The article discusses the means and directions for improving the results of simulation modeling of suburban agriculture and, as a result, the creation of digital twins of farms. Most innovative technologies are still considered new areas for experimentation in agriculture. However, the digital twins being developed for agriculture implement many of the ideas that have already been tested in other industries. The article presents an optimization problem that allows the simulation of suburban agriculture to provide the city with fresh products. Particular attention is paid to modeling the sustainable development of suburban agriculture and the characterization of related data. At the same time, one of the biggest challenges is the need to constantly collect and update expanding data about the object in order to create digital twins. The result of the study is the construction of a simulation modeling system that forms digital twins of suburban crop and livestock production, and the determination of priorities for the selection of relevant data. In order to determine the conditions for realizing opportunities in the transition from suburban farming simulation to digital twins, a general modeling system is presented, consisting of simulation and optimization models, and a set of metrics is selected for the constant collection and updating of the digital twin. The created simulation model was previously worked out by running dozens of different options in the form of sets of initial data, and as a result of the model's operation, the article presents the best (optimal) responses. The necessary steps for the realization of this transition are defined. As a result of the activity of the proposed conceptual system, real-time information, and analytics allows to optimize the performance of the farm

Keywords: simulation modeling, suburban agriculture, digital twins, updated data, virtual analog

UDC 631.1, 631.6
DOI: 10.15587/1729-4061.2023.273975

OPPORTUNITIES AND PERSPECTIVES OF THE DIGITAL TWINS' CONCEPTION: THE CASE IN AGRICULTURE

Fuad Ibrahimov
Researcher
Public Association "Center for Socio-Economic and Environmental Research"
H. Javid ave., 25, Baku, Azerbaijan, AZ 1073
E-mail: fuad.ibrahimov@fmg.az
Ulviyya Rzayeva
Corresponding author
PhD on Mathematics, Associated Professor*
Rasul Balayev
D.Sc on Economics, Professor*
*Department of Digital Technologies and Applied Informatics
Azerbaijan State University of Economics (UNEC)
Istiglyaliyat str., 6, Baku, Azerbaijan, AZ 1001

Received date 23.11.2022
Accepted date 13.02.2023
Published date 28.02.2023

***How to Cite:** Ibrahimov, F., Rzayeva, U., Balayev, R. (2023). Opportunities and perspectives of the digital twins' conception: the case in agriculture. Eastern-European Journal of Enterprise Technologies, 1 (13 (121)), 102–112. doi: https://doi.org/10.15587/1729-4061.2023.273975*

1. Introduction

Agriculture is a complex, dynamic system covering the processes of production, exchange, distribution, and consumption. In agriculture, production processes have a number of important features, such as dependence on natural and climatic conditions, diseases, pests, soil conditions, etc. In addition, farmers should carefully consider the best way to address potential risks. As a result, farms must aim for maximum efficiency, meet high-quality standards and environmental guidelines, and adapt to rapidly changing market conditions.

In the context of environmental awareness, strict regulations, and high production costs, the introduction of new technologies for suburban agriculture is very relevant today. The use of the so-called "digital twin for agriculture" provides easy access to digital maps of suburban farms. In turn, this opens up a whole world of possibilities. In addition, users can identify early signs of stress in large areas, create accurate, ready-to-use maps of pests, weeds, and soil conditions, and follow the progress of all processes in real-time.

Considering digital twins primarily as a concept rather than a technology is believed to be an acceptable approach in terms of evaluating the capabilities of the underlying digital technologies [1]. A digital twin is a computer model that is a virtual analog of a real process (object), a dynamic connection between digital reality and the physical world. Digital twins can reproduce the main characteristics of an object even under very different conditions [2]. Digital twins consist of an object model, an expanding object data set, a means of dynamically updating or adapting the model to data, and expanding the scope of the characteristics under discussion, are targeting to reduce the cost of complex experiments by more accurate reproduction of physical reality and informing about dangerous situations that may directly threaten the environment and people [3].

Digital twinning is the process of creating the digital equivalent of physical objects [4] and almost all digital technologies can be used in this process. The technologies discussed allow the control of physical objects at a previously impossible level [5].

The efficiency of agricultural production from a technological point of view depends on many factors: the progressiveness of the technologies and technological processes used the rationality of the choice of technical means, and the optimal use of available production resources.

Simulation is chronologically one of the foundations and nowadays is an important part of the concept of digital twins in agriculture [6]. Of course, the concept of digital twins should be viewed from a broader perspective than simulation. If simulation allows predicting an event that will happen, then digital twins allow observing the implementation of this prediction in real-time [7].

The main difficulty in building and analyzing a simulation model for the formation of a digital twin is associated with the stochastic nature of the functioning of an agricultural enterprise. The cumulative impact of various non-linear dynamic factors and their random nature affect the degree of uncertainty of the main agricultural parameters, which must be taken into account in the simulation model and product strategy as a whole.

Digital twins, being digital copies of the real world, remain relevant due to the constant flow of data. In other words, the transition to digital twins will increase the ability to adapt simulations to a changing environment. Most likely, this will happen thanks to aggregated digital twins, which involve the coverage of all digital twins and their real prototypes, as we collect and exchange data in real-time.

Scientific research in this area proves that digital technologies can further increase labor productivity in agriculture, and optimize the use of land and water resources. An effective assistant in solving these problems is digital twins developed on the basis of complex simulation models of agricultural objects. The relevance of the topic under study is justified by the fact that the digital twin of a farm is actually a virtual model of a physical object that covers the life cycle of an object and uses real-time data to model behavior and monitor operations in the future. The digital twin can replicate the operation of many real-life items and operations, from single pieces of equipment on a farm to supply chain optimization. Digital twin technology allows us to monitor the operation of a real object, identify potential flaws and make more informed decisions about processes, procedures, and life cycles. Digital twin simulation models run through hundreds of options with different inputs to find the most favorable outcome and make the decision that leads to it.

2. Literature review and problem statement

The paper [8] focuses on the fact that the creation of digital agricultural twins in itself requires complex mathematical calculations: here each of the elements is not complicated in itself, but their uninterrupted coordinated interaction is important both in normal and extreme conditions. However, the authors are more focused on the virtual model than on physical products. When developing a digital twin, it is necessary to take into account a comprehensive analysis of the physical product, because one of its most important tasks is to prevent problems even before the start of operation. This should be taken into account when developing a digital twin because one of its most important tasks is to prevent problems even before the start of operation. The studies carried out in the article [9] show how investigations in the field of suburban (urban) agriculture are expanding from year to year.

The paper conducted a bibliometric analysis and presented a way to visualize changes in knowledge about urban agriculture. The authors confirm the need for a transition to technological innovation to achieve sustainable development. However, they do not provide specific measures to increase the level of sustainable development of the food system, fully considering the sustainability, resilience, and versatility of urban agriculture. Article [10] explores various aspects of innovative development, focusing on vertical farming (VF). At the same time, the authors do not convincingly enough discuss the reasons why serious scientific studies of the potential of VF are currently lacking. Article [11] considers ecology, food security, gender, and efficient use of resources that affect urban agriculture, using examples taken from East Asia, South America, and East Africa. The work describes innovative systems, including organoponics and simplified soilless cultures.

However, the work is only review material without a predictive model. Research [12] considers the innovative approach to building a suburban farm as a response of the agricultural division to the desire to develop civilian agriculture. The essence of the article is reduced to the construction of residential areas, originally designed to include working farms. Despite the innovative approach, these criteria for the value creation of civilian agriculture are not suitable for implementation in developing countries. Article [13] points to the same aspects, revealing the value of urban agriculture (UA). The authors point to the UA concept as a strategic means to achieve sustainable urban food security at present and in the future. Of particular interest is the use of social remnants (abandoned land, unused roofs, plastic and wooden containers, etc.) in the means of production. However, the article lacks a specific model tool to present UA as an important platform for community participation and sustainability to improve food security. Article [14] also focuses on urban and peri-urban agriculture, considering the strategies that can bring multiple benefits and help create sustainable urban food systems in urban areas. The article focuses on acute or chronic climate change that threatens a growing population's access to essential urban services such as water, energy, and food. However, the approaches used in the article are not suitable for overcrowded cities with several tens of millions of people, and in fact, for such cities, the problem of the climate change emergency and its mitigation remains unresolved.

Article [15] examines the economic, social, and environmental benefits and opportunities of agriculture close to urban settlements in Gothenburg, Sweden. As a rule, rapid urbanization and global restructuring of agriculture on various scales become a threat to the survival of peri-urban agriculture. Based on the authors' statistical and spatial analysis of land-use change and interviews with farmers and authorities, the processes and drivers of local agricultural change are analyzed. The obtained results are presented, shedding light on the theory of agricultural localization. However, the solution to this problem is not connected with the use of innovative technologies in such a developed country as Sweden. On the contrary, article [16] interprets farm survival in terms of applying innovative adaptation and investment to take advantage of the characteristics of the suburban environment. The results of the study are based on interviews with 21 suburban Southern Ontario farmers using data sources such as farmer mental maps, interview transcripts, and questionnaires. Protecting a sustainable and efficient agricultural sector requires technical, technological, and innovative changes, but the indicators of improvements based on the application of new technologies are not given in the article.

As it is mentioned in [17] thanks to the creation of new technologies in agriculture, entrepreneurs will be able to more preventively and accurately calculate the parameters of farming, the use of growing technologies, feeding, breeding, and fertilizing. In addition, the digital twins will act as intelligent agriculture assistants and help the agricultural producer plan its activities.

As stated above, digital twins can significantly expand the necessary management capabilities, allowing them to separate of the physical and informational aspects of farm management, creating a virtual prototype of a real agricultural enterprise, the meaning of which is to collect, analyze, and use already processed digital information. However, the introduction of digital twins in farm management has a number of key features. These features include the construction of a model of localization and specialization of suburban agricultural production, to which a system of indicators should be applied. These indicators characterize the use of important factors of agricultural production – sources of feed and energy resources, labor costs, fertilizers, and transportation, as well as indicators of demand for and supply of agricultural products of suburban farms.

3. The aim and objectives of the study

The aim of the study is to evaluate the possibilities of transition from simulation modeling to digital twins of suburban agriculture.

To achieve this aim, the following objectives are accomplished:

– to develop a conceptual model for the implementation of the "digital twins" technology for suburban agriculture enterprises taking into account the agglomeration effect (i.e. additional potential benefits from the proximity of the city);

– to present a mathematical description of the structure of suburban agricultural production in the form of a simulation model demonstrating the operation of agglomeration, and an optimization problem, in which the objective function assumes the maximization of an agricultural product;

– to present an implementation model for the digital twin using statistical data.

4. Materials and methods

The suburban area of the city of Baku, limited by the Absheron Peninsula, was taken as the object of study. The main hypothesis of this work is to consider the prospects from an economic point of view of the digital transformation of suburban farming and the creation of a digital twin to increase productivity in agriculture and optimize the use of resources. Research assumptions are based on the possibility of creating a digital twin of a farm in the logic of evaluating the results in the transition from simulation modeling to digital twins of suburban agriculture. A solution to the problem of choosing the best version of a simulation model from a finite set of options is proposed.

Although the approach to the possibilities of simulating suburban farming is simplified in nature and spatial characteristics, it is justified from a practical point of view. There are many factors that need to be modeled and they are varied. In this regard, the main emphasis was placed on updating the issues of suburban farming and the implementation of the proposed principles and methods in specific practical conditions.

The advantages of the proposed model for constructing a digital twin are due to the fact that it allows significantly simplify the mathematical construction with a sufficiently detailed consideration of farm objects, which is associated with the following circumstances. First, the factors that determine the level of agricultural suitability of territories are not taken into account in the model, but at the preliminary stage of simulation. Secondly, the dimension of the problem is reduced due to the fact that the system of ranks of labor resources, technical means, etc., and their relative positions also refer to the array of initial information of the simulation and optimization processes. Thirdly, with such a formulation, it is not required to reflect the links imposed by existing farm objects and territorial management structures, since they are also taken into account when developing a simulation model.

The methodology is represented by the development of a conceptual apparatus focused on the creation of a new prototype, as a kind of entity within a symbolic platform for implementation ("symbolic" because of the "digital twins" concept as a physical embodiment, especially in the field of suburban agriculture, does not exist in Azerbaijan).

The model of localization and specialization of suburban agricultural production should consider the input sources of feed and energy resources (with special mention of the big city's food and heat "waste"), as well as the levels of processing of agricultural products. Also, when updating and supplementing the information base of the proposed model, the possibilities of using monitoring data collected in the database of digital technologies, as well as in monitoring the state of compliance with sanitary and hygienic requirements of suburban agricultural production, should be considered. When describing the conditions for implementing the opportunities for the transition from suburban agriculture simulation to digital twins, the characteristics of urban and suburban agriculture that need to be simulated should be presented. To this end, it is necessary to create a system of simulation modeling of agricultural development in urban areas [18]. For the purpose of simulation modeling the agricultural production, it is necessary to describe the model of localization and specialization of suburban agricultural production, that is, the model for optimizing the structure of the suburban economy [19].

The case study is carried out within the framework of farms operating on the Absheron peninsula in Azerbaijan, with the consideration of two options for predicting digital twins within the proposed optimization problem.

The factual information on the topic is the data collected as a result of a survey of farmers in Absheron. Surveys consist of a list of multiple-choice questions or ratings that were asked in person or through online questionnaires.

The case considered in the article represents a conceptual framework for designing and implementing digital twins in managing a suburban farm. The development of a massive reference model that implements the concept of digital twins is not the purpose of this article. The control model is a task of optimizing stage processes, the state of each phase is characterized by a relatively large number of variables, taking into account the specifics of the study area. To assess the applicability of the presented scheme in the context of smart agriculture, an approach based on real statistical data is used.

The system-dynamic model is tested on the basis of current statistical indicators of real farms operating in Absheron, considering two options for predicting digital twins within the proposed optimization problem. The model is implemented with the support of the MATHCAD package of mathematical applications.

5. Results of research presenting opportunities and perspectives of the digital twins' conception

5. 1. A conceptual model for the implementation of the "digital twins" technology for suburban agriculture enterprises

A distinctive feature of suburban farms in Absheron is economic and social heterogeneity. Large high-commodity farms coexist there with small peasant farms. However, small peasant farms are far from homogeneous. Those that are engaged in commodity production supply surplus products to food markets and receive their share of the benefits from expanding market demand for new high-yield agricultural products. But many others are subsistence farming, largely because of insufficient assets and unfavorable external conditions. Consuming the bulk of the food produced, they enter the market as buyers of food and sellers of labor. Belonging to a particular group is determined not only by the presence of assets but also by gender, ethnicity, and social status since all this implies an unequal ability to use the same assets and resources in response to opportunities. The illiteracy of farmers also plays a detrimental role, when in the age of information technology, agricultural workers often make the necessary measurements and forecasts "by eye". Another problem for local farmers is that all records in the agricultural industry are still made by hand, they are entered into the granary books. Such data cannot be stored, their array cannot be analyzed, and consequently, forecasts are inaccurate. To ensure that cereals, grains, fruits, vegetables, and other crops bring income to large and small farms, and not losses, accurate calculations are needed. It should also be noted that in Azerbaijan, the size of farms is measured in hundreds of hectares, and in order to manage them as efficiently as possible, the use of a digital twin is becoming an important aspect of doing business. The development of digital farming in Azerbaijan requires full coverage of agricultural areas with data transmission networks, as well as the training of subject-oriented specialists. One of the key barriers to digitalization in the agro-industrial complex is the lack of specialists in the agro-industrial complex with digital knowledge, the lack of standards in the field of the Internet of things, as well as administrative difficulties – for example, permission to fly drones.

To modernize the industry, the creation of digital twins (a mathematical model that accurately describes an object) of fields or farmlands allows one to plan the time and sort of planting crops and when, the number of fertilizers to apply, controlling the acid composition of soils, and so on. In recent years, the introduction of innovative technologies in agriculture has led to adjustments in how farmers cultivate crops and fields. As a result, modern farms are benefiting greatly from digital farming technologies that are constantly evolving.

Given the above, when creating a conceptual model for creating a digital twin of a farm, the following steps should be implemented [20]:

– to define a management structure that provides full-featured integration of farm automation systems;

– to adapt digital twin technology for use at a farm facility;

– to identify innovative technologies and approaches to digitalization, taking into account modern conditions;

– to determine the feasibility of using a digital twin for various stages of the life cycle of objects.

Taking into account the specifics of the problem being solved, the digital twin is a unified integrated, constantly updated model used to optimize an enterprise's technological and business processes. The purpose of creating a digital twin is to transfer an object into a digital space, simulate a change in the state of an object under the influence of various factors and possible control actions, and determine and implement optimal control actions to achieve the target state of the object.

Schematically, the digital twin concept is shown in Fig. 1 and includes six layers:

– Layer 1. Regulatory and reference information is the foundation of the digital twin and is integrated with all its layers.

– Layer 2. Electronic design and estimate, construction and installation, execution and operation documentation include all specialized forms of accounting documentation in agriculture, presented in unified and specialized forms.

– Layer 3. Graphical representation of objects (including 3D and 2D models, cartographic geoinformation models, technological schemes, etc.) designs architectural models of objects (process equipment, buildings, and structures) in the format of computer-aided design (CAD) systems.

– Layer 4. Engineering data is presented in the form of technical characteristics that determine the properties of agricultural objects (passport data of agricultural production objects, unique characteristics of the land plot, diagnostic survey data on air humidity, physical and technological properties of the soil, etc.).

– Layer 5. A mathematical model which is a formalized mathematical description of the relationship between the input, output, and internal parameters of models. The simulation results obtained in this layer are used to predict the technical condition of equipment, and forecast and control technological processes. The layer also includes a resource economic-mathematical model that allows calculating complex indicators of production efficiency.

– Layer 6. Online data, which is a series of time data for all parameters obtained in automatic and automated mode and calculated. Their source is mainly automated control systems or mobile applications.

At the same time, the key component in creating a digital twin in accordance with the described architecture is the online data warehouse. This is a corporate base for measuring technological parameters, information about actual and simulated modes of operation, and the state of production assets.

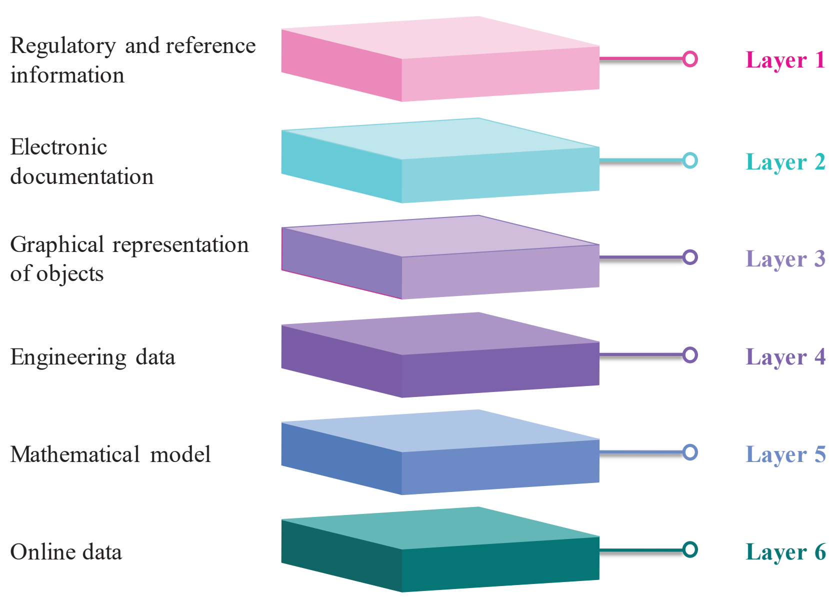

Fig. 1. Schematic representation of the digital twin concept

5. 2. A mathematical description of the structure of suburban agricultural production in the form of an optimization problem

It is believed that through modeling, simulation, and augmented reality technologies, digital twins can help create a better working environment for farmers [21].

Solutions based on digital twin modeling, including simulation, can cover the physical and virtual agricultural world at all life cycle stages to optimize operations and predict deviations (rejections) [22].

With that simulation creates new possibilities. Development options tracked through simulation models are more fully reflected in digital twins that expand the scope of intelligent systems [23].

The suburban area of Baku, taken as the object of study, is limited by the Absheron Peninsula. There are about 60 settlements, two of which are cities. Historically, fruits and vegetables are grown in the Absheron suburbs and villages, livestock breeding is also quite developed there.

We have studied changes in the transportation of fresh food to the Baku agglomeration. For this, the indicator of the "weighted average transportation distance" is proposed and the corresponding calculations are carried out [24].

A general simulation system, which consists of simulation and optimization models is presented below.

Taking into account the effect of agglomeration, the zone of transportation of fresh food products to the city was taken as an object of simulation of agricultural production. Below are some fragments of the model that serve to account for the effect of agglomeration in crop production:

$$gm_{it}=BM_{it}+bma(argt_{it}, BAM_{it})+bmg(mggt_{it}, BMG_{it}), \quad (1)$$

$$bmh_{it}=gm_{it}\cdot AS_{it}, \quad (2)$$

$$ymh_{it}=(1-YD_{it})\cdot bmh_{it}, \quad (3)$$

$$infmh_{it}=(1-\dot{I}NF_{it})\cdot ymh_{it}, \quad (4)$$

$$D_{it}=L_t\cdot \dot{I}NFT_t$$

or

$$\dot{I}NF_{it}=1/L_t\cdot D_{it}=\alpha_t\cdot D_{it}, \quad (5)$$

$$D_{it}=\beta_t\cdot MU_t, \quad (6)$$

$$infm_{it}=(1-\alpha_t\cdot\beta_t\cdot MU_t)\cdot ymh_{it}+\Delta_{it}. \quad (7)$$

Here $ASit$ (i=1,...,BS; t=1,...,IS) is an alleged planting area, BS is a number of plant species, IS is a number of periods; labor and mineral fertilizer costs in the base period are expressed accordingly BAM_{it}, BMG_{it} and their multiplication BM_{it} (i=1,...,BS; t=1,...,IS).

Performance dependency gm_{it} (i=1,..., BS; t=1,...,$\dot{I}S$) of ith plant in в tth year on labor costs $argt_{it}$ (i=1,...,BS; t=1,...,$\dot{I}S$) and volume of mineral fertilizers $mggt_{it}$ (i=1,...,BS; t=1,...,$\dot{I}S$), given to the plant, is assumed to be piecewise linearly dependent. By the way, when constructing digital twins, the assumption of piecewise linear dependence may not be necessary.

In (1) $bma(argt_{it}, BAM_{it})$ and $bmg(mggt_{it}, BMG_{it})$ represent productivity gains as a result of optimizing labor costs and the volume of mineral fertilizers supplied to the ith plant. When switching to digital twins, these allowances will be determined depending on the differences (proportions) between the actual and expected levels and the availability of quantitative resources, the level of implementation of agronomic regulations, etc.

Total volume of biological (grown) crop bmh_{it} in (2) calculated based on productivity gm_{it}. The total amount of accumulated ymh_{it} and infrastructural $infmh_{it}$ product is determined by formulas (3) and (4), respectively. Here YD_{it} is the coefficient of crop loss at harvest, and INF_{it} is the coefficient of infrastructure crop losses. According to formulas (5) and (6), the product loss coefficient D_{it} is calculated in the process of delivering products to the consumer, taking into account the factor of transportation distance MU_t. L_t is a coefficient of proportionality. Currently, it is determined as a result of correlation analysis. Cumulative value Δ_{it} is added to the right-hand side of equation (7) to account for the increase in production due to loss reduction measures.

The model of location and specialization of suburban agricultural production takes into account the input sources of feed and energy resources (with a separate mention of food and heat "waste" of the big city), the levels of processing of agricultural products, the levels of specialization of vehicles in transportation between cities and suburban farms.

The presented optimization problem, which describes the operation of a suburban farm, is the task of determining the best, in a sense, structure or values of object parameters, allowing the collection of direct and indirect indicators necessary for farm modeling.

In the problem of optimizing the structure of suburban agricultural production presented in the article, the objective function assumes the maximization of a marketable product:

$$\sum\nolimits_{j\in J_1} p_j x_j + \sum\nolimits_{j\in J_2} p_j x_j \to \max. \quad (8)$$

Let's consider a number of conditions that take into account the characteristics of the proximity of an agricultural object to the city, describing the limitations of this function:

– regarding the involved production resources of the city (labor resources, technical means, etc.):

$$\sum\nolimits_{j\in J_1} a_{ij}x_j + \sum\nolimits_{j\in K_k} a_{ij}\cdot\sum\nolimits_{k=1}^{3} x_k - x_i + \sum\nolimits_{j\in J_2} a_{ij}x_j \le b_i; \quad (9)$$

– regarding the use of urban food waste as animal feed:

$$c_j x_j - x'_j = 0, j\in J_2, \quad (10)$$

$$\sum\nolimits_{j\in J_2} \nu_j - x_i - x_{ij} \le 0, \quad (11)$$

$$d_j x'_j - x_{ij} \ge 0, i\in I_3, j\in J_2, \quad (12)$$

$$e_i x'_j - \sum x_i \le 0, i\in I_2, j\in J_2. \quad (13)$$

Here j, J are the index and the set of suburban agricultural production areas, respectively. This set consists of the following disjoint subsets: J_1 is a subset of sowing fields; J_2 is a subset of livestock plots. K is a set of agricultural products by purpose and consists of the following disjoint subsets: K_1 is a subset of personal consumer products and marketable products; K_2 is a subset of products used for feed; K_3 is a subset of seeds and products of on-farm non-productive consumption. i, I are the index and the set of production resources, respectively. The set I consists of the following disjoint subsets: I_1 is a subset of the involved production resources of the city (labor resources, technical means, etc.); I_2 is a subset of feed types; I_3 is a subset of city food waste types.

In the study, the analysis of territories using digital twins includes the following diverse information. Variables: x_j is a development intensity of j-th plot of animal husbandry; x_i is a number of involved production resources of the city; x'_j is a total need for food products of the j-th plot of animal husbandry; x_{ij} is an amount of the optimal additive of the th type of feed for the j-th plot of animal husbandry.

Fixed values: a_{ij} are special norms of resource consumption in agricultural fields. This does not include costs associated with the collection and initial processing of agricultural products; a'_{ij} are special rates of resource consumption for harvesting and initial processing of agricultural products; c_j is a coefficient of demand in units of feed per unit of measurement of the th plot of animal husbandry; υ_j is a minimum specific weight of food waste per feed ration per unit of measurement of the j-th plot of animal husbandry; d_j is a difference between the maximum and minimum specific weight of food waste in the feed ration per unit of measurement of the j-th plot of animal husbandry; e_i is a difference between the total need for feed (taken as a unit) and the sum of the minimum specific weight of certain types of feed in the diet per unit of the th plot of animal husbandry; b_i is an amount of the i-th type of resource; p_j are marketable products in the j-th plot of animal husbandry [25].

The simulation system is real, and in some cases, due to the complexity of information support, it was verified in a generally accepted and normative database [25]. Based on the presented mathematical description of the digital farm, a linear model of the future digital twin is created after collecting telemetry data from sensors. So far, it is still static and shows how the object is arranged and its elements are located in space.

5. 3. An implementation model for the digital twin using statistical data

The implementation of the conceptual model of the digital twin is a separate task since the choice of assumptions and simplifications accepted in the model is dictated by the requirements for the calculation result.

Below are the calculated data obtained as a result of solving the problem (8)–(13). The digital twin of the farm, which simulates the operation of a suburban economy depending on the parameters of the external environment, was implemented in the MATHCAD package environment with decision support based on formalized knowledge and real data. If at the output according to the data, there are changed values of the controlled parameters, then the forecast for the development of the farm should also be recalculated, which, in fact, will determine a possible plan for carrying out future agrotechnical measures.

Implementing the digital twin concept requires confidence in the simulation model, data, and model update algorithm. The results of our survey were used to determine priorities in the selection of data. Therefore, it is considered appropriate to include the influence of resource use characteristics among the factors to be modeled. In general, in order to move from modeling sustainable agricultural production in the suburbs to digital twins, it is necessary to ensure continuous collection and updating of data on the following group of indicators (the article provides indicators of key factors influencing consumer choice): the level of satisfaction of demand for fresh food by the urban population; the state of the environment and the natural resource base and the dynamics of changes; resource efficiency; competitiveness of agricultural products; relevant indicators of the quality of life of producers and consumers [26].

The data on which digital twins are based is divided into pre-collected data and data collected specifically for the creation of digital twins (Tables 1–4). Although these divisions are arbitrary, in practice it will be possible to gain new reasoning and knowledge thanks to the connections between them. The results of digital twin modeling involve a combination of a data-driven model and mathematical modeling of natural and anthropogenic processes that allow predictive control actions to select the optimal operation of the farm.

Table 1

Some parameters of the production structure optimization model of farms of Baku and the suburban Absheron-Khizi economic district [26]

Variables used	Baku	Suburban zone
1	2	3
J_1 – crop fields (potatoes, vegetables in the open field, vegetables in the closed field, cereals, gardens, grapes, fruits, etc.)	7 units	8 units
J_2 – livestock farming (cattle breeding, sheep farming, pig farming, poultry farming, etc.)	4 units	4 units
K_1 – personal consumption and commodity product	100 %	100 %
K_2 – used as feed	–	–
K_3 – seed and on-farm non-production consumption	–	0,1 %
I_1 – involved production resources of the city (labor resources, technical means, etc.)*	3 %	3.6 %
I_2 – types of fodder (green, coarse, juicy, complex fodder and mineral supplements)**	5 units	5 units
I_3 – types of urban food waste (expired food, food scraps, food industry waste)	3 units	3 units
a_{ij} – special norms of resource consumption in agricultural fields. This does not include the costs of collection and initial completion	14.0 man/hour	14.7 man/hour
a'_{ij} – special norms of resource consumption for harvesting and preliminary completion of agricultural products	6.6 man/hour	5.9 man/hour
c_j – the coefficient of demand for units of fodder per measurement unit of jth plot of animal husbandry***	n/a	n/a
υ_j – the minimum specific weight of food waste per fodder ration per unit of measurement jth plot of animal husbandry	12.0 %	10.0 %

Continuation of Table 1

1	2	3
d_j – the difference between the maximum and minimum specific weights of food waste in the fodder ration per measurement unit of j-th plot of animal husbandry	8.0 %	10.0 %
e_i – the difference between the total demand for fodder (taken as a unit) and the sum of the minimum specific weights of individual feed types in the ration per unit th plot of animal husbandry	78 %	83 %
p_j – commodity production (as a percentage of the finished product):	–	–
vegetables in the open field	90 %	90 %
vegetables in a closed area	95 %	95 %
grain	–	95 %
melon plants	90 %	90 %
fruit	90 %	90 %
grapes	90 %	90 %
potato	90 %	90 %
etc.	95 %	95 %
b_i the volume of th type of feed	8000 ha	12700 ha

*Note: * – here it is assumed that manual labor and the use of machinery are mutually substitutable;*
*** – forages: green grass; coarse grass, stubble; juicy – silica, hay, roots and fruits, garden products; complex fodder – cereal fodder, groats (bran), corn, meal, combined fodder; mineral additives – calcium, phosphorus, sodium, chlorine, magnesium, potassium;*
**** – to determine the conditional number of livestock and poultry, the number of each species of livestock and poultry should be calculated according to the following coefficients: cows – 1.0; nowt – 0.6; pigs – 0.3; sheep and goats – 0.1; birds – 0.02. It is taken into account that 4 feed units are required for one conventional head of a cow*

Table 2

Actual data of Baku and suburban Absheron-Khizi economic district farms for 2020 in natural terms

Agricultural product	Baku-	Absheron-Khizi economic district	Selling price, centner/manat	Value, manat	
				Baku	Absheron-Khizi economic district
Cultivated area, hectares					
Potato	8	36	n/a	n/a	n/a
Vegetables (open ground)	989	736	n/a	n/a	n/a
Vegetables (closed ground)	583	449	n/a	n/a	n/a
Cereals and legumes	–	5961	n/a	n/a	n/a
Melon plants	11	158	n/a	n/a	n/a
Fruits and berries	4,024	5,100	n/a	n/a	n/a
Grapes	1,308	176	n/a	n/a	n/a
Production of the main agricultural products, tons					
Potato	46	316	31.47	14476.2	99445.2
Vegetables (open ground)	89,476	120,751	19.15	17,134,654	23,123,816.5
Vegetables (closed ground)	84,879	117,382	1.00	848,790	1,173,820
Cereals and legumes	n/a	11,294	34.16	n/a	3,858,030.4
Melon plants	44	1,469	16.65	7,326	244,588.5
Fruits and berries	5,023	2,410	101.49	5,097,842.7	2,448,953.7
Grapes	15,240	970	45.97	7,005,828	445,909
Crop production, total	n/a	n/a	n/a	30,108,916.9	31,121,518.6
Production of livestock products, tons					
Meat (slaughter weight)	5,635	7,337	490.0	27,611,500	35,951,300
Milk	5,144	58,775	56.05	2,883,212	32,943,387.5
Eggs (thousands)	3,400	547,018	153.29	5,211,860	838,523,892.2
Wool (physical weight)	41	370	146.03	59,872.3	540,311
Livestock, total	n/a	n/a	n/a	35,766,444.3	907,958,890.7
Total	–	–	–	65,875,361.2	939,080,409.3

Taking into account the proximity to the city, according to the model for optimizing the structure of suburban production, options were considered to increase the production of vegetables in greenhouses by 15 % and 30 %, milk by 30 % and 40 %, eggs by 0 % and 25 %, respectively (Table 5). In the suburban Absheron-Khizi economic region, calculations were made to increase the production of vegetables on the open ground by 20 % and 35 %, milk by 30 % and 40 %, and egg production by 0 % and 15 % (Table 6).

Table 3

Actual data on the value expression and structure of production of Baku and suburban Absheron-Khizi economic district farms in 2020

Agricultural product	Value, manat		Special weight, %	
	Baku	Absheron-Khizi economic district	Baku	Absheron-Khizi economic district
Potato	14,476.2	99,445.2	0.02	0.01
Vegetables (open ground)	1,7134,654	23,123,816.5	26.0	2.46
Vegetables (closed ground)	848,790	1,173,820	1.3	0.01
Cereals and legumes	n/a	3,858,030.4	n/a	0.41
Melon plants	7326	244,588.5	0.1	0.03
Fruits and berries	5,097,842.7	2,445,909	7.7	0.26
Grapes	7,005,828	445,909	10.6	0.05
Crop production, total	30,108,916.9	31,121,518.6	45.7	3.31
Meat (slaughter weight)	27,611,500	35,951,300	41.9	3.8
Milk	2,883,212	32,943,387.5	4.4	3.5
Eggs (thousands)	5,211,860	838,523,892.2	7.9	89.3
Wool (physical weight)	59,872.3	540,311	0.1	0.1
Livestock, total	35,766,444.3	907,958,890.7	54.3	96.69
Total	65,875,361.2	939,080,409.3	100	100

Table 4

Actual data on the value expression and structure of commodity products of Baku and suburban Absheron-Khizi economic district farms in 2020

Agricultural product	Value, manat		Special weight, %	
	Baku	Absheron-Khizi economic district	Baku	Absheron-Khizi economic district
Potato	14,476.2	99,445.2	n/a	n/a
Vegetables (open ground)	17,134,654	23,123,816.5	26.0	2.5
Vegetables (closed ground)	848,790	1,173,820	1.3	n/a
Cereals and legumes	n/a	3,858,030.4	n/a	0.4
Melon plants	7326	244,588.5	0.1	n/a
Fruits and berries	5,097,842.7	2,445,909	7.7	0.3
Grapes	7,005,828	445,909	10.6	0.1
Crop production, total	30,108,916.9	31,121,518.6	45.7	3.3
Meat (slaughter weight)	27,611,500	35,951,300	41.9	3.8
Milk	2,883,212	32,943,387.5	4.4	3.5
Eggs (thousands)	5,211,860	838,523,892.2	7.9	89.3
Wool (physical weight)	59,872.3	540,311	0.1	0.1
Livestock, total	35,766,444.3	907,958,890.7	54.3	96.7
Total	65,875,361.2	939,080,409.3	100	100

Table 5

Forecast for 2025 on commodity production in Baku farms

Agricultural product	Commodity product value, manat		Commodity product structure, %	
	I variant	II variant	I variant	II variant
Potato	14476.2	14476	n/a	n/a
Vegetables (open ground)	17,134,654	17,134,654	26.0	24.4
Vegetables (closed ground)	976,109	1,060,988	1.4	1.5
Melon plants	7,326	7,326	0.1	0.1
Fruits and berries	5,097,842.7	5,097,843	7.7	7.3
Grapes	7,005,828	7,005,828	10.6	10.0
Crop production, total	30,236,236	30,321,115	45.2	43.3
Meat (slaughter weight)	27,611,500	27,611,500	41.3	39.4
Milk	3,748,176	5,651,096	5.6	8.0
Eggs (thousands)	5,211,860	6,514,825	7.8	9.2
Wool (physical weight)	59,872.3	59,872	0.1	0.1
Livestock, total	36,631,408.3	39,837,293	54.8	56.7
Total	66,867,644	70,158,408	100	100

Table 6

Forecast for 2025 on commodity production in the farms of suburban Absheron-Khizi economic district

Agricultural product	Commodity product value, manat		Commodity product value, manat	
	I variant	II variant	I variant	II variant
Potato	99,445.2	99,445	n/a	n/a
Vegetables (open ground)	27,748,580	31,217,153	2.9	2.9
Vegetables (closed ground)	1,173,820	1,173,820	n/a	n/a
Cereals and legumes	3,858,030.4	3,858,030	0.4	0.4
Melon plants	244,588.5	244,589	n/a	n/a
Fruits and berries	2,445,909	2,445,909	0.3	0.3
Grapes	445,909	445,909	0.1	0.04
Crop production, total	35,746,282	39,214,854	3.7	3.6
Meat (slaughter weight)	35,951,300	35,951,300	3.8	3.3
Milk	42,826,403.75	46,120,743	4.5	4.2
Eggs (thousands)	838,523,892.2	964,302,476	87.9	88.8
Wool (physical weight)	540,311	540,311	0.1	0.1
Livestock, total	917,841,907	1,046,914,830	96.3	96.4
Total	953,588,189	1,086,129,683	100	100

It is expected that the volume of marketable output of farms in Baku will increase by 1.5 % under the first option of calculations and by 6.5 % under the second option. The volume of marketable output for farms in the suburban Absheron-Khizi economic region will increase by 1.5 % according to the first calculation option and by 15.7 % according to the second option. It is expected that the cost of fresh vegetables, fresh milk, and eggs in the farms of both districts will not change under the first option, and under the second option, this figure will decrease by 7–10 %.

Digital twins will improve simulation results by supporting suburban farms at all stages of operation through continuous real-time monitoring [27].

By influencing the relationship between reproduction and resource consumption, digital twins can optimize performance. For this purpose, the proposed digital twin architecture [28] is suitable for suburban agriculture. According to this understanding of the digital twin, a digital farm can be considered as a set of processes for monitoring, analyzing the state, forecasting, and planning the development of a territory in order to support decisions on managing this territory.

6. Discussion of experimental results of the study of perspectives of the digital twins' conception implemented in agriculture

It is possible to talk about a whole range of solutions within the concept of digital twins from the lightest to the heaviest. The latter can already have the size of a city or a country. This article is about national digital twins in the area of suburban agriculture.

The main contribution of the manuscript is that it proposes an innovative structural conceptual model for the implementation of the project of digital twins for "smart" suburban agriculture.

The paper presents the most preferred options for the development of suburban agriculture as the results of simulation experiments. Meanwhile, the following results are also reflected:

1. The conceptual model for the implementation of the "digital twins" technology for suburban agriculture enterprises taking into account the agglomeration effect (i.e. additional potential benefits from the proximity of the city) was developed (Fig. 1). In the modern market economy, little attention is paid to the location of agricultural production due to the lack of demand from authorities for these developments (especially in developing countries), since it is assumed that the market, as a regulator of the economy, can solve this problem. In the paper, the factor of the proximity of agricultural production to the city gives a certain opportunity to use the results obtained. In previous studies, the effect of agglomeration (the factor of proximity to the city) was not taken into account.

2. A mathematical description of the structure of suburban agricultural production in the form of a simulation model was presented (1)–(7). This simulation demonstrates the work of agglomeration, and an optimization problem, in which the objective function assumes the maximization of an agricultural product (8)–(13). A model for optimizing the structure of production in suburban agriculture was implemented in order to increase production within the preferred options. The structure presented in the article is based on a mathematical model, which is further used to analyze the behavior of a digital double in practice.

3. An implementation model for the digital twin using statistical data was presented (Tables 5, 6). In agriculture, digital twins are a virtual representation of a farm with great potential to improve productivity and labor efficiency, as well as reduce energy consumption and waste. In suburban agriculture, due to the proximity of a large city, it is necessary to simulate the action of factors that create additional opportunities to reduce energy consumption and losses in this economy.

Achieving synchrony between physical and virtual twins remains a challenge in agriculture, including natural systems such as crop and livestock production. The synchronization process must work in both directions – from virtual to physical and from physical to virtual objects, which implies the creation of cyber-physical production systems. For the reliability and predictability of the operation of production systems at all stages of their life cycle, it is necessary to use a digital design environment that is capable of analyzing the performance of system components and managing their errors in real-time.

To implement the transition from suburban farming simulation to digital twins, it is necessary to have an appropriate database. The insufficiency of the system of knowledge about the delivery of the results of the application of simulation models to society should be eliminated due to the growing possibilities of the digital environment. Obviously, the analysis of territories using digital twins should include a wide variety of information: databases and maps of landscapes, water basins, transport routes, land and soil types, cadastral maps, and other information. Full-scale systematic and efficient processing and analysis of farms are currently hardly possible, both due to the lack of an appropriate concept and due to the existing limitations on computing power.

The presented simulation model, describing the state of the original, unfortunately, does not provide information about the trajectory of movement (degradation or development) of the suburban economy. This simulation model does not contain the correlation of the connection of many variables, including those with a non-linear form.

Most of the problems of automated processing of socio-economic information can be described in the form of linear differential equations of the first order, the numerical solution of which, in the general case, does not present problems even with a very large dimension of the required vector variables. This cannot be said about our particular case of using an optimization model, the analysis of which is associated with solving a qualitatively different class of optimal control problems. As in our particular case the solution to real problems of territory management using optimization models is limited by the dimension of the vectors of the initial variables, often at the limit of their numerical analysis, especially when using dynamic and even more so non-linear models.

7. Conclusions

1. The article proposes a conceptual model for the implementation of the “digital twins” technology for suburban agriculture enterprises. Taking into account the specifics of objects, the technology of digital twins is considered the basic one, built on the implementation of a single integrated constantly updated six-layer model. In this paper, the constructed simulation system based on simulation and optimization models implements the concept of a digital twin of suburban farming, taking into account additional benefits from the agglomeration effect.

2. The presented economic and mathematical model makes it possible to determine the main parameters of product development for current and long-term planning and can be used to analyze the current structure of production, which makes it possible to identify more appropriate ways to use resources and the possibility of increasing production volumes, based on actual data for previous years. The main features of this economic and mathematical model are that it provides for the use of the city’s production resources (food and heat waste, wood, waste paper, etc.). Although these data are not presented separately in the conditions of the model, they are provided in the parameters that were determined thanks to the experiments carried out in the created simulation system.

3. The proposed implementation model performs technical functions at the application layer, offering a predictive model. The peculiarity of the proposed model lies in its intermediary mode in the transition from a modeling system to digital twins. The data on which digital twins are based is divided into pre-collected data and data collected specifically for the creation of digital twins. Digital twins have improved simulation results by supporting suburban farms at all stages of operation through constant real-time monitoring of the physical world. By influencing the relationship between reproduction and resource consumption, digital twins have optimized performance. The proposed digital twin architecture is suitable for suburban agriculture.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship, or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

The manuscript has data included as electronic supplementary material.

References

1. Liu, M., Fang, S., Dong, H., Xu, C. (2021). Review of digital twin about concepts, technologies, and industrial applications. Journal of Manufacturing Systems, 58, 346–361. doi: https://doi.org/10.1016/j.jmsy.2020.06.017
2. Shahzad, M., Shafiq, M. T., Douglas, D., Kassem, M. (2022). Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges. Buildings, 12 (2), 120. doi: https://doi.org/10.3390/buildings12020120
3. Wright, L., Davidson, S. (2020). How to tell the difference between a model and a digital twin. Advanced Modeling and Simulation in Engineering Sciences, 7 (1). doi: https://doi.org/10.1186/s40323-020-00147-4
4. Singh, M., Fuenmayor, E., Hinchy, E., Qiao, Y., Murray, N., Devine, D. (2021). Digital Twin: Origin to Future. Applied System Innovation, 4 (2), 36. doi: https://doi.org/10.3390/asi4020036
5. Pylianidis, C., Osinga, S., Athanasiadis, I. N. (2021). Introducing digital twins to agriculture. Computers and Electronics in Agriculture, 184, 105942. doi: https://doi.org/10.1016/j.compag.2020.105942
6. Dahmen, U., Rossmann, J. (2018). Experimentable Digital Twins for a Modeling and Simulation-based Engineering Approach. 2018 IEEE International Systems Engineering Symposium (ISSE). doi: https://doi.org/10.1109/syseng.2018.8544383
7. Wagg, D. J., Worden, K., Barthorpe, R. J., Gardner, P. (2020). Digital Twins: State-of-the-Art and Future Directions for Modeling and Simulation in Engineering Dynamics Applications. ASCE-ASME J Risk and Uncert in Engrg Sys Part B Mech Engrg, 6 (3). doi: https://doi.org/10.1115/1.4046739

8. Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., Sui, F. (2017). Digital twin-driven product design, manufacturing and service with big data. The International Journal of Advanced Manufacturing Technology, 94 (9-12), 3563–3576. doi: https://doi.org/10.1007/s00170-017-0233-1
9. Yan, D., Liu, L., Liu, X., Zhang, M. (2022). Global Trends in Urban Agriculture Research: A Pathway toward Urban Resilience and Sustainability. Land, 11 (1), 117. doi: https://doi.org/10.3390/land11010117
10. Beacham, A. M., Vickers, L. H., Monaghan, J. M. (2019). Vertical farming: a summary of approaches to growing skywards. The Journal of Horticultural Science and Biotechnology, 94 (3), 277–283. doi: https://doi.org/10.1080/14620316.2019.1574214
11. Orsini, F., Kahane, R., Nono-Womdim, R., Gianquinto, G. (2013). Urban agriculture in the developing world: a review. Agronomy for Sustainable Development, 33 (4), 695–720. doi: https://doi.org/10.1007/s13593-013-0143-z
12. Cohen, N. (2007). The Suburban Farm: An innovative model for civic agriculture. UA-Magazine, 55–58. Available at: https://www.researchgate.net/publication/242766513_The_Suburban_Farm_An_innovative_model_for_civic_agriculture
13. Stefani, M. C., Orsini, F., Magrefi, F., Sanyé-Mengual, E., Pennisi, G., Michelon, N. et al. (2018). Toward the Creation of Urban Foodscapes: Case Studies of Successful Urban Agriculture Projects for Income Generation, Food Security, and Social Cohesion. Urban Horticulture, 91–106. doi: https://doi.org/10.1007/978-3-319-67017-1_5
14. Dubbeling, M., van Veenhuizen, R., Halliday, J. (2019). Urban agriculture as a climate change and disaster risk reduction strategy. Field Actions Science Reports, 20, 32–39. Available at: https://journals.openedition.org/factsreports/5650#text
15. Owens, G. R. (2016). 'We are not farmers': Dilemmas and prospects of residential suburban cultivators in contemporary Dar es Salaam, Tanzania. The Journal of Modern African Studies, 54 (3), 443–467. doi: https://doi.org/10.1017/s0022278x16000392
16. Hite, D., Sohngen, B., Templeton, J. (2003). Zoning, Development Timing, and Agricultural Land Use at the Suburban Fringe: A Competing Risks Approach. Agricultural and Resource Economics Review, 32 (1), 145–157. doi: https://doi.org/10.1017/s1068280500002562
17. Purcell, W., Neubauer, T. (2023). Digital Twins in Agriculture: A State-of-the-art review. Smart Agricultural Technology, 3, 100094. doi: https://doi.org/10.1016/j.atech.2022.100094
18. Balayev, R. A., Mirzayev, N. S., Bayramov, H. M. (2021). Sustainability of urbanization processes in the digital environment: food security factors. Acta Scientiarum Polonorum Administratio Locorum, 20 (4), 283–294. doi: https://doi.org/10.31648/aspal.6819
19. Neethirajan, S., Kemp, B. (2021). Digital Twins in Livestock Farming. Animals, 11 (4), 1008. doi: https://doi.org/10.3390/ani11041008
20. Boschert, S., Rosen, R. (2016). Digital Twin – The Simulation Aspect. Mechatronic Futures, 59–74. doi: https://doi.org/10.1007/978-3-319-32156-1_5
21. Schluse, M., Rossmann, J. (2016). From simulation to experimentable digital twins: Simulation-based development and operation of complex technical systems. 2016 IEEE International Symposium on Systems Engineering (ISSE). doi: https://doi.org/10.1109/syseng.2016.7753162
22. Balaev, R. (2007). Urbanization: the urban economy and the food problem. Baku: Elm, 223–234.
23. Semenov, P. V., Semishkur, R. P., Diachenko, I. A. (2019). Conceptual model of digital twin technology implementation for oil and gas industry. Gas industry, 7 (787), 24–30. Available at: https://cyberleninka.ru/article/n/kontseptualnaya-model-realizatsii-tehnologii-tsifrovyh-dvoynikov-dlya-predpriyatiy-neftegazovogo-kompleksa
24. Walters, J. P., Archer, D. W., Sassenrath, G. F., Hendrickson, J. R., Hanson, J. D., Halloran, J. M. et al. (2016). Exploring agricultural production systems and their fundamental components with system dynamics modelling. Ecological Modelling, 333, 51–65. doi: https://doi.org/10.1016/j.ecolmodel.2016.04.015
25. van der Burg, S., Kloppenburg, S., Kok, E. J., van der Voort, M. (2021). Digital twins in agri-food: Societal and ethical themes and questions for further research. NJAS: Impact in Agricultural and Life Sciences, 93 (1), 98–125. doi: https://doi.org/10.1080/27685241.2021.1989269
26. State Statistical Committee of the Republic of Azerbaijan. Available at: https://stat.gov.az/menu/6/statistical_yearbooks/?lang=en
27. Nasirahmadi, A., Hensel, O. (2022). Toward the Next Generation of Digitalization in Agriculture Based on Digital Twin Paradigm. Sensors, 22 (2), 498. doi: https://doi.org/10.3390/s22020498
28. Chaux, J. D., Sanchez-Londono, D., Barbieri, G. (2021). A Digital Twin Architecture to Optimize Productivity within Controlled Environment Agriculture. Applied Sciences, 11 (19), 8875. doi: https://doi.org/10.3390/app11198875