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RESEARCH ARTICLE

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Intellectual Assessment of Integral Indicators for Grain Crop Yield and Structure Using Expert System

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ABSTRACT

Grain crops are crucial to the food security of all countries worldwide. Humanity benefits greatly from them as they provide the primary source of nourishment and a wide range of food products, such as wheat, grains, and animal feed. Analyzing grain yields in the context of sustainable agricultural development and food security is an urgent task for farming producers and many countries' economies. Maintaining production indicators enables the optimization of business activities in agro-industrial enterprises, such as forecasting supply volumes and managing risks. This work aims to develop an expert system that analyzes the yield of grain crops and their main structural elements. This system will take into account various input parameters such as crop information, botanical description, harvest year, number of plants per square meter, number of shoots per square meter, number of productive shoots per square meter, height of shoots, weight of a sheaf without roots, ear length, number of grains per ear, grain weight per ear, actual grain moisture, and seed germination. In the present study, the authors concentrated on examining the functional, informational, and behavioral models and the expert system components. Implementing these system models allows the user to analyze the yield of the crops in question, identify their main structural elements, forecast yield, determine their structure and seeding rate, receive recommendations for potential crops, and improve the conditions for maximizing production.

Keywords: Crops, Yield, Crop structure, Information technology, Data analysis, Machine learning, Expert system

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INTRODUCTION

Cereals are the most important source of nutrition for most people on the planet. Food products based on them provide a person with the energy, protein, vitamins, and minerals necessary for successful life activity (Ali et al., 2023a). Grain crops also play a crucial role in ensuring food security in many countries worldwide.

Note the importance of grain crops in animal feeding, both in their pure form and as compound feed (Haroon et al., 2022a; Mustafaev et al., 2023). Grain provides essential elements for organism viability, such as starch, alcohol, amino acids, and medicines. Farm animals feed on by-products like straw and glume, which they use as bedding. We grow various crops to produce hay, silage, and haylage (Haroon et al., 2022b).

Information technologies play an important role in grain crop production and agriculture in general. These technologies enable agricultural businesses to successfully manage resources, analyze data to optimize sowing, caring for, and harvesting crops, and more (Haroon et al., 2023; Shevtsov, 2023). The introduction of information technologies into Russia's agro-industrial complex (AIC) allows agriculture to reach a global level that can compete with developed countries (Kadomtseva, 2024; Jumabayeva et al., 2023).

Modern information technologies allow business entities to automate their business processes, improve productivity, increase efficiency, reduce costs, increase competitiveness, and provide opportunities to adapt to changing market conditions (Zemlyansky and Bystrenina, 2013; Bystrenina, 2017; Bystrenina et al., 2017; Bystrenina et al., 2019; Tatarintsev et al., 2021; Khudyakova et al., 2021; Zaruk et al., 2024). All of this emphasizes the significance of their implementation in agricultural enterprises' activities (Ershov and Bobrovnikova, 2024).

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In foreign practice, there is a clear trend towards introducing digital technologies for crop cultivation process analysis and forecasting. Thus, the scientists calculate and predict the optimum dose of nutrient application in crop cultivation. The prediction of nutrient requirements is based on an assessment of potential yield, soil nutrient supply, and other assumptions regarding the quality of the resulting crop (for example, the protein content in grain), as well as the efficiency of nutrient absorption from fertilizers (Meisinger et al., 2008; Ahmed et al., 2023).

Researchers evaluated the nitrogen fertilizers for wheat and barley crops in Australia (Colaço et al, 2024). In their work, they analyzed crop data for a specific land plot to assess the reaction of crops to fertilizers applied, local functions, and optimal fertilizer application rates.

The researchers made a prediction and produced a digital map of the spatial distribution and variability of phosphorus available in the soil. Phosphorus is one of the most essential elements in crop cultivation. They calculated the influence of environmental conditions on the variability of phosphorus in the upper soil layers. The researchers used three types of machine learning to guess if there was a connection between the environment and the amount of variation in phosphorus levels in the top 10 centimeters of soil and the environment. These were random forest, artificial neural network, and regression of support vectors (Hojati et al., 2024).

Recently, there has been an active use of remote sensing using unmanned aerial vehicles (UAVs) to effectively obtain crop growth parameters (Aasen et al., 2015; Aasen et al., 2018; Adão et al., 2017; Bendig et al., 2015). Scientists are looking into how to use multi-temporal data collected by UAVs at key stages of plant development to predict rice yield when different varieties are planted directly and nitrogen levels are managed (Yang et al., 2024).

Foreign studies generally aim to forecast yields using data analytics and machine learning, taking into account factors such as weather conditions, natural soil fertility, organizational and man-made conditions, and plant varieties. Furthermore, foreign innovations in crop forecasting use remote sensing, drones, and satellite technologies to monitor fields. It is worth noting that domestic scientists use information technology to forecast crops. By utilizing statistical data on grain crop yields in the Oryol region from 1985 to 2009, represented as chain indices and majorant relations, they can identify patterns in natural crop production conditions and forecast yields (Sidorenko and Gulyaeva, 2010). The economic and mathematical model for predicting grain yields was built, considering its a priori cyclicity and production characteristics in arid climatic conditions (Tyuryakova, 2009). An algorithm developed for building and adapting neural network information technologies and tools for modeling crop yields based on time-series autocorrelation functions. As characteristics of the yield time series, he used the period of a priori cyclicity and the empirical distribution of their levels (Shubnov, 2013). An analysis of the research problem's literature revealed that both foreign and domestic literature contain a variety of methods for forecasting yields (Ali et al., 2023b).

The purpose of this work is to design and implement an expert system for analyzing the yield of grain crops and the main elements of its structure based on an intellectual assessment of integral indicators. This system is based on an analysis of existing agricultural system architectures and organizational principles (Asperov et al., 2023).

This change is important because the smart systems on the Russian market (FarmWorks, eLMID, AGRO-NET NG, AGRO-MAP PF, Agrar Office, Ag Leader SMS, FarmWorks, Panorama AGRO, 1C Agricultural Enterprise Management) take care of management, accounting, and tax work in agriculture. They also make sure that precision farming technologies are used (controlling machines, measuring tools, and field mapping) (Zolkin et al., 2024; Fedotova et al., 2024).

There exists a contradiction between the necessity of implementing an information system to analyze grain yields and their main structural elements, and the deficiency of available tools for processing and analyzing data in the relevant subject area. The revealed contradiction led to the need to develop an expert system for analyzing the yield of grain crops and the main elements of its structure based on an intellectual assessment of integral indicators. The implementation of the system models proposed by the author of the article allows users to obtain calculations of biological yield and crop structure, analyze yield, and make forecasts.

MATERIALS & METHODS

The developed expert system for analyzing the yield of grain crops and the main elements of its structure will enable employees and managers of agricultural entities to solve tasks such as calculating biological yield, crop structure, seeding rates, determining the most significant parameters for yield prediction, and its subsequent implementation.

The input parameters include the types of grain crops, their botanical description, the year of harvest, the number of plants per square meter, the number of shoots per square meter, the number of productive shoots per square meter, the height of shoots, the weight of a sheaf without roots, the length of the ear, the number of grains per ear, the weight of grain per ear, the actual grain humidity, and the germination of seeds. The implemented system functionality will make it possible for the heads of business entities in the agro-industrial complex to reasonably make managerial decisions.

The key points of this article are functional, informational, behavioral models, and system components. The authors analyzed scientific and technical literature and conference materials on the use of information systems in forecasting grain yields. The authors also conducted a critical analysis of foreign and domestic literature on the analysis of grain yield and it’s forecasting, utilizing various methodologies. The study's authors presented functional, informational, and behavioral models as well as expert system components using the modeling notations UML, IDEF1X, IDEF0, and DFD. This system will allow for analyzing the yield of the crops in question, the main elements of their structure, making yield forecasts, determining their structure and seeding rate, receiving recommendations on possible crops, and improving production conditions.

RESULTS & DISCUSSION

Currently, most areas of human activity use intelligent systems to automate and improve several processes. These systems include the implementation of algorithms capable of analyzing, extracting information, making decisions, and performing professional tasks without direct human involvement. Successfully developing intelligent systems necessitates careful planning, data collection and analysis, the selection of optimal processing methods, and ensuring the system's safety and reliability.

When implementing the information system, we put forward the following user requirements: control of access to data; provision of access to reference information; working with data; calculation of biological yield; calculation of crop structure and its visualization; determination of the seeding rate; determination of correlation between structure parameters; building a yield forecast; formation of accounting documents; information storage. Thus, the user has the ability to work with data at all levels to analyze yields, the main elements of its structure, as well as its forecasting.

Expert agronomists in the studied subject area collected their knowledge during the implementation of the proposed system, which will form the basis for decision-making in the system. The formalization of this knowledge in the form of system models includes the data structure, algorithms for their processing, and the necessary infrastructure for the system to function.

By sampling the harvest, an algorithm determines the yield at the root of row crops. It allows for estimating the average yield for the entire field, based on data collected from various field sections.

The yield level of grain crops consists of the following elements: the number of ears, the number of grains in the ear, and the grain's absolute weight. Therefore, using specific sample data on these elements' sizes, we can determine the grain yield per hectare in tons using the following formula:

$Y_{nk} = K \cdot Z \cdot A / 100{,}000$,

where K is the number of ears per 1 m^2;

Z is the number of grains in the ear;

A is the absolute weight of the grain, i.e. the weight of 1000 grains, g.

When measuring the yield in the farm, plots with visible differences in yield are considered separately. After determining the yield in each field, the average weighted by the farm is found.

The main elements of the crop structure, which make up its value, are the number of plants per 1 m^2 during harvesting, productive bushiness, the number of spikelets in the ear, the number of grains in the spikelet, the number of grains in the ear, the mass of 1000 grains. They form the biological basis of productivity.

Based on these biological elements, researchers proposed to determine the yield value according to the structural formula (Savitsky and Nikolaev, 1974).

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Based on these biological elements, M.S. Savitsky proposed to determine the yield value according to the structural formula (Savitsky and Nikolaev, 1974):

$$Yb = \frac{(P*K)*(3*A)}{10\ 000},$$

P is the average number of plants per 1 m^2 during harvesting, pcs.

K – productive bushiness.

3 – the average number of grains in an ear, pcs.

A is the mass of 1000 grains, g.

Productive bushiness is calculated as the ratio of the number of productive stems of the main variety to the number of plants of this fraction, total bushiness is calculated as the ratio of the number of all stems to the number of plants.

The calculated yield results in a standard grain moisture content - 14%. The conversion of the crop from field humidity to standard is carried out according to the formula:

$$Ys = \frac{Yb*(100-V)}{(100-G)},$$

where Y_s is the grain yield at standard humidity, c/ha;

Y_b – grain yield without correction for humidity, c/ha;

V– grain moisture content when weighing in the field, %;

G – standard humidity – 14%;

An important indicator that ensures a full-fledged harvest is the seeding rate, which is expressed by the number of germinating seeds (in millions of pieces) and the weight of seeds (in kg), and is calculated using the formula:

$$Nv = \frac{A*K*100}{PG},$$

where A is the weight of 1000 grains (g);

K is the number of germinating grains per 1 ha (million pieces);

PG – sowing suitability, %.

The calculation of sowing seeds with 100% sowing suitability determines the seeding rate for each farm. Seeding rates for crops varied throughout various production zones.

Various factors can influence it, including soil and climatic conditions, the sowing method, the crop's cultivation purpose, the quality of the seeds, and more. Therefore, we must calculate the sowing season using the following formula:

$PG = H \cdot V/100$,

$PG = \frac{H*V}{100}$ where PG is the sowing suitability, %;

H – purity (%);

V – germination rate (%).

The crop's structural formula allows us to analyze not only the value of a specific productivity element, but also the logical combination of optimal parameters of structural units, growth, and maintenance in later stages of vegetation. The information system model incorporates the algorithms used in data processing for grain yield analysis and forecasting.

Examining the system's information model will help us understand how expert systems may be effectively operational using storage, access, updating, and knowledge integrity maintenance. The subject area's analysis identifies the following entities: types of crops, botanical descriptions, information about the inputs used, flow process charts, and crop structures. Let's take a closer look at the content of each entity. The essence of the "Crop structure" contains attributes such as id, year, number, total plants, number of productive shoots, plant height, sheaf weight, number of grains, total shoots, amount of grain from the sheaf, ear length, grain weight, and grain weight from the sheaf. The essence of the "Crop type" includes the following attributes: ID and name. The "flow process chart" essence contains attributes such as ID, number, type of work, time of application, brand of agricultural machinery, and agrotechnical requirements. The essence of a "botanical description" includes attributes such as id, description, species, development stages, and image. "Information about the indicators used" includes ID, name, description, and formula. The author of the study constructed a conceptual, logical, and physical model of the database in question. Fig. 1 displays the logical data model.

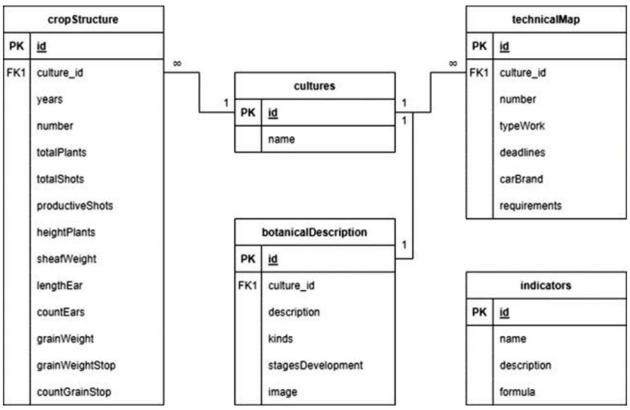


Fig. 1: Logical data model of the system.

To implement the model of functional diagrams in IDF0 notation and data flow diagrams in DFD notation, Ramus Educational structural design CASE-tool was used. A contextual diagram of the grain yield analysis system and the main elements of its structure based on an intelligent assessment of integral indicators is shown in Fig. 2.

The information system's input is comprised of a botanical description of cereal crops, data for yield evaluation, and background information regarding the indicators applied.

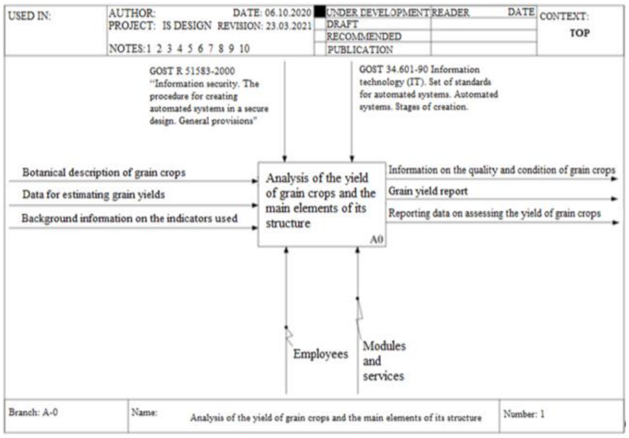


Fig. 2: Context diagram of the system in IDEF0 notation.

A functional decomposition was carried out after creating a context diagram describing the simulated system context. Its essence is separating the system into subsystems with the same syntax. Then, each subsystem is broken down into smaller ones until it achieves the appropriate level of detail. Fig. 3 depicts the grain yield analysis system's decomposition diagram and the key structural elements based on an intelligent assessment of integral indicators.

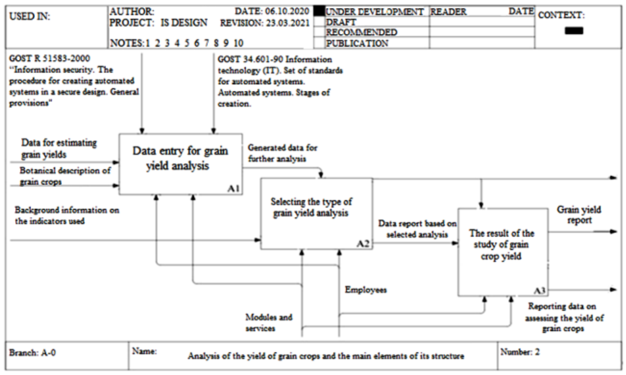


Fig. 3: Diagram of the system decomposition in IDEF0 notation.

When decomposing the context diagram, the author highlights such blocks as data entry for the analysis of grain yield, the choice of the type of grain yield analysis, and the result of the grain yield study.

C++ and Python have become the main languages for data processing within the system. The system selected the MS SQL Server database management system for its implementation.

Let's examine the primary features of the information system's user interface, which analyzes the yield of grain crops, as well as the key components of its structure. Fig. 4 displays the authorization window to the user when the system starts.

Upon successful user authorization, a transition takes place to the main menu of the program, consisting of commands: crop structure analysis, yield analysis, flow process chart, botanical description, and information on indicators (Fig. 5).

Fig. 4: The "User Authorization" form.

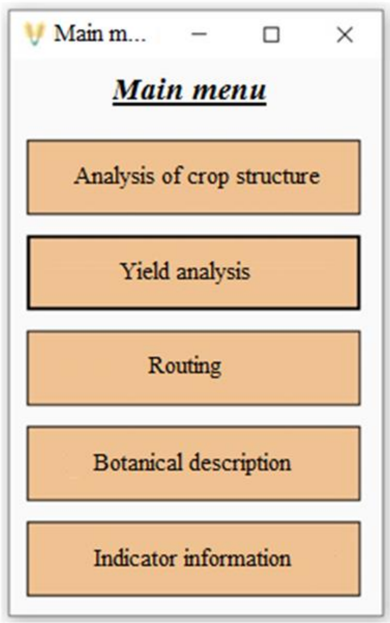


Fig. 5: The "Main Menu" form.

When you select the "Crop structure analysis" item, a screen form opens with two tables: the crop structure and calculated indicators (Fig. 6).

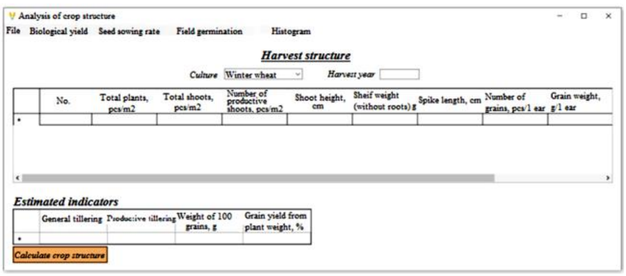


Fig. 6: The "Crop structure analysis" form.

Several options are available to the user on this screen form. To calculate the structure of the crop, it is necessary to fill in the upper table. There are several selections for this, namely, enter manually, download an Excel file, or select the necessary rows from the database. If desired, you can combine all three methods.

When you click on the "File", a drop-down menu appears (Fig. 7), in which you select the method of data uploading. In addition, the functionality for saving data in excel format, as well as printing, is constructed. If necessary, it is also possible to clear the Table.

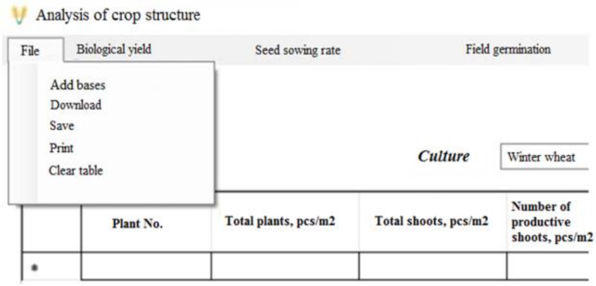


Fig. 7: Drop-down "File" menu.

When downloading, the user opens a dialog box in which the file location is selected. To work correctly, the number of columns in the file must match the number of columns in the table.

Clicking on the "Add from database" item, an additional form appears with the available data in the database (Fig. 8).

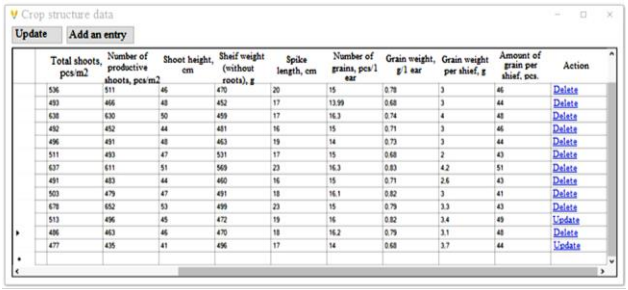


Fig. 8: The "Crop structure data" form.

In the table, the user is allowed to manipulate data, namely; adding, deleting, and updating. These functions are available in the rightmost column. At the same time, validation is conFig.d, i.e. it is impossible to enter special characters and letters, only numbers.

The next step, after entering the data into the first table, is to click on the button "Calculate the crop structure" (Fig. 9). After that, additional lines of the sum and the average value of the columns will appear.

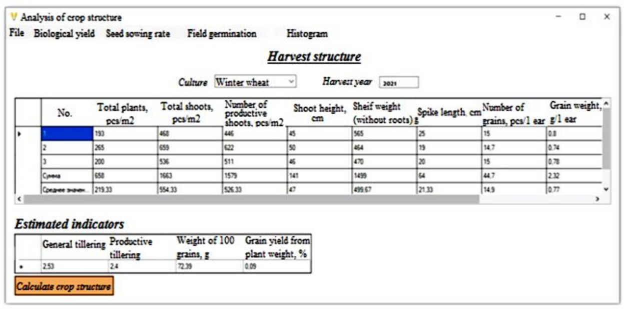


Fig. 9: Calculation of the crop structure.

To calculate other indicators, such as biological yield, seeding rate, seed germination, it is necessary to select the appropriate menu item. Fig. 10 shows the screen form of biological yield. The calculation of the seeding rate is shown in Fig. 11.

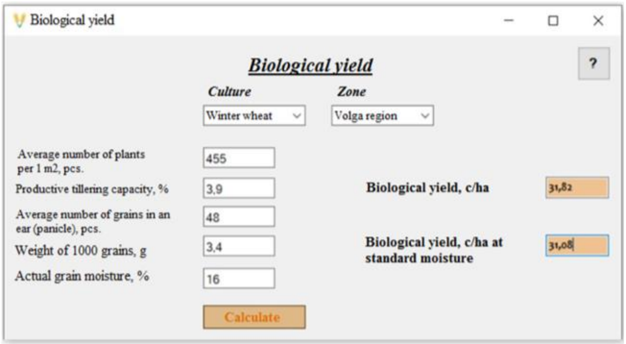


Fig. 10: The "Biological yield" form.

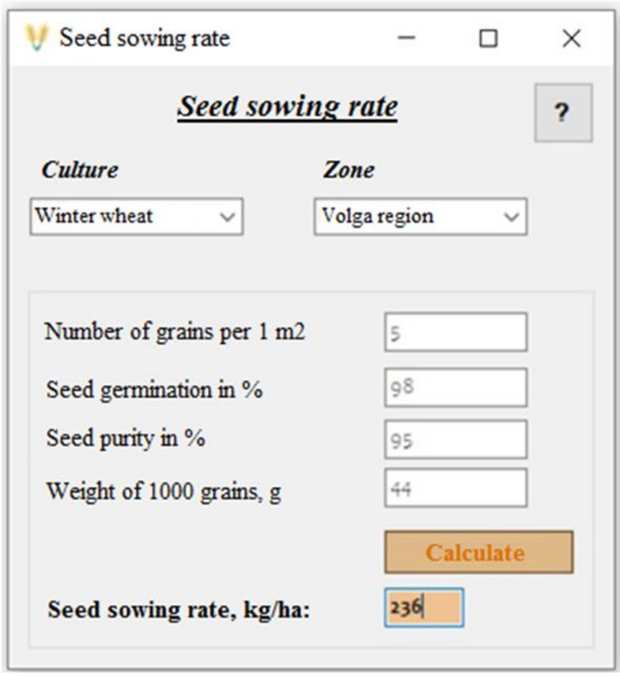


Fig. 11: The "Seeding rate" form.

When you click on the question mark, a table appears with approximate quantitative seeding rates (million per 1 ha) by zone. Verification of the correctness of field fillings is also conFig.d.

If it is necessary to analyze the structure of the crop according to the entered data, you can use the Histogram tool by selecting the necessary parameter for visualization (Fig. 12).

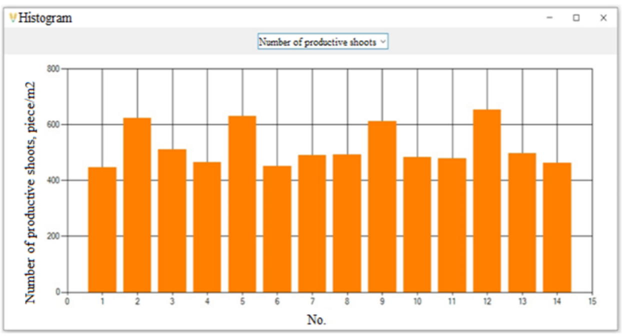
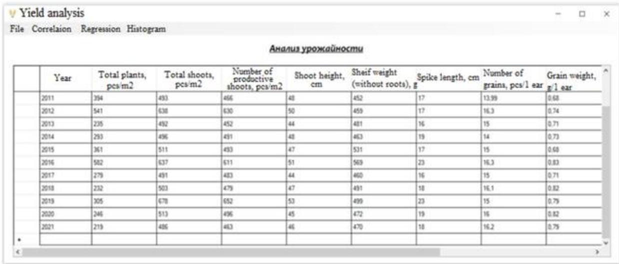


Fig. 12: The "Histogram" form.

This form contains a graph of the histogram of the crop structure. In combo box, the necessary indicator is selected, for example, the number of productive shoots, and the result is shown depending on it.

Also, the user of the system can analyze the yield of grain crops, the execution command is located in the second item of the main menu. When switching to the yield analysis menu, an on-screen form with a table of crop data opens in front of the user (Fig. 13).


Yield analysis

File Correlaion Regression Histogram

Анализ урожайности

Year	Total plants, pcs/m2	Total shoots, pcs/m2	Number of productive shoots, pcs/m2	Shoot height, cm	Sheif weight (without roots), g	Spike length, cm	Number of grains, pcs/1 ear	Grain weight, g/1 ear
2011	394	493	466	48	452	17	13.99	0.68
2012	541	638	630	50	459	17	16.3	0.74
2013	235	492	452	44	481	16	15	0.71
2014	293	496	491	48	463	19	14	0.73
2015	361	511	493	47	531	17	15	0.68
2016	502	637	611	51	569	23	16.3	0.83
2017	279	491	483	44	460	16	15	0.71
2018	232	503	479	47	491	18	16.1	0.82
2019	305	678	652	53	499	23	15	0.79
2020	246	513	496	45	472	19	16	0.82
2021	219	486	463	46	470	18	16.2	0.79

Fig. 13: The "Yield analysis" form.

The expert system implements the functionality for determining the correlation of crop structure indicators and yield forecasting, which can be accessed when switching to the menu items "Correlation" (Fig. 14) and "Regression" (Fig. 15), respectively.

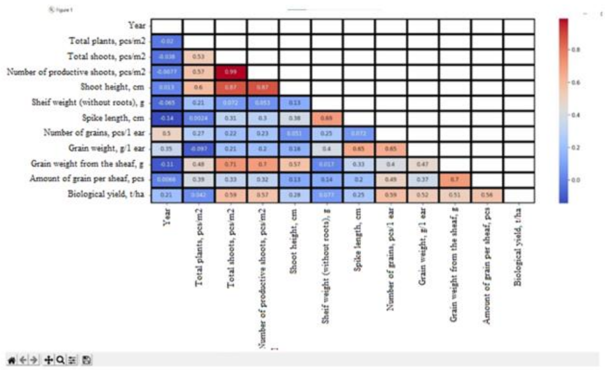


Fig. 14: The "Correlation" form.

Based on the available data, we correlated the elements of the winter wheat crop and found that certain characteristics have the strongest simultaneous relationships with biological yield. You must choose only significant factors in order to construct a multiple regression. Here, it refers to the quantity of grains and fruitful shoots.

We implement the module for grain crop yield forecasting in Python. In this instance, the Python Scikit-Learn package is used in a multiple regression-based technique to determine it. The reason for the decision was that, in a comparison of three machine learning algorithms—random forest, k-nearest neighbor, and linear regression—the linear regression approach produced the best results because of its greatest determination coefficient.

Click the "Regression" menu item in the "Yield Analysis" form to see the regression coefficients. The regression equation coefficients will then show up on a screen form (Fig. 15).

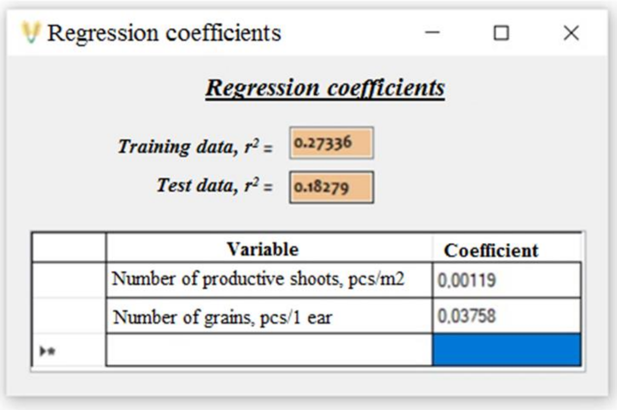


Fig. 15: The "Regression Coefficients" form.

The "Flow process chart" window, which is accessible through the system's primary menu, provides details regarding the types of work that are performed during the cultivation of an agricultural crop, their deadlines, agrotechnical requirements, and the brand of equipment that is employed (Fig. 16).

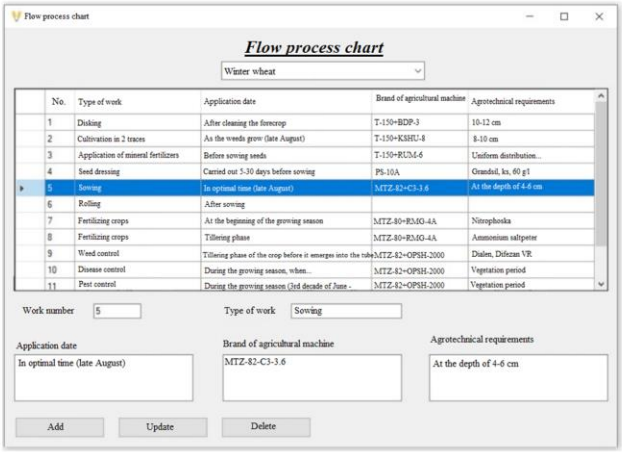


Fig. 16: The "Flow process chart" form.

The system's main menu also allows users to navigate to the "Botanical Description" window, which contains background information on each crop (Fig. 17). After selecting the desired crop, the user is presented with its image, description, types, and stages of development.

When working with the system, the user has the opportunity to study the indicators used when receiving calculations in the work. This functionality is presented in the main menu item "Information about indicators" (Fig. 18).

The implementation of the described models of the expert system for analyzing the grain yield and the main elements of its structure. It makes it possible to predict the characteristics of the cultivated crops, seed rates, and yield forecasts for subsequent periods under constant production conditions. The user also has the opportunity to receive recommendations on the cultivation of crops and improvement of production conditions on request. The described functionality of the system allows us to assert that it has expert system functions. Thus, by adjusting the input parameters for the botanical description of crops, and crop yield assessment data, producers receive recommendations for the manufacture of products.

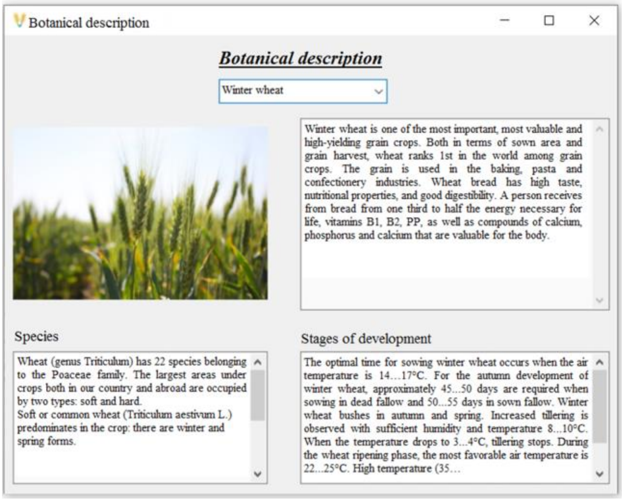


Fig. 17: The "Botanical Description" form.

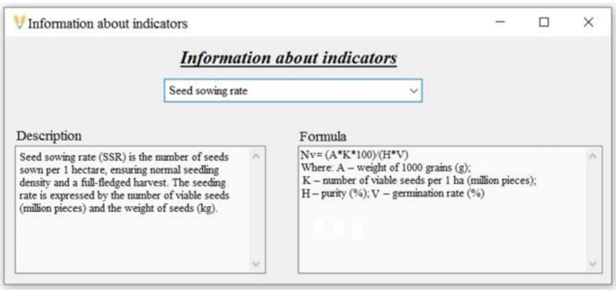


Fig. 18: The "Information about indicators" form.

Conclusion

The information system models for grain yield analysis and crop structure are built on the principles of expert system implementation. The developed expert system is based on the knowledge and experience of crop production experts. Additionally, we implemented the system using the rules, logic, and knowledge base of the subject area under consideration. We use information about crops, including their botanical description, harvest year, number of plants per square meter, number of shoots per square meter, number of productive shoots per square meter, height of shoots, sheaf weight without roots, ear length, number of grains per ear, grain weight per ear, actual humidity of grains, and seed germination, as input data. Implementing algorithms for processing available raw data on crops allows solving the tasks of employees and managers of agricultural entities: calculating biological yield, crop structure, seeding rates, and determining the most significant parameters for predicting the yield and its further implementation.

Therefore, it is important to note that the authors' proposed expert system for analyzing grain crop yield and key structural components will help the crop industry grow into a globally competitive agricultural sector that satisfies Russia's "green" production requirements.

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