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Computer-Oriented Method of Adaptive Monitoring and Control of Temperature and Humidity Mode of Greenhouse Production

Ivan LAKTIONOV[1], Oleksandr VOVNA[2], Maryna KABANETS[3]

[1]Faculty of Information Technologies, Department of software of computer systems, Dnipro University of Technology, av. Dmytra Yavornytskoho, 19, Dnipro, UA49005, Ukraine
[2]Faculty of Computer and Information Technologies and Automation, Department of Electronic Engineering, SHEI 'Donetsk National Technical University' of the Ministry of Education and Science of Ukraine, Sofii Kovalevskoi st., 29, Lutsk, UA43024, Ukraine
[3]Language Training Department, Faculty of Economics and Management, SHEI 'Donetsk National Technical University' of the Ministry of Education and Science of Ukraine, Sofii Kovalevskoi st., 29, Lutsk, UA43024, Ukraine

Laktionov.I.S@nmu.one, oleksandr.vovna@donntu.edu.ua, maryna.kabanets@donntu.edu.ua

ORCID: 0000-0001-7857-6382, 0000-0003-4433-7097, 0000-0002-7961-8350

Abstract. Nowadays, development and implementation of applied information technologies is one of the major trends in improving the efficiency of agrotechnological processes in agricultural production. Greenhouse production is a science-intensive process and requires the introduction of computer-oriented technologies that meet today’s requirements for intelligence, adaptability and scalability. The purpose of the article is to substantiate the scientific and applied provisions for improving the efficiency of information technologies for agrotechnical purposes by developing a computer-oriented method of adaptive monitoring and control of temperature and humidity mode of greenhouse production based on Fuzzy logic. The research object is information processes of complex intellectualised transformation of measurement data on temperature and humidity of greenhouse growing zones. The main result of the article is substantiation of scientific and practical provisions on synthesis of the method of computer-oriented monitoring and control of temperature and humidity mode of vegetable crops growing in greenhouse conditions, which is adaptive to the factors of crop rotation, crop types and vegetation periods.

Keywords: fuzzy logic, temperature, humidity, control, greenhouse, monitoring.

1. Introduction

1.1. Relevance of the research topic

Nowadays, the development and implementation of applied computer and information technologies is one of the major trends in improving the integrated efficiency of technological processes of industrial and agricultural production and infrastructure facilities. This tendency encourages the world scientific community to the continuous search for effective approaches to the creation of new and improvement of existing methods and means of digitalization, automation and intellectualization of production and agrotechnical processes. One of the main sectors of the national economies of many countries of the world, which is dynamically transforming and modernising due to the introduction of modern achievements of information and digital technologies, is agriculture. In turn, the field of greenhouse vegetable growing stimulates the positive dynamics of ensuring food security in a significant number of countries through the implementation of year-round production of its own vegetable products. However, greenhouse agriculture is, to a large extent, a science-intensive process, and, therefore, requires introducing computer-oriented technologies that meet today's requirements for intelligence, adaptability and scalability, which can increase the integral precision, efficiency and effectiveness of online monitoring and automatic control of greenhouse agricultural processes. The relevance of the research task on the scientific substantiation of technical solutions for creating information technologies for agrotechnical purposes is confirmed by the rapid dynamics of publication activity in specialised journals from world science databases, as shown in Figure 1.

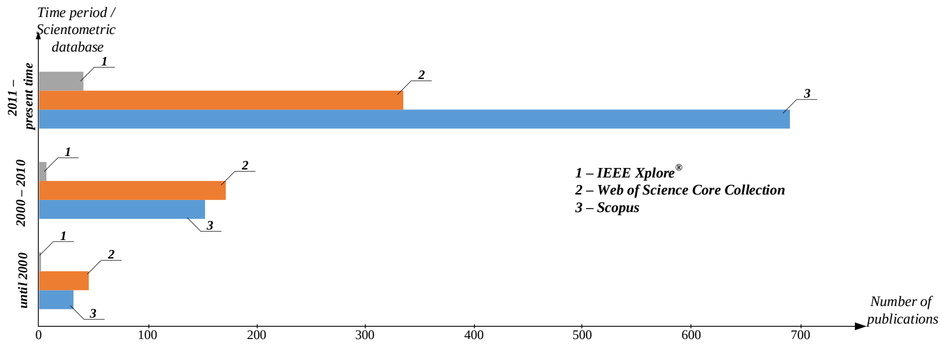


Figure 1. Statistics of publication activity: search query – (Measuring OR Monitoring OR Control) AND Microclimate AND Greenhouse

One of the most informative physical and chemical parameters that affect the cultivation rate and the final quality and volume of greenhouse crops is temperature and humidity of the physical environment of the growing zone. This is caused by the fact that for each type of plant in specific periods of vegetation, the integrated temperature and humidity conditions are specific due to the determining influence on the efficiency of photosynthesis, respiration and transpiration of greenhouse crops. Therefore, reproduction and maintenance of optimal growth conditions for specific types of greenhouse crops throughout the entire growth cycle through the development and implementation of intelligent information technologies is an important scientific and applied task.

1.2. Review, critical analysis and logical generalisation of scientific and analytical works

In the context of global trends in the development of the agricultural sector, taking into account current market requirements, the international organisation FAO has accumulated statistical data on the production of vegetable products in different countries since 1961 (WEB, a). Table 1 shows indicative statistics for 2020 (the latest update) on the use of greenhouse areas for growing various types of crops in the countries of Eastern and South-Eastern Europe.

Table 1. Indicative statistics on the use of greenhouse areas for different crops

Crops	Area of glass greenhouses, ha	Area of plastic greenhouses, ha	Total area, ha
Tomatoes	231	3562	3793
Cucumbers	102	1700	1802
Pepper	53	1581	1634
Salad, cabbage	15	2592	2607
Others	no data available	27	27

Also, based on the analysis of the data archive (FAO, 2021), the statistical distribution of the popularity of growing vegetable crops around the world was established, as shown in Figure 2.

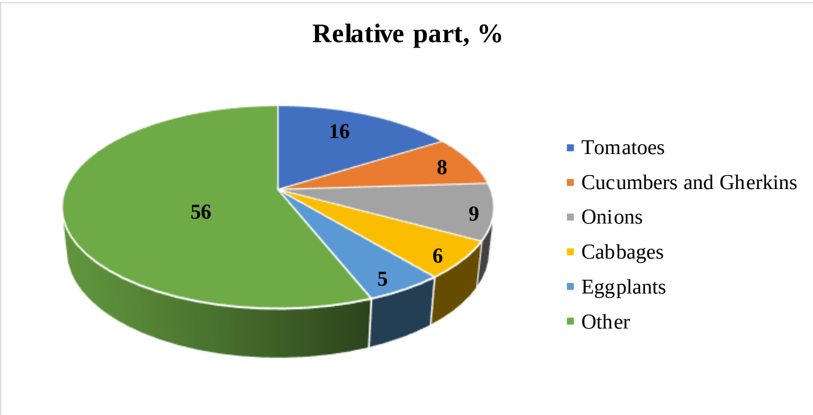


Figure 2. Statistical distribution of vegetable crop production for 2019 (last update)

By logical generalisation of differentiated data presented in Table 1 and Figure 2, it was found that the most popular greenhouse crops are tomatoes and cucumbers. This fact determines the priority of developing a computer-integrated model, namely, for the above types of vegetable crops, taking into account the full cycle of their vegetative period.

Regulatory, analytical (Baudoin et al., 2017; VNTP APK, 2007) and scientific sources (Shamshiri et al., 2018; Soussi et al., 2022) provide requirements for optimal values of temperature and humidity of the physical environment of the greenhouse growing zone, which were summarised on the basis of many years of expert experience in the field of greenhouse vegetable production. The results of systematisation of these data are shown in Table 2.

Based on the analysis of the results presented in Table 2, it was found that during the development of a computer-integrated method for monitoring and controlling the temperature and humidity mode of greenhouse cultivation, it is necessary to take into account the destabilising effect of the following factors: daily dynamics of effective energy illumination in the visible wavelength range (from 380 nm to 760 nm), seasonal crop rotation, type and vegetation period of crops grown.

Table 2. Recommended norms of temperature and humidity of the growing zone

Parameters	**Before fruiting**		**During fruiting**	
	tomatoes	cucumbers	tomatoes	cucumbers
winter-spring crop rotation				
Air temperature, °C				
on sunny days	from 21 to 22	from 22 to 24	from 23 to 25	from 24 to 26
on cloudy days	from 19 to 20	from 20 to 22	from 20 to 22	from 22 to 24
at night	from 16 to 18	from 19 to 21	from 15 to 17	from 18 to 20
Soil temperature, °C	from 20 to 22	from 23 to 25	from 18 to 20	from 23 to 24
Relative air humidity, %	from 60 to 65	from 75 to 80	from 65 to 70	from 80 to 85
Relative soil humidity, %	from 65 to 70	from 70 to 80	from 70 to 75	from 85 to 90
autumn crop rotation				
Air temperature, °C				
on sunny days	from 24 to 26	from 25 to 26	from 20 to 22	from 21 to 23
on cloudy days	from 18 to 20	from 22 to 23	from 17 to 19	from 19 to 21
at night	from 16 to 18	from 19 to 20	from 15 to 16	from 17 to 19
Soil temperature, °C	from 18 to 19	from 22 to 24	from 17 to 18	from 20 to 22
Relative air humidity, %	from 60 to 70	from 70 to 75	from 60 to 70	from 75 to 80
Relative soil humidity, %	from 65 to 70	from 70 to 80	from 70 to 75	from 85 to 90

Currently, one of the priority areas for the sustainable development of applied information and computing technologies is the use of artificial intelligence and machine learning methods in the development of computer-oriented models for reliable and valid processing of the results of online monitoring of distributed measurement data based on the Hooman-in-the-Loop concept (Mosqueira-Rey et al., 2022; Wang et al., 2022). The most widespread ones during the analytical transformation of data in applied information systems are artificial neural networks, fuzzy logic and combined neuro-fuzzy networks (Mukhamediev et al., 2022; Ibrahim, 2004; Salleh et al., 2017), which are integrated into microcomputer devices in the form of software components (Laktionov et al., 2021; Laktionov et al., 2019; Laktionov et al., 2018*a*). The results of a detailed analysis of the current state of research and engineering solutions in the field of using artificial intelligence and machine learning methods in the development of information technologies for monitoring and control of agrotechnical processes are given in Table 3. It is worth noting that the list of scientific and practical achievements in the field of methods and means of intellectualization of agrotechnical information technologies given in Table 3 is not complete. It presents typical recent results that outline the significant effectiveness and width of the spectrum of tendencies in the use of machine learning and artificial intelligence methods in systems for monitoring and control of agrotechnical processes in greenhouses during the full cycle of crop vegetation.

Based on the analysis of the research results presented in Table 3, general trends in the use of artificial intelligence methods in agrotechnical information technologies were identified. Artificial neural networks are mainly used to solve the problem of predicting the dynamics of greenhouse microclimate, and Fuzzy logic and ANFIS – in solving the problems of intelligent and adaptive control of technological processes of greenhouse crop production.

Table 3. Results of the analysis of modern scientific and technical developments in the field of intellectualization of information technologies for agricultural use

The research subject	Used intelligent technologies	Reference source
Investigation of the effectiveness of using different machine learning methods with a teacher in solving the problem of predicting the energy performance of smart greenhouses	Artificial neural networks, Support vector machine, Gaussian process regression, Boosting	Ouazzani Chahidi et al., 2021
Research of methods of ensuring the integrity of intelligent data processing on the greenhouse microclimate based on U-Net technology	Convolutional neural networks	Moon et al., 2021
Development and research of methods for optimization of greenhouse microclimate control processes	Fuzzy logic	Faouzi et. al, 2016
Development of a computer model for assessing and forecasting the temperature and relative humidity of the greenhouse growing area based on the integrated intellectual processing of a number of factors of internal and external environment	Artificial neural networks (multilayer perceptron)	Petrakis et al., 2022
Development of hardware and software for adaptive control of greenhouse microclimate in the form of built-in fuzzy-PID controller	Fuzzy logic	Wang L. and Wang B., 2020
Research of methodology of centralised intelligent control of greenhouse microclimate based on hierarchical combination of neural networks and expert systems	Artificial neural networks and Expert systems	Capella et al., 2003
Development of a model for forecasting the temperature and humidity of the greenhouse growing area in the short term (for one day)	Artificial neural networks	Singh and Tiwari, 2017
Development of a computer dynamic model in Matlab & Simulink for processing experimental data on temperature and humidity control algorithms in greenhouses	Fuzzy logic	Riahi et al., 2020
Implementation of the software component of intelligent greenhouse microclimate control as a functional component of a microcomputer wireless monitoring system	Fuzzy logic, Wireless sensor networks	Rahmawati et al., 2018
Research of methods and means to improve the efficiency of regulation of greenhouse microclimate parameters	Adaptive neural-fuzzy inference system (ANFIS)	Oubehar et al., 2020
Development and experimental verification of the strategy of intelligent forecasting of temperature and humidity of the greenhouse growing area	Adaptive neural-fuzzy inference system (ANFIS)	Hamidane et al., 2021

Taking into account the qualitative solution of a wide range of problems in the development of computer models and software and hardware of applied information technologies, the theory of intelligent adaptive monitoring and control of agrotechnical processes is in the stage of its dynamic development and formation. One of the main issues of this theory, which requires additional research, is to consider the types and vegetation periods of greenhouse crops and crop rotation during the implementation of intelligent computer-oriented models and methods of online monitoring and automatic control of greenhouse microclimate.

1.3. Purpose, object, subject and structure of the study

The main purpose of the article is to substantiate the scientific and applied provisions for improving the efficiency of information technologies for agrotechnical purposes by developing a computer-oriented method of adaptive monitoring and control of temperature and humidity conditions of greenhouse cultivation based on Fuzzy logic. The research object is information processes of complex intellectualised transformation of measurement data on temperature and humidity of physical environments of greenhouse growing zone. The research subject is computer-oriented methods and models for processing measurement data on the integral temperature and humidity conditions of greenhouses. The structure of the article: section 1 grounds the relevance, purpose, objectives and expected scientific and applied effect of the research; section 2 provides information on the used technical means, methods and approaches to the research; section 3 presents the main results of theoretical and experimental studies; section 4 substantiates the priority areas for further research in this subject area; section 5 presents general conclusions.

1.4. Expected scientific and applied effect

The scientific novelty and practical significance of the results obtained in the article is the development of a computer-oriented method of intelligent transformation of measurement data of online monitoring and automatic control of air and soil temperature and humidity in the greenhouse growing zone. This method is based on the theory of Fuzzy logic and, unlike previously known ones, implements data processing algorithms taking into account the following destabilizing processes and factors: the dynamics of effective energy illumination in the visible wavelength range, seasonal crop rotation, type and vegetation period of crops grown.

2. Methods, tools and approaches to the research

2.1. Generalised approaches to the research

The methodological basis for solving the scientific problem is an integrated approach based on the following methods approved by the world science: analysis and generalisation of scientific, engineering and analytical results; computer modelling; fuzzy logic; synthesis and testing of software and hardware of technology. The planned research of this article is a logical continuation of the authors’ own theoretical and experimental research on the formalised description and physical modelling of the greenhouse microclimate monitoring systems (Laktionov et al., 2020*a*; Laktionov et al., 2020*b*; Laktionov et al., 2018*b*). The validity of the main research results was proved by computer experiments, which were implemented in the licensed software Matlab & Simulink.

2.2. Structural and algorithmic description of the computer-oriented model

The synthesis of scientific and applied provisions on the structural and algorithmic organisation of the computer-oriented model of adaptive monitoring and control of the temperature and humidity mode of greenhouse crop growing under conditions of uncertainty and scale of measurements at the first stage is associated with the solution of the problem of formalised description of information flows of the studied agrotechnical technology. In accordance with the general principles of the theory of situational modelling, a structural and algorithmic diagram of aggregation and transformation of measurement data was developed, as shown in Figure 3.

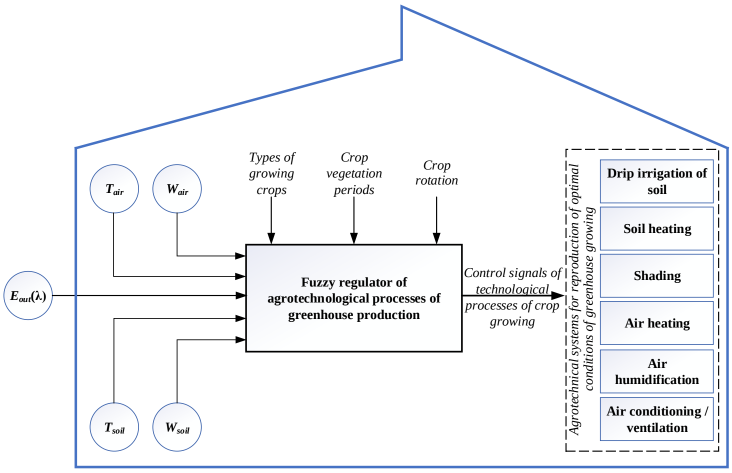


Figure 3. Structural and algorithmic organisation of information flows of monitoring and control of temperature and humidity mode of greenhouse cultivation

The following abbreviations and symbols are introduced in Figure 1: T_{air} – air temperature in the growing area; T_{soil} – soil temperature; W_{air} – air humidity of the growing area; W_{soil} – soil humidity; $E_{out}(\lambda)$ – effective energy illumination of the environment in the visible wavelength range.

The structural and algorithmic organisation shown in Figure 3 is the functional basis of the processes of transformation of information flows during the adaptive to crop types and vegetation periods computer-integrated monitoring and control of temperature and humidity growing conditions.

2.3. Theoretical and applied principles of the algorithm of fuzzy transformation of measurement data

Based on the analysis of the structural and algorithmic organisation of information technology, which is shown in Figure 3, it was found that generation of control signals for agrotechnical systems of reproduction and maintenance of optimal temperature and humidity conditions of greenhouse farming is influenced by three factors (types of crops, growing season and crop rotation) and five measured physical and chemical parameters (air temperature, air humidity, soil temperature, soil moisture, effective energy illumination). Thus, taking into account a significant number of factors and parameters, as well as the presence of functional relationships between them, we decided to build a fuzzy transformation model, which consists of two consecutive stages of fuzzification / defuzzification of information flows (see Fig. 4). This approach allows increasing the reliability, validity and precision of the automatic generation by the investigated computer-integrated model of decisions on adjusting the temperature and humidity conditions of greenhouse crop production.

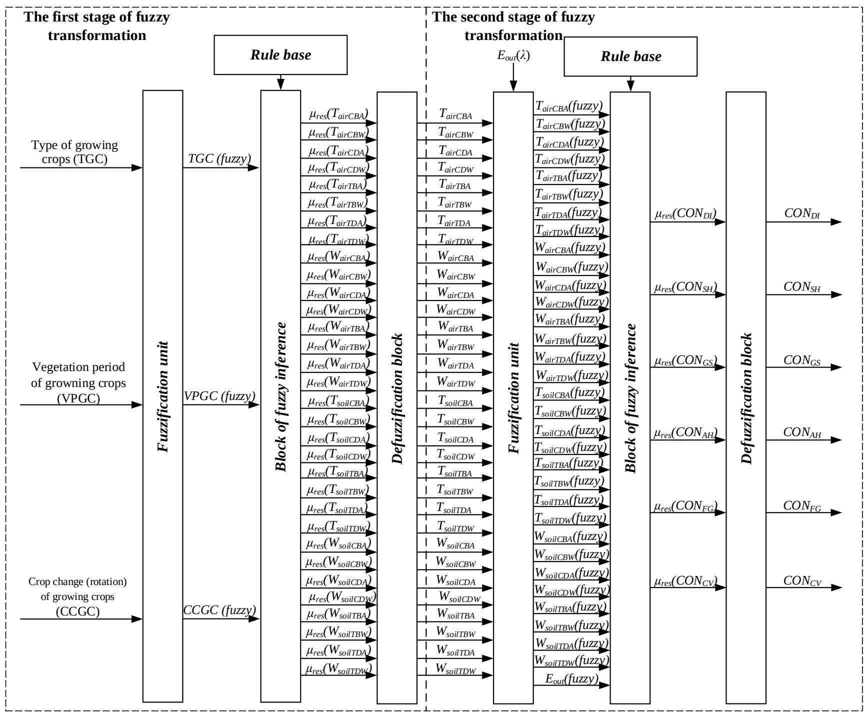


Fig. 4. Block diagram of fuzzy transformation of factors and measurement data

The following abbreviations and symbols are introduced in Figure 4: *TGC* – type of growing crops; *VPGC* – vegetation period of growing crops; *CCGC* – crop change (rotation) of growing crops; μ_{res} – resulting belonging function; T_{air} – air temperature in the growing area; T_{soil} – soil temperature; W_{air} – air humidity of the growing area; W_{soil} – soil humidity; indices: *C* – cucumber, *T* – tomato, *B* – before fruiting, *D* – during fruiting, *A* – autumn crop rotation, *W* – winter-spring crop rotation; $E_{out}(\lambda)$ – energy illumination of the environment; CON_{DI} – drip irrigation control signals; CON_{SH} – soil heating control signals; CON_{GS} – control signals for greenhouse shading mechanisms; CON_{AH} – control signals for heating the air of the growing area; CON_{FG} – control signals for humidifying the air by generating fog; CON_{CV} – control signals for air conditioning / ventilation.

Taking into account the current experience in the field of computer-integrated online monitoring and intelligent automatic control of agrotechnical modes of greenhouse crops growing based on the theory of fuzzy logic (Azaza et al., 2016; Alpay and Erdem, 2019; Ben Ali et al., 2016), the Mamdani algorithm was chosen as the basic fuzzy inference algorithm. At the first stage of developing a fuzzy computer-oriented model (see Fig. 4), the fuzzification of factors (crop change, type and vegetation period of greenhouse crops) affecting the temperature and humidity mode of greenhouse production was carried out. At the second stage, these results, together with the synthesised rule base, were used to implement fuzzy inference and defuzzification procedures for a set of physical and chemical parameters (temperature and humidity in the growing area and soil temperature and humidity) differentiated by the above factor requirements. At the third algorithm step, this set of physical and chemical parameters, taking into account the destabilising effect of light intensity, based on a synthesised rule base and complex data transformation (fuzzification – fuzzy inference – defuzzification), was used to generate solutions for automatic control of technical systems for reproducing and maintaining a regulated microclimate in greenhouses (drip irrigation; soil heating; shading; heating the air of the growing area; humidification and air conditioning / ventilation).

The fuzzy inference and defuzzification procedures are implemented based on the maximum algorithm and the centre of gravity method, respectively. The development of the fuzzy inference rule base is based on the logical generalisation of the experience of experts in the field of greenhouse vegetable production (Baudoin et al., 2013; Baudoin et al., 2017; WEB, a; FAO, 2021; VNTP APK, 2007). All factors and measured physical and chemical parameters are phased by piecewise linear (trapezoidal and triangular) membership functions that satisfy the condition of falling into a certain interval. The control signals of technical systems of greenhouses were fuzzified by s-shaped and inverse functions based on the requirement to prevent abrupt switching of control influences.

3. Research results

3.1. Models of functional units of fuzzy transformation

Based on the principle of decomposition of the research task and based on the developed structural diagram of processing information flows of data (see Fig. 4), computer models of the first (see Fig. 5) and second (see Fig. 6) stages of fuzzy transformation of factors and measurement data were developed in the Fuzzy Logic Toolbox extension package of the Matlab & Simulink software environment.

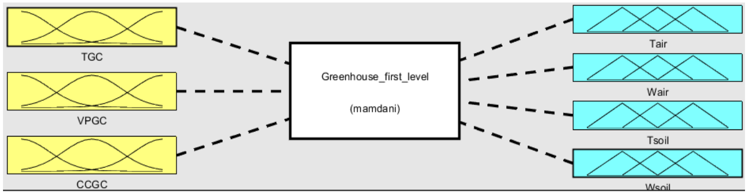


Figure 5. Functional diagram of the computer model of the first stage of fuzzy transformation of information flows

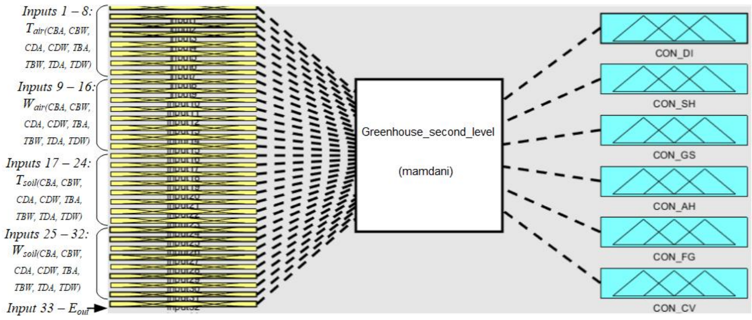
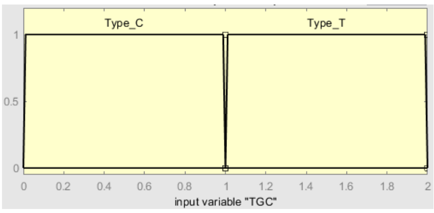


Figure 6. Functional diagram of the computer model of the second stage of fuzzy transformation of information flows

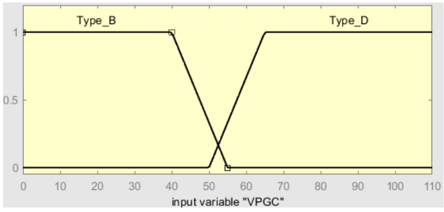
The symbolic notations in Figures 5 and 6 are identical to those in Figure 4. The above computer models are the structural and functional basis for further research on the synthesis and testing of a computer-oriented method of adaptive monitoring and control of temperature and humidity mode of greenhouse production.

3.2. Fuzzification of factors, input physical and chemical parameters and output control signals

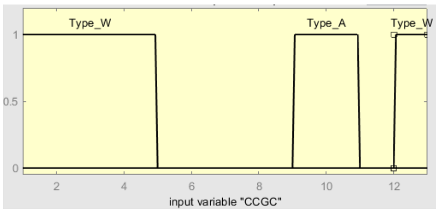
The process of fuzzification of the influencing factors, input physical and chemical parameters and output control signals of agrotechnical systems of greenhouses is implemented by software in the Fuzzy Logic Designer extension package of the Matlab & Simulink modelling environment in accordance with the methodology given in section 2.3 “Theoretical and applied principles of the algorithm of fuzzy transformation of measurement data”. The results of fuzzification of informative factors that affect the procedures for establishing and maintaining the recommended temperature and humidity mode of greenhouse growing are shown in Figure 7.



a) Type of crops grown
(*Type_C* – cucumbers; *Type_T* – tomatoes)



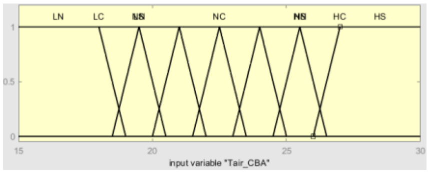
b) Vegetation period (*Type_B* – before fruiting;
Type_D – during fruiting): number of days



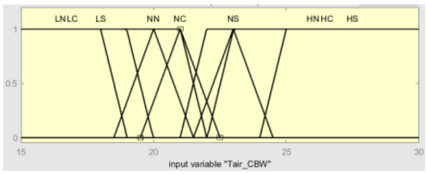
c) Crop rotation (*Type_A* – autumn; *Type_W* – winter-spring): serial numbers of months

Figure 7. Results of fuzzification of influencing factors

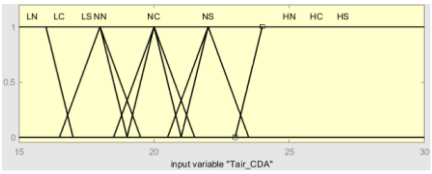
The results of fuzzification of parameters of soil and climatic conditions of the greenhouse are shown in Figure 8. When defining the terms of the linguistic variables of air and soil temperature and humidity, the corresponding numerical values were selected based on the data given in Table 2. All variables are fuzzified by three possible states (terms): below normal (*L*), normal (*N*) and above normal (*H*); for effective energy illumination: sunny weather (*S*); cloudy weather (*C*) and night (*NI*). The exception is air temperature (nine terms). This fact is due to the circumstance that the recommended standards are dependent on the effective energy illumination of the environment in the visible wavelength range, namely: for sunny conditions – below normal (*LS*), normal (*NS*) and above normal (*HS*); for cloudy weather conditions – below normal (*LC*), normal (*NC*) and above normal (*HC*); at night – below normal (*LN*), normal (*NN*) and above normal (*HN*). The intersection zones of the terms of the corresponding linguistic variables are determined on the basis of the boundary values of the monitoring uncertainties of soil and air temperature and humidity in the growing area (Both et al., 2015).



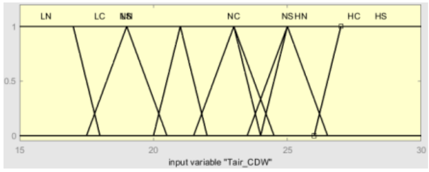
a) T_{airCBA}, °C



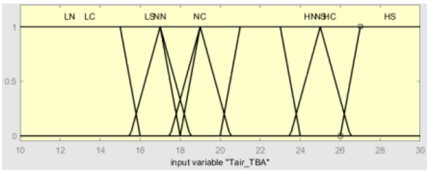
b) T_{airCBW}, °C



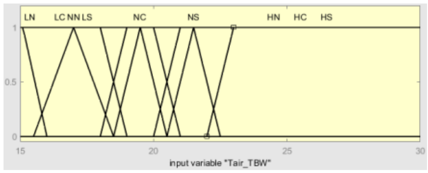
c) T_{airCDA}, °C



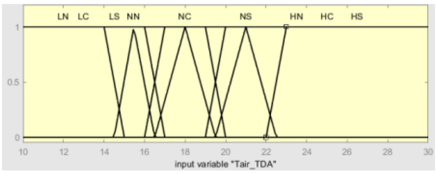
d) T_{airCDW}, °C



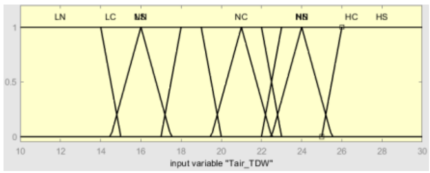
e) T_{airTBA}, °C



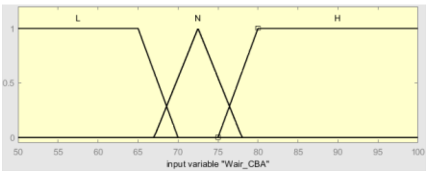
f) T_{airTBW}, °C



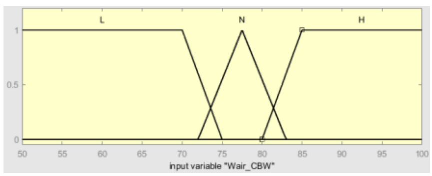
g) T_{airTDA}, °C



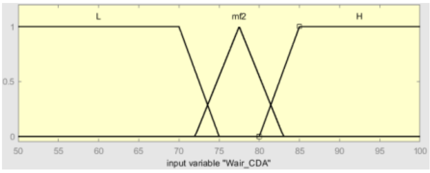
h) T_{airTDW}, °C



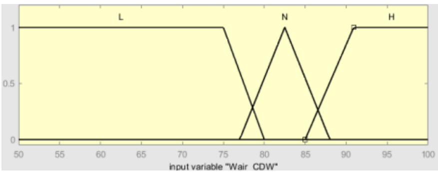
i) W_{airCBA}, %



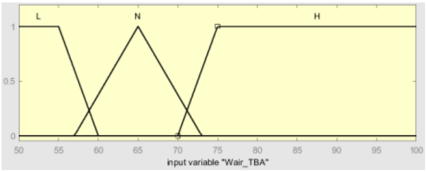
j) W_{airCBW}, %



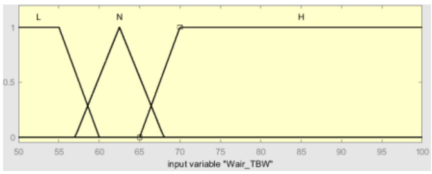
k) W_{airCDA}, %



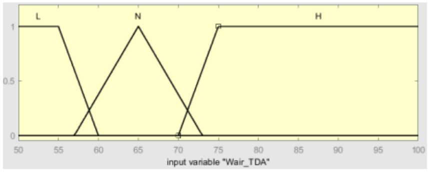
l) W_{airCDW}, %



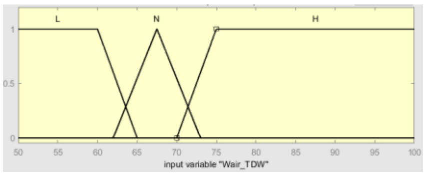
m) W_{airTBA}, %



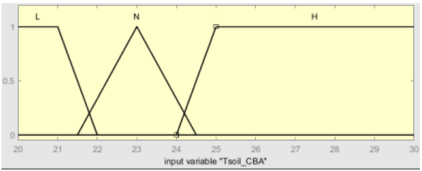
n) W_{airTBW}, %



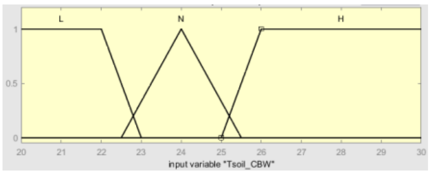
o) W_{airTDA}, %



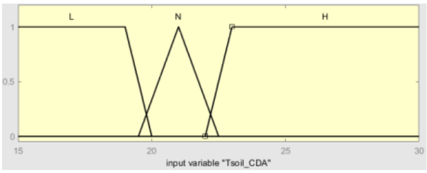
p) W_{airTDW}, %



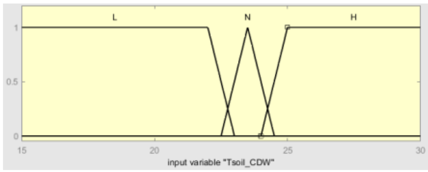
q) $T_{soilCBA}$, °C



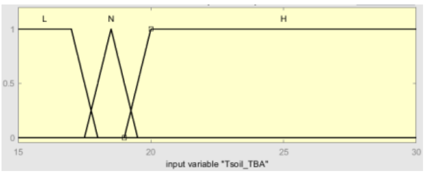
r) $T_{soilCBW}$, °C



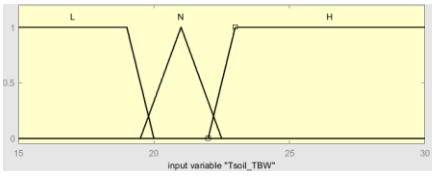
s) $T_{soilCDA}$, °C



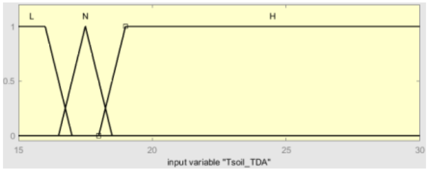
t) $T_{soilCDW}$, °C



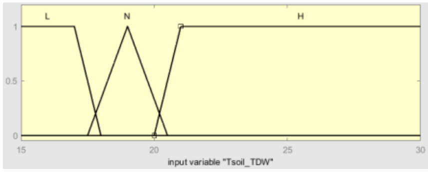
u) $T_{soilTBA}$, °C



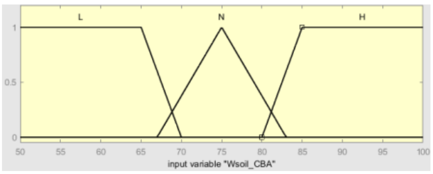
v) $T_{soilTBW}$, °C



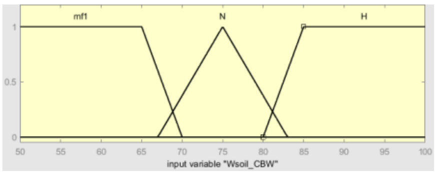
w) $T_{soilTDA}$, °C



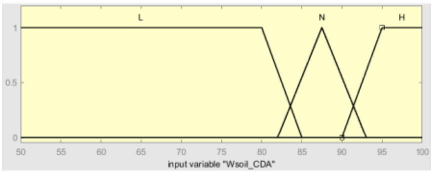
x) $T_{soilTDW}$, °C



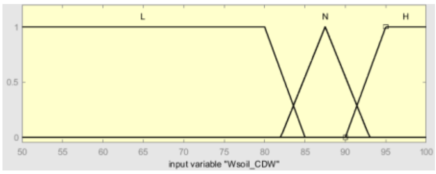
y) $W_{soilCBA}$, %



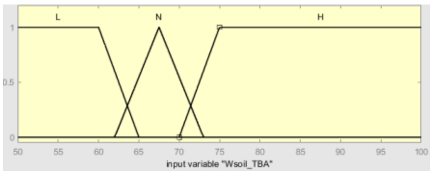
z) $W_{soilCBW}$, %



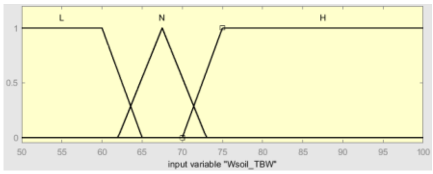
aa) $W_{soilCDA}$, %



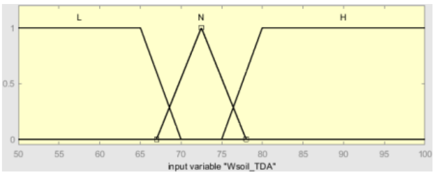
ab) $W_{soilCDW}$, %



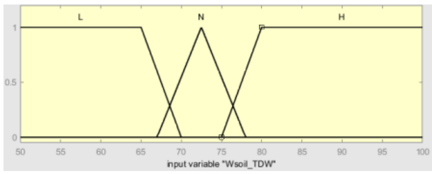
ac) $W_{soilTBA}$, %



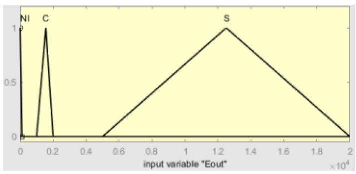
ad) $W_{soilTBW}$, %



ae) $W_{soilTDA}$, %



af) $W_{soilTDW}$, %



ag) $E_{out} \cdot 10^4$, lx

Figure 8. Results of fuzzification of input parameters (T_{air}, W_{air}, T_{soil}, W_{soil} – air and soil temperature and humidity; *C* – cucumber; *T* – tomato; *B*, *D* – before and during fruiting; *A*, *W* – autumn and winter-spring crop change; E_{out} – illumination of the environment)

The results of fuzzification of control signals for technical greenhouse systems are shown in Figure 9. These control signals are typical for all technical systems, because the logic of fuzzification of these signals is based on the algorithm of two position control and all linguistic variables are defined by the following terms: *ON* – on (for shading system – open and light enters the greenhouse); *OFF* – off (for shading system – closed and light does not enter the greenhouse).

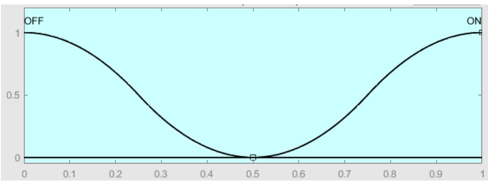


Figure 9. Results of fuzzification of control signals of greenhouse technical systems

The above results of fuzzification (see Figs. 7–9) are the informational and analytical basis for the development of rule bases of computer-integrated technology for intelligent monitoring and control of temperature and humidity mode of greenhouse vegetable production.

3.3. Fuzzy control rule base

The proposed and software implemented in the Fuzzy Logic Designer extension package of the Matlab & Simulink modelling environment the base of fuzzy control rules based on the principle of decomposition of the research problem was divided into two groups: for the first and second stages of fuzzy transformation of information flows (see Fig. 4). The set of rules for the first stage of transformation is as follows:

– IF TGC=Type_C and VPGC=Type_B and CCGC=Type_A THEN $T_{air}=T_{airCBA}$ and $W_{air}=W_{airCBA}$ and $T_{soil}=T_{soilCBA}$ and $W_{soil}=W_{soilCBA}$;
– IF TGC=Type_C and VPGC=Type_B and CCGC=Type_W THEN $T_{air}=T_{airCBW}$ and $W_{air}=W_{airCBW}$ and $T_{soil}=T_{soilCBW}$ and $W_{soil}=W_{soilCBW}$;
– IF TGC=Type_C and VPGC=Type_D and CCGC=Type_A THEN $T_{air}=T_{airCDA}$ and $W_{air}=W_{airCDA}$ and $T_{soil}=T_{soilCDA}$ and $W_{soil}=W_{soilCDA}$;
– IF TGC=Type_C and VPGC=Type_D and CCGC=Type_W THEN $T_{air}=T_{airCDW}$ and $W_{air}=W_{airCDW}$ and $T_{soil}=T_{soilCDW}$ and $W_{soil}=W_{soilCDW}$;
– IF TGC=Type_T and VPGC=Type_B and CCGC=Type_A THEN $T_{air}=T_{airTBA}$ and $W_{air}=W_{airTBA}$ and $T_{soil}=T_{soilTBA}$ and $W_{soil}=W_{soilTBA}$;
– IF TGC=Type_T and VPGC=Type_B and CCGC=Type_W THEN $T_{air}=T_{airTBW}$ and $W_{air}=W_{airTBW}$ and $T_{soil}=T_{soilTBW}$ and $W_{soil}=W_{soilTBW}$;
– IF TGC=Type_T and VPGC=Type_D and CCGC=Type_A THEN $T_{air}=T_{airTDA}$ and $W_{air}=W_{airTDA}$ and $T_{soil}=T_{soilTDA}$ and $W_{soil}=W_{soilTDA}$;
– IF TGC=Type_T and VPGC=Type_D and CCGC=Type_W THEN $T_{air}=T_{airTDW}$ and $W_{air}=W_{airTDW}$ and $T_{soil}=T_{soilTDW}$ and $W_{soil}=W_{soilTDW}$.

The second group includes rules that implement adaptive control of technical systems of greenhouses on the basis of intelligent transformation of the results of measuring monitoring physical and chemical parameters, taking into account the factors of crop rotation, crop types and vegetation periods:

– IF ((T_{airCBA}=NS or T_{airCBW}=NS or T_{airCDA}=NS or T_{airCDW}=NS or T_{airTBA}=NS or T_{airTBW}=NS or T_{airTDA}=NS or T_{airTDW}=NS) and E_{out}=S) or ((T_{airCBA}=NC or T_{airCBW}=NC or T_{airCDA}=NC or T_{airCDW}=NC or T_{airTBA}=NC or T_{airTBW}=NC or T_{airTDA}=NC or T_{airTDW}=NC) and E_{out}=C) or ((T_{airCBA}=NN or T_{airCBW}=NN or T_{airCDA}=NN or T_{airCDW}=NN or T_{airTBA}=NN or T_{airTBW}=NN or T_{airTDA}=NN or T_{airTDW}=NN) and E_{out}=NI) THEN CON_{AH}=OFF and CON_{GS}=ON;

– IF T_{airCBA}=LS or T_{airCBW}=LS or T_{airCDA}=LS or T_{airCDW}=LS or T_{airTBA}=LS or T_{airTBW}=LS or T_{airTDA}=LS or T_{airTDW}=LS or T_{airCBA}=LC or T_{airCBW}=LC or T_{airCDA}=LC or T_{airCDW}=LC or T_{airTBA}=LC or T_{airTBW}=LC or T_{airTDA}=LC or T_{airTDW}=LC or T_{airCBA}=LN or T_{airCBW}=LN or T_{airCDA}=LN or T_{airCDW}=LN or T_{airTBA}=LN or T_{airTBW}=LN or T_{airTDA}=LN or T_{airTDW}=LN THEN CON_{AH}=ON and CON_{GS}=ON and CON_{CV}=OFF and CON_{SH}=ON;

– IF (T_{airCBA}=HS or T_{airCBW}=HS or T_{airCDA}=HS or T_{airCDW}=HS or T_{airTBA}=HS or T_{airTBW}=HS or T_{airTDA}=HS or T_{airTDW}=HS) and E_{out}=S THEN CON_{AH}=OFF and CON_{GS}=OFF and CON_{CV}=ON;

– IF (T_{airCBA}=HC or T_{airCBW}=HC or T_{airCDA}=HC or T_{airCDW}=HC or T_{airTBA}=HC or T_{airTBW}=HC or T_{airTDA}=HC or T_{airTDW}=HC or T_{airCBA}=HN or T_{airCBW}=HN or T_{airCDA}=HN or T_{airCDW}=HN or T_{airTBA}=HN or T_{airTBW}=HN or T_{airTDA}=HN or T_{airTDW}=HN) and (E_{out}=C or E_{out}=NI) THEN CON_{AH}=OFF and CON_{GS}=ON and CON_{CV}=ON;

– IF W_{airCBA}=N or W_{airCBW}=N or $W_{sairCDA}$=N or W_{airCDW}=N or W_{airTBA}=N or W_{airTBW}=N or W_{airTDA}=N or W_{airTDW}=N THEN CON_{FG}=OFF and CON_{CV}=OFF;

– IF W_{airCBA}=L or W_{airCBW}=L or $W_{sairCDA}$=L or W_{airCDW}=L or W_{airTBA}=L or W_{airTBW}=L or W_{airTDA}=L or W_{airTDW}=L THEN CON_{FG}=ON and CON_{CV}=OFF and CON_{AH}=OFF;

– IF W_{airCBA}=H or W_{airCBW}=H or $W_{sairCDA}$=H or W_{airCDW}=H or W_{airTBA}=H or W_{airTBW}=H or W_{airTDA}=H or W_{airTDW}=H THEN CON_{FG}=OFF and CON_{CV}=ON and CON_{DI}=OFF;

– IF $T_{soilCBA}$=N or $T_{soilCBW}$=N or $T_{soilCDA}$=N or $T_{soilCDW}$=N or $T_{soilTBA}$=N or $T_{soilTBW}$=N or $T_{soilTDA}$=N or $T_{soilTDW}$=N THEN CON_{SH}=OFF and CON_{AH}=OFF;

– IF $T_{soilCBA}$=L or $T_{soilCBW}$=L or $T_{soilCDA}$=L or $T_{soilCDW}$=L or $T_{soilTBA}$=L or $T_{soilTBW}$=L or $T_{soilTDA}$=L or $T_{soilTDW}$=L THEN CON_{SH}=ON and CON_{CV}=OFF and CON_{DI}=OFF and CON_{GS}=ON;

– IF $T_{soilCBA}$=H or $T_{soilCBW}$=H or $T_{soilCDA}$=H or $T_{soilCDW}$=H or $T_{soilTBA}$=H or $T_{soilTBW}$=H or $T_{soilTDA}$=H or $T_{soilTDW}$=H THEN CON_{SH}=OFF and CON_{AH}=OFF and CON_{CV}=ON and CON_{GS}=OFF;

– IF $W_{soilCBA}$=N or $W_{soilCBW}$=N or $W_{soilCDA}$=N or $W_{soilCDW}$=N or $W_{soilTBA}$=N or $W_{soilTBW}$=N or $W_{soilTDA}$=N or $W_{soilTDW}$=N THEN CON_{DI}=OFF and CON_{SH}=OFF;

– IF $W_{soilCBA}$=L or $W_{soilCBW}$=L or $W_{soilCDA}$=L or $W_{soilCDW}$=L or $W_{soilTBA}$=L or $W_{soilTBW}$=L or $W_{soilTDA}$=L or $W_{soilTDW}$=L THEN CON_{DI}=ON and CON_{SH}=OFF and CON_{CV}=OFF;

– IF $W_{soilCBA}$=H or $W_{soilCBW}$=H or $W_{soilCDA}$=H or $W_{soilCDW}$=H or $W_{soilTBA}$=H or $W_{soilTBW}$=H or $W_{soilTDA}$=H or $W_{soilTDW}$=H THEN CON_{CV}=ON and CON_{SH}=ON and CON_{FG}=OFF.

The above base of rules for fuzzy transformation of data and informative factors regarding the temperature and humidity mode of greenhouse production takes into account the functional relationships between the physical and chemical parameters of the soil and climatic state of the greenhouse microclimate, and also during its synthesis, the mutually destabilising effects of technical systems were taken into account when generating the corresponding control signals. The synthesised rule base is the algorithmic basis of the software component of the investigated computer-integrated method.

3.4. Formalised description of fuzzy aggregation and defuzzification procedures

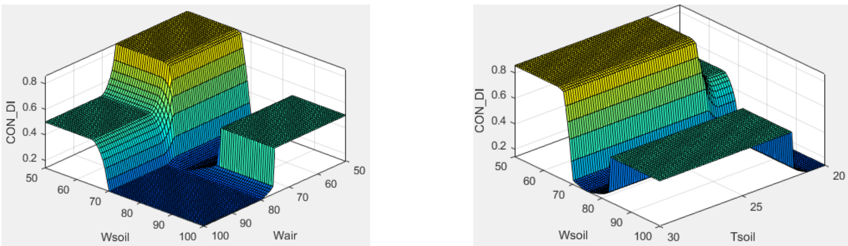
The stages of aggregation and defuzzification of the data transformation model during the implementation of the computer-integrated control method of temperature and humidity mode are implemented on the basis of the centroid maximal algorithm for all agrotechnical systems. The formalised description of these stages is as follows:

$$\begin{cases} \mu_{res}\left(CON_{DI}\right) = \max\left\{\min\left(TGC,\ VPGC,\ CCGC,\ W_{air},\ T_{soil},\ W_{soil}\right)\right\}; \\ \mu_{res}\left(CON_{SH}\right) = \max\left\{\min\left(TGC,\ VPGC,\ CCGC,\ T_{air},\ T_{soil},\ W_{soil}\right)\right\}; \\ \mu_{res}\left(CON_{GS}\right) = \max\left\{\min\left(TGC,\ VPGC,\ CCGC,\ T_{air},\ E_{out},\ T_{soil}\right)\right\}; \\ \mu_{res}\left(CON_{AH}\right) = \max\left\{\min\left(TGC,\ VPGC,\ CCGC,\ T_{air},\ W_{air},\ E_{out},\ T_{soil}\right)\right\}; \\ \mu_{res}\left(CON_{FG}\right) = \max\left\{\min\left(TGC,\ VPGC,\ CCGC,\ W_{air},\ W_{soil}\right)\right\}; \\ \mu_{res}\left(CON_{CV}\right) = \max\left\{\min\left(TGC,\ VPGC,\ CCGC,\ T_{air},\ W_{air},\ E_{out},\ T_{soil},\ W_{soil}\right)\right\}, \end{cases} \quad (1)$$

where μ_{res} – resulting membership function of the linguistic variable; *TGC* – type of crops; *VPGC* – vegetation period of crops; *CCGC* – crop rotation; T_{air} – air temperature in the growing area; T_{soil} – soil temperature; W_{air} – air humidity of the growing area; W_{soil} – soil humidity; E_{out} – integrated energy illumination of the environment; CON_{DI} – control signals for drip irrigation; CON_{SH} – control signals for soil heating; CON_{GS} – control signals for shading mechanisms; CON_{AH} – control signals for air heating; CON_{FG} – control signals for air humidification; CON_{CV} – control signals for air conditioning / ventilation.

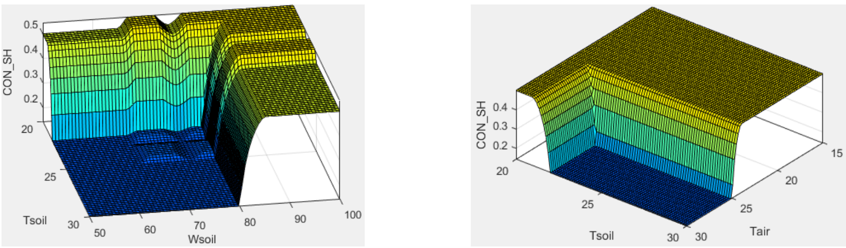
3.5. Results of the computer experiment

Based on the logical generalization and software implementation of the results of the developing computer-oriented method, which are set out in sections 3.1 – 3.4, a series of computer experiments were conducted in the Matlab & Simulink modelling environment. Differentiated for each agrotechnical system of microclimate regulation test results are shown in Figures 10 – 15. The graphical view of the results is given for the factors: crop rotation – autumn, crop type – cucumbers, vegetation period – before fruiting. For other factors, the results are identical in the shape of the surfaces and differ only in the numerical values of the ranges along the axes T_{air}, W_{air}, T_{soil} and W_{soil} (see Fig. 8).



a) $CON_{DI}=f(W_{soil}, W_{air})$ *b*) $CON_{DI}=f(W_{soil}, T_{soil})$

Figure 10. Dependence of drip irrigation system control signals



a) $CON_{SH}=f(T_{soil}, W_{soil})$ *b*) $CON_{SH}=f(T_{air}, T_{soil})$

Figure 11. Dependence of control signals of soil heating system

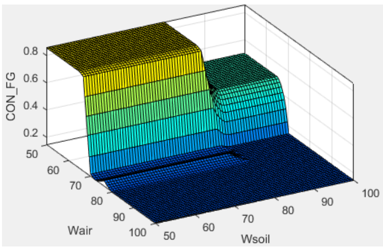
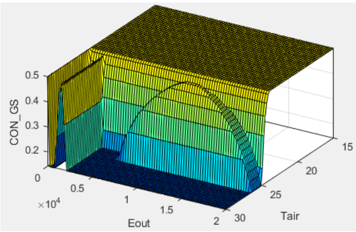
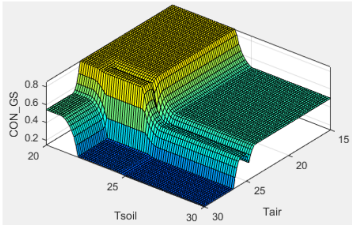


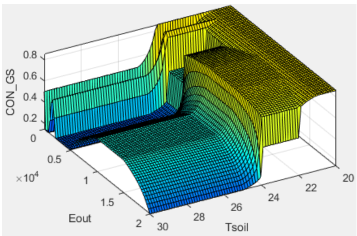
Fig. 12. Dependence of control signals of the air humidification system



a) $CON_{GS}=f(T_{air}, E_{out})$

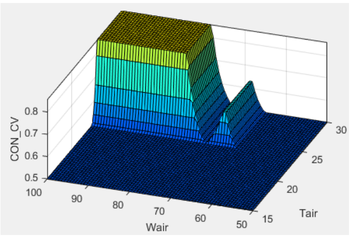


b) $CON_{GS}=f(T_{air}, T_{soil})$

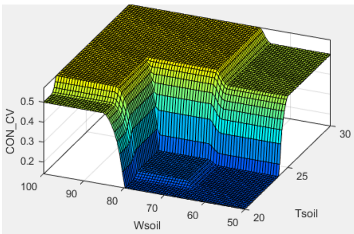


c) $CON_{GS}=f(E_{out}, T_{soil})$

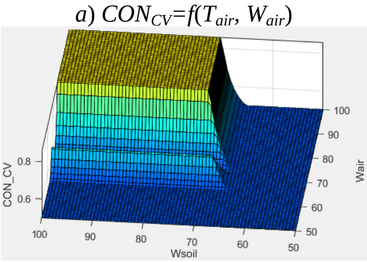
Figure 13. Dependence of greenhouse shading system control signals



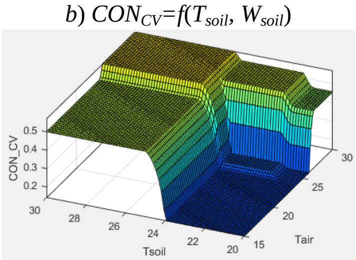
a) $CON_{CV}=f(T_{air}, W_{air})$



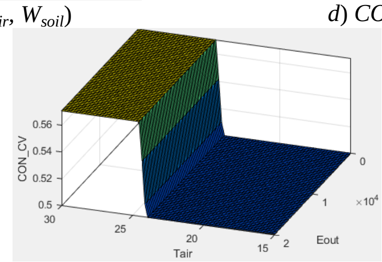
b) $CON_{CV}=f(T_{soil}, W_{soil})$



c) $CON_{CV}=f(W_{air}, W_{soil})$

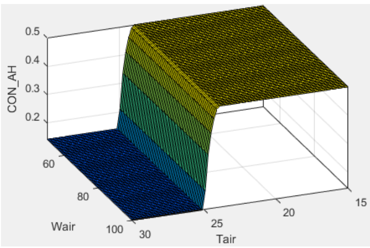


d) $CON_{CV}=f(T_{air}, T_{soil})$

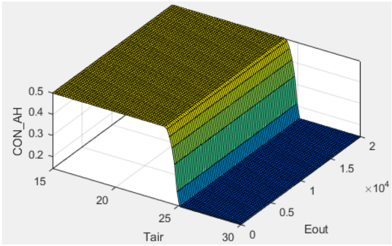


e) $CON_{CV}=f(T_{air}, E_{out})$

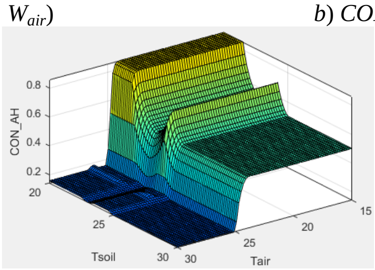
Figure 14. Dependence of air conditioning / ventilation system control signals



a) $CON_{AH}=f(T_{air}, W_{air})$



b) $CON_{AH}=f(T_{air}, E_{out})$



c) $CON_{AH}=f(T_{air}, T_{soil})$

Figure 15. Dependence of control signals of the air heating system of the growing zone

The obtained results of the computer experiment (see Figs. 10–15) prove the adequacy of the proposed method of intelligent monitoring and control of temperature and humidity mode of greenhouse production according to the following criteria: the algorithmic basis of the model is linguistically complete – each input state is matched with at least one output linguistic state; the rule base is numerically complete – each distinct input state leads to the activation of at least one rule; the functioning algorithms are consistent – under the same conditions there are no results with different conclusions; the rule base is functionally connected – there are no adjacent rules in which the intersection of the conclusions of fuzzy sets is empty. The proposed implementation of the monitoring and control method allows integrating complex adaptive computational algorithms into the microcontroller processing of measurement data. This, in turn, causes a positive effect of increasing reliability (by reducing hardware redundancy), efficiency (by implementing distributed computing at the physical level) and flexibility (due to the possibility of software reconfiguration by updating databases based on expert data) of industrial information systems and networks. Consequently, the developed computer-oriented method can be used as a structural and algorithmic basis for the design of applied information technologies for monitoring and controlling the greenhouse microclimate, subject to additional research, which are listed below as priority areas.

4. Discussion and suggestions for future investigations

The main scientific and practical effect of the results obtained in this article is the development of the theory of creation and implementation of applied intelligent information technologies for agrotechnical purposes through the development of a computer-oriented method of adaptive fuzzy transformation of measurement data of online monitoring and automatic control of air and soil temperature and humidity of the greenhouse growing zone.

The priority areas of further research of the developed computer-oriented method are: software and hardware implementation of the computer model based on serial sensor and microprocessor devices with further experimental tests in different climatic conditions of operation; scaling the model to a wider range of crops; integrated assessment of technical and economic indicators of the information technology.

In the near future, the priority tasks of further development of the proposed method are its adaptation to a wider range of crops and scaling in accordance with different volumes and sizes of greenhouses. The adaptation task may be implemented by varying the number and form of terms of the linguistic variables mentioned above in accordance with the recommended operating ranges of temperature and humidity of soil and air of greenhouses cultivation zone for specific agricultural crops. When solving the scaling problem, it is necessary to collect measurement data from a larger number of typical sensors with preliminary statistical processing of these measurement data. After that, these data may be used as informative in the developed computer-oriented model. The specified directions of research must go through the stages of theoretical development, laboratory and experimental testing in real agrotechnical conditions.

5. Conclusions

The article solves the topical problem of substantiating the scientific and practical provisions for the synthesis of a method of computer-oriented monitoring and control of temperature and humidity mode of growing vegetable crops in greenhouse conditions, which is adaptive to the factors of crop rotation, crop types and vegetation periods. The main results of the article are:

– critical criterion analysis and systematisation of known modern scientific and analytical research results in the field of computer-oriented and information technologies for intelligent monitoring and automatic control of agrotechnical purposes;

– detailed structural and algorithmic description of the computer-oriented model of monitoring and control of temperature and humidity of soil and air in the greenhouse growing area, taking into account informative factors and destabilising influences;

– software implementation, methodology and testing results of the computer model of information technology of fuzzy aggregation and transformation of measured data on temperature, humidity and soil conditions of greenhouse microclimate;

– substantiation of the evidence base for the feasibility of using the theory of fuzzy logic in computer-oriented intelligent monitoring and adaptive control of agrotechnical processes of greenhouse vegetable growing;

– substantiation of priority areas for further research on the modernization of the software and hardware base of agricultural enterprises of vegetable growing in greenhouses.

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Authors' information

Ivan LAKTIONOV is the Professor of the Department of Computer systems' software of Dnipro University of Technology (Dnipro, Ukraine). He received his Doctor of Science degree in 2021 majoring in computer systems and components. He specialises in advanced computer, sensor, infocommunication and microprocessor technologies of physical and chemical parameters monitoring and control systems. He is the author of more than 75 scientific works.

Oleksandr VOVNA is the Head of the Department of Electronic Engineering of SHEI 'DonNTU' (Lutsk, Ukraine). He received his Doctor of Science degree in 2015 majoring in computer systems and components. He specialises in development, simulation and research of computerized information-measuring systems for industrial applications. He is the author of more than 270 scientific works.

Maryna KABANETS is the Head of the Language Training Department of SHEI 'DonNTU' (Lutsk, Ukraine). She received her Doctor of Science degree in 2019 majoring in general pedagogy and history of pedagogy and her full professorship in 2021. She specialises in vocational education, teacher training, gifted education, creativity development and theory of higher education. She is the author of more than 80 scientific work.

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