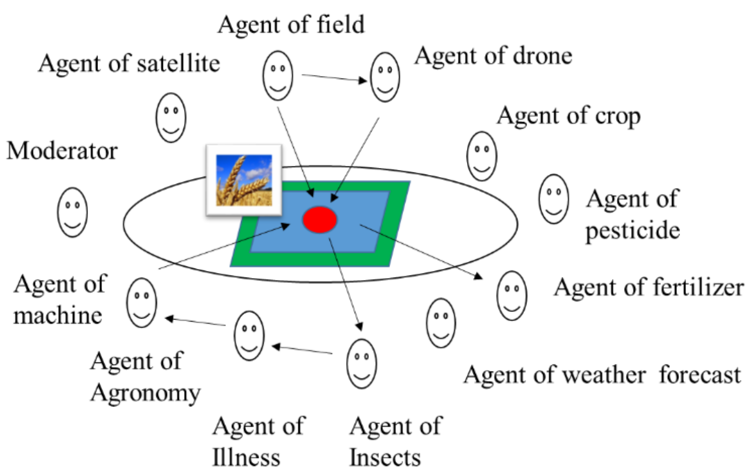
The virtual round table model assumes the possibility of creating and applying various methods and algorithms for developing and making coordinated collective decisions. At the same time, instead of real experts and specialists, software agents of agricultural services act on their behalf and in their interests. Figure 4 shows an example of a team of agents working at the virtual round table:

- The satellite agent identifies that one of the farm’s fields is has a problem situation.
- The drone agent plans an updated survey of the field.
- Agents of plant diseases and agents of harmful insects determine high probability of pests as the cause of this problem.

- The agronomist's agent plans a visit to the field to make decisions on the spot. As a result, it turns out that the reason is different – it is all due to the lack of fertilising in plants.
- The system introduces the event 'lack of plant fertilisation'. Consequently, he fertiliser agent plans application of fertilisers taking into account available or quickly delivered ones.
- Machinery agents and agents of machine operators plan new shift-daily tasks and send them to the machine operators' tablets.

Upon completion of the fertilisation process, the field is put on monitoring and control in order to track changes and achieve results.

Figure 4 Virtual round table of agents in the smart farming system (see online version for colours)



The overall architecture of the virtual round table includes the following components:

1 A knowledge base containing the main roles and rules of negotiations of service agents and other participants of the virtual round table, description of tasks and properties of cultures. All this data is needed for making agreed decisions.

2 Staff agent (enterprise agent), managing the course of negotiations, including calling the necessary agents, representatives of services, choosing negotiation rules, initialising a new round of negotiations, managing the queue of participants, working out the next move, fixing and issuing the result.

3 Agents, which are representatives of services, know the general state of their services. If necessary, they can send requests to their services to work out certain events, at the same time generating a copy of the current state of the service;

4 The scene of the round table, which hosts a formalised data model of the problem situation requiring resolution, as well as an action plan developed through negotiations, and the result of negotiations between agents to solve the problem.

The most generic method of coordinating solutions is the method of negotiations in a circle with refunds to resolve conflicts that arise when the specified general restrictions are violated (for example, the cost of investments in a season).

6 Knowledge base with ontology for precision farming

Ontologies are increasingly used for computer representation and formalisation of knowledge. In this approach, domain knowledge is separated from their coding (Domingue et al., 2011). Agents receive the necessary subject knowledge and rules for decision-making from the ontology. A detailed overview of existing ontologies for agriculture can be found in (Repository for the Plant Ontology, 2022). However, these ontologies are not fully applicable for modelling the work of an agricultural enterprise using available resources.

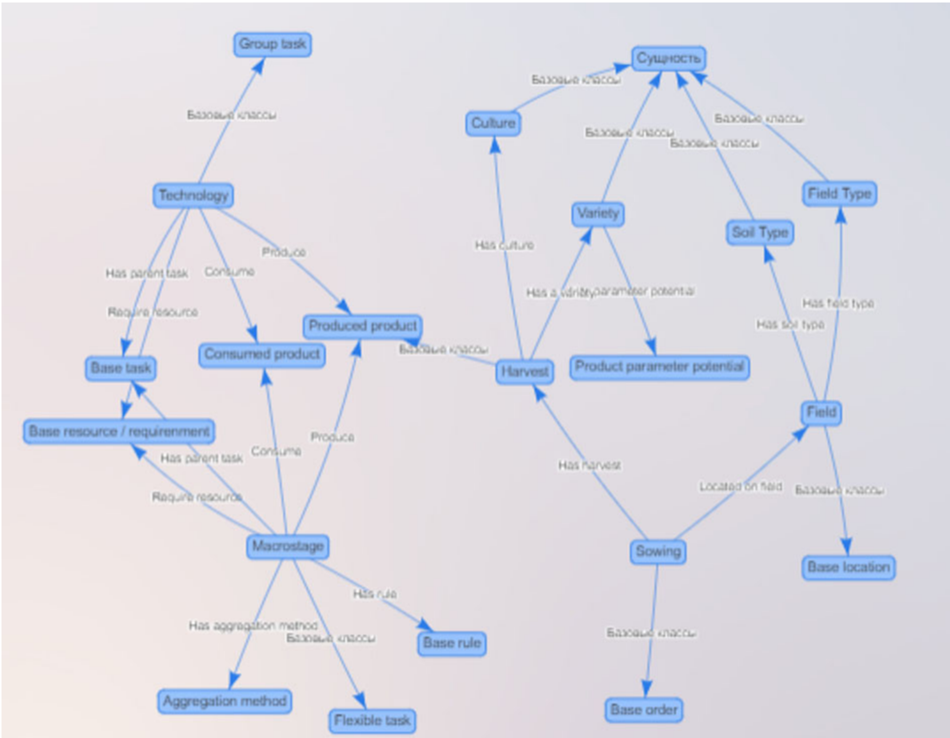
The developed ontology of precision farming of the smart farming system includes the following main classes of concepts and relations:

- classes for describing climatic conditions and weather (climatic conditions)
- classes for describing soil types and characteristics, as well as tillage systems (soil and tillage system)
- a class for describing the plant taking into account biological features of its structure (plant), as well as a class for describing a specific variety of plant (for example, wheat or rice)
- classes for describing agricultural crops (crop, variety)
- classes for describing macro stages of plant growth and development (macro stage)
- classes for describing diseases of crops and insect pests (plant pests, weeds, plant diseases)
- classes for describing plant protection products, biologics and biotechnologies (plant protection products)
- classes for describing fertilisers (fertilisers and fertiliser system)
- classes for describing agrotechnological processes of crop cultivation (cultivation technologies, technological process, sowing, field, yield)
- classes for describing farmers' competencies.

The ontology of precision farming, presented in the form of a semantic network of concepts and relations, is shown in Figure 5.

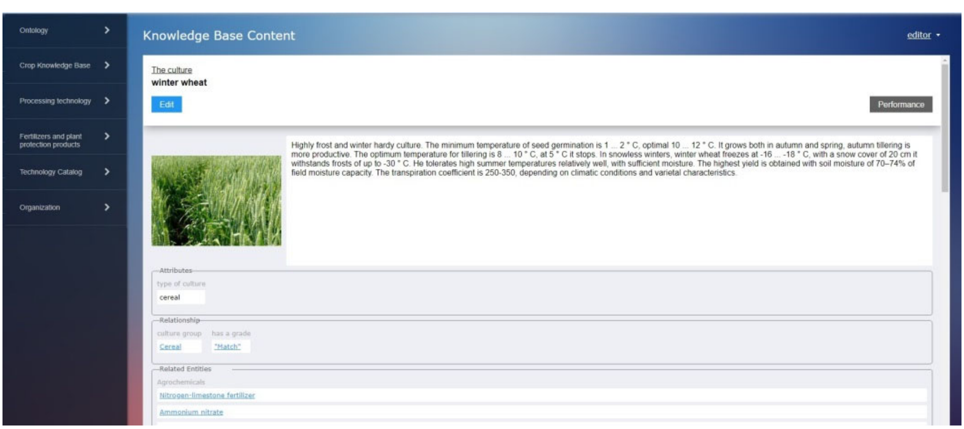
The smart farming system provides structured and related data for automatic processing. Both specialists in management of agricultural enterprises and employees of the industry can simultaneously work in it. They can input new knowledge obtained as a result of practical work in fields (varieties, crops, fertilisers, soil tillage technologies, machinery) indicating values of their attributes and relations between objects and processes).

Figure 5 Ontology of precision farming in the smart farming system



To ensure the possibility of creating a knowledge base, accessing, editing and replenishing it with new knowledge directly by end users, an ontology editor has been developed (Figure 6). It can present the knowledge base for users in the form of Wikipedia.

Figure 6 Ontology editor for the knowledge base (see online version for colours)



Using ontology, it becomes possible to create an ontological model of the enterprise with specification of available resources, problem situations, plans and schedules of daily operations, which can be loaded into a unified multi-agent system to support negotiations and conflict resolution.

7 Smart digital twin of plant

To solve the problem of predicting plant growth, a prototype of a smart digital twin of plant has been developed (Skobelev et al., 2020). This service simulates parameters of plant growth, based on the expert rules of agronomists for growing crops and data acquisition from field sensors (e.g., weather stations, soil sensors, agricultural services). Agronomists and scouts are among the data providers, while they collect man-made artefacts regarding the crop (photos, daily descriptions, etc.).

The model of plant growth and development stages is taken as the basis for designing SDTP (for example, wheat always goes through 100 zadoks growth stages, organised into ten main macro stages described in the ontology of precision farming). This model can be formalised in order to more accurately control the course of plant development by comparing the expected (average) and actual (observed) state at each step of crop cultivation in real time. If one of the stages is delayed or if reduced values of controlled parameters are observed at the end of a stage, then the forecast of plant development for the next stages should also be recalculated. Factual weather conditions also guides SDTP recalculation permanently after refreshing new data. This, in fact, will determine a possible plan for future agrotechnical activities, for example, fertilisation.

For each stage of plant growth, the SDTP creates an agent with certain parameters and requirements and provides a multi-agent environment for negotiations among agents. Based on environmental data, the SDTP calculates the duration of each stage of crop growth and forecasts yield. Environmental data includes air temperature, solar radiation, precipitation, air and soil humidity, water level, chemical composition of soil, and some others. Agrotechnical operations for growing crops are also planned with respect to changes in the parameters of the environment.

SDTP uses a method of assessing the yield and duration of plant development stages based on the concept of optimal and extreme intervals (the so called ‘tubes’) for the most important parameters of plant development, obtained during the interview of experienced agronomists. These tubes refer to the ideal (nominal) range of each parameter affecting plant development. As the first step in describing plant growth and development at different stages, we propose that output parameter (yield assess or stage duration) are linearly related from parameters inside the tube. Deviation of the input parameter of the external environment from the ideal will cause a linear (proportional) change in the yield and timing of plant stages in one way or another. If the parameter values exceed the extreme interval, then the plant usually dies, and the yield is lost. Basically, the behaviour for such conditions is described by rules, which could result not only plant death, but other special circumstances. The proposed method describes the relation between input and output parameters of the stages.

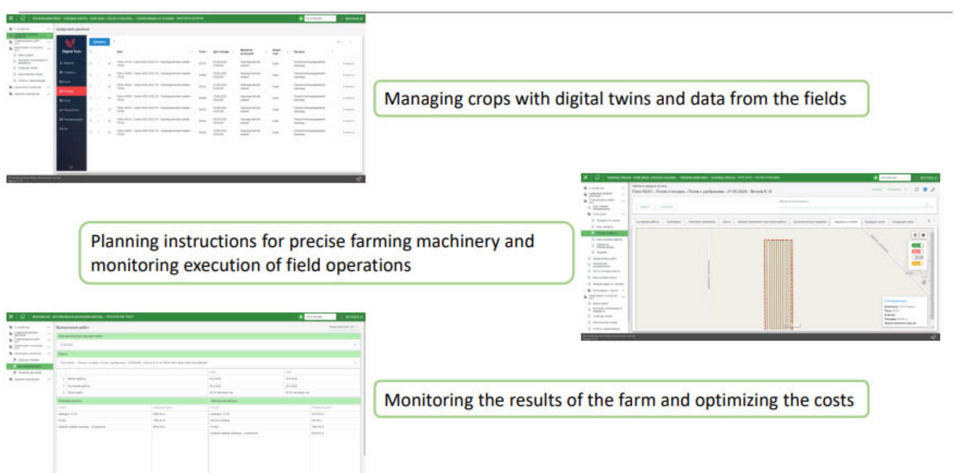
The SDTP establishes the ideal growth process of each crop for a certain variety, location and season. The system is guided by the rules of transition through plant growth and development stages in the knowledge base in the case when yield evaluation is maximum. With any change in the initial data, the SDTP adaptively recalculates parameters of plant growth stages in real time. And deviation of parameters from the ideal process leads to yield losses. In order to bring the growth process closer to the ideal and increase yield, the SDTP offers recommendations, for example, application of fertilisers with a certain dosage on exact timing, calculated based on growth stage and environmental conditions.

The SDTP also has a simulation mode where all input data is modelled by the user to observe the yield change in case of any environmental changes. The decrease in crop yield due to unfavorable external conditions is modelled using the function of bonuses and penalties, which determines the yield drop compared to the initial estimate, which is taken as 100%.

The use of SDTP as part of the smart farming system is designed to help farmers obtain an assessment of the timing of plant growth and development stages and the yield forecast, which allows for more reasonable planning of crop cultivation operations and estimate economical effect from particular agricultural activities and the whole season. The developed prototype of SDTP was tested on the data of two real farms and showed directions for further improvement of the applied models and methods of decision making (Skobelev et al., 2020).

The interface of the digital SDTP platform in smart farming is shown on Figure 7.

Figure 7 Web interface of the digital platform (see online version for colours)



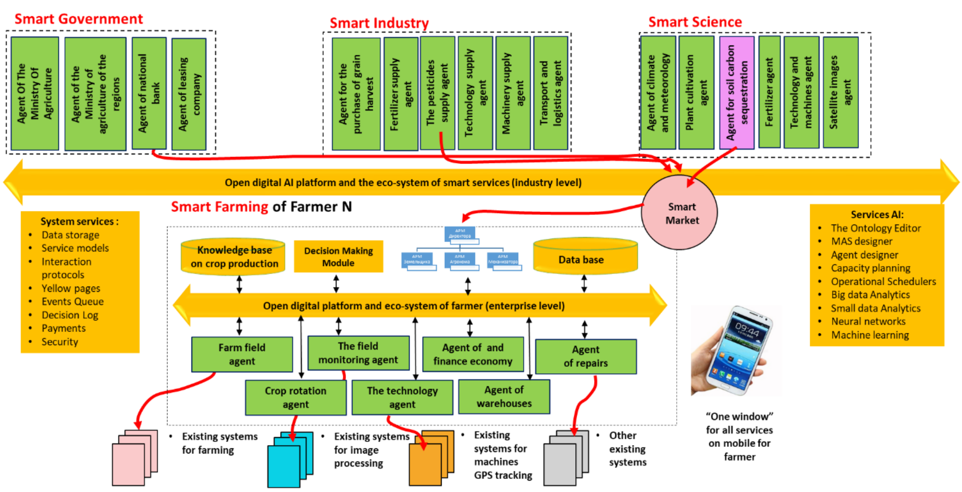
At the next stage of SDTP development, it is proposed to expand the composition of input and output parameters and dependencies between them, as well as to start daily monitoring of plant growth and development in comparison with the data of SDTP.

8 Possibility of developing a cloud-based smart farming system into a digital platform and ecosystem of smart services on a national scale

An important feature of the developed smart farming system is its openness, which allows the developers to complement smart services. This concept of openness can be extended to external developers who can supplement the system with their services, following the general protocols of interaction built on the basis of a virtual round table, allowing both competition and cooperation of agents of intelligent services. In this case, consumers of these services, represented by farmers, have the opportunity to choose between competing services in the system's virtual market, paying for them according to the subscription model or the final result.

Development of this idea has led to expansion of the smart farming concept for possible application to the entire industry in case of success for various farmers as an inter-cloud platform (InterCloud, 2022) for wheat, which will allow for combining various services that are already available to farmers as cloud-based into a 'one stop shop' (Figure 8).

Figure 8 National-se multi-agent platform and ecosystem of smart services for precision farming (see online version for colours)



In addition, the main possible benefit is that the platform's extensibility allows users to create a win-win situation for a number of full-fledged participants. Possible applications for different types of customers and users are explained below:

1 state authorities will be able to plan and stimulate production of certain types of agricultural products in regions (for example, durum wheat)

2 grain buyers – large corporations that process agricultural products for food production (in this case, from wheat), which will be able to observe the process of plant growth and development in the supplier's fields

3 scientific institutes that are engaged in grain breeding will be able to remotely accompany crops, issuing recommendations, and accumulate data for processing at the end of each season in different regions;

4 suppliers of fertilisers and plant protection products will be able to receive information about how plant crops are developing in each field when using their products and offer their consulting services and result-based payment

5 suppliers of machinery and mechanisms will be able to receive timely data on planning and operation of their machines, assemblies and aggregates in real time and also offer their consulting services

6 bread buyers will be able to see the environmental friendliness of products, as well as choose and consume those products that meet their requirements

7 elevators, transport companies and others will be able to receive requests for their services in advance and in real time.

Thus, on the basis of the platform, it becomes possible to ensure more productive and efficient work not only within precision farming enterprises, but also at the industry level, reducing transaction costs tenfold. The prospect of developing such a platform is associated with introduction of automatic smart contracts based on blockchain technologies for guaranteed payment settlement among all participants.

9 Results and discussion

Knowledge in precision farming is usually accumulated for a long time and is got experimentally, taking into account the features of each farm. The knowledge and best practices of advanced farmers need to be spread among users to assist daily crop management with decision making. In recent years, research in this area has become especially relevant.

At the Taiwan Agricultural Research Institute under the State Council of Agriculture, under the smart agriculture R&D program to combine natural and artificial intelligence, Digital Twin Solutions for Smart Farming is being developed to accumulate farmers' experience and provide real-time smart, adaptive and dynamic management and decision making (Digital Twin Solutions for Smart Farming, 2022).

Teng (2021) analyses the impact of advanced crop technologies on food security in the 21st century in the context of Industry 4.0. Intelligent systems for farm management, including IoT systems with sensors and devices for collecting data on the environment and plant development, decision support software based on big data analytics, digitalisation of knowledge is critical to empower small farmers for obtainment of timely information about crop state and the necessary terms.

Mikhailov et al. (2021) propose a comprehensive system for precision farming, which includes digital platforms, artificial intelligence programs, feedback sensors, tools for the preparation and precise balanced fertilising, plant protection at the exact time, in the exact location and in the required quantities.

The described smart farming solution is actually a digital ecosystem of intelligent services using knowledge bases and multi-agent technologies. In the proposed concept, precision farming is considered as a complex adaptive system with a high level of uncertainty and dynamics. The following distinctive features of the smart farming system can be distinguished in comparison with the solutions discussed above:

1 smart farming system is a complex scientific and technical solution for creating models, methods and a multi-service platform for coordinated network planning and real-time management of agricultural farm resources based on multi-agent technologies and domain-specific ontology

2 smart farming system uses a service of digital twin of plants and knowledge base of crop cultivation, designed to create, edit, store, provide access to information related to the agricultural products.

Expected results from development and application of the system are as follows:

1 accelerated introduction of precision farming technologies to improve environmental friendliness of production and reduce soil erosion, increase the efficiency of farms, etc.

2 increased efficiency of agricultural enterprises by increasing yields in farms and reducing costs

3 reduced complexity and labour intensity of solving the problem of managing the crop production enterprise that is implementing precision farming

4 automated decision-making processes for identifying problem situations, choosing problem-solving scenarios, planning and using resources

5 accumulation, systematisation, formalisation, mutual linking and integration of knowledge necessary for making high-quality and efficient decisions within the crop cultivation business

6 increased operational responsiveness, flexibility and efficiency in decision making

7 reduced reaction time from identifying the problem to making the required decisions and resolving the problem

8 accurate calculation and visualisation of the enterprise economy in real time regarding fields, crops, machinery, etc.

9 advanced forecast of the situation development to identify problems and risks

10 reduced dependence on the human factor in decision making

11 the possibility of business development without increasing the number of management personnel.

In addition, the proposed concept is developing up to the level of a national multi-agent platform and ecosystem of smart precision farming services with a significant expansion in the number of its possible participants.

The developed ecosystem also shows advantages for all participants of such a platform and the possibility of a drastic reduction in transaction costs in the industry, as well as the prospects for its technological development.

10 Conclusions

This paper develops the previously proposed concept of a smart farming ecosystem for precision farming enterprises with a wide and expandable range of AI services such as digital twins of plants and other decision-support solutions.

A comprehensive market analysis shows that various smart AI services for precision farming application are available, but a novel purpose of plant simulation, which allows to predict crop state and effect of field operations, haven't discussed before the current research.

In this paper, a previously proposed concept of a smart farming ecosystem for precision farming enterprises is further developed. Proposed ecosystem could be enlarged with a wide and flexible range of AI services such as digital twins of plants and other decision-support solutions. An architecture of the ecosystem applies various AI autonomous services, which are proposed for resource planning and decision making and based on multi-agent ontology-based technologies.

The possible application of the smart farming ecosystem is described in the paper, and includes governmental, public, research and commercial consumers.

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