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Synthesis and research of the intelligent automatic control system for a fruit drying apparatus

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ABSTRACT

Modern drying technologies are essential for extending the shelf life of fruits and vegetables while minimizing energy consumption and maintaining product quality. This study presents the development and implementation of an intelligent automatic control system for a conveyor-type fruit drying apparatus, integrating fuzzy logic and artificial neural network (ANN) methodologies. The novelty of the work lies in the first real-time application of a NARMA L2 neural network controller for regulating the air relative humidity in the drying chamber. Ripe fruits (apples, pears, apricots, and plums) with high moisture content were selected and processed under industrial conditions using a G4-KSK-15 conveyor-type dryer. A dynamic mathematical model of the drying process was constructed by approximating transient characteristics via a second-order transfer function. This model served as the foundation for simulating three control strategies in MATLAB/Simulink: classic PID, PID-Fuzzy, and PID-NARMA L2. Experimental validation demonstrated that the NARMA L2 controller significantly outperformed the other methods, achieving a 57% reduction in settling time and a 74% reduction in overshoot compared to the conventional PID regulator. The improved control response directly contributed to reduced energy consumption during the drying phase. This work confirms that intelligent control systems—particularly those incorporating ANN—enhance process stability, product quality, and energy efficiency in industrial fruit drying operations. The findings provide a foundation for broader application of AI-driven control systems in the food industry.

Keywords: fruit, drying, apparatus, intelligent system, computer model, Fuzzy controller, Narma L2 regulator, synthesis.

INTRODUCTION

Modern methods are being explored in drying fruits to enhance the quality of food products and their long-term storage. Drying is considered the best way to store fruits and vegetables, which reducing the amount of raw materials and their weight. This leads to a reduction in transportation costs and increases the shelf life of products, thereby limiting food losses. The quality of dried fruits and vegetables is closely connected with the development and optimization of new drying techniques, which should ensure high quality and energy efficiency of the dried product, so it becomes relevant to use intelligent control systems to carry out the drying process in the optimal mode **[1]**, and **[2]**.

The weaknesses of standard drying methods used for fruits and vegetables and the possible options for improving the quality of dried products by using various new drying techniques or their combination are discussed in the paper **[3]**. To improve the quality of the single-channel velocity ARS of apple residual moisture, a new stable ARS was developed using parametric synthesis and the root hodography method, which also provides better quality indicators compared to the two-channel ARS system **[4]**.

During the drying process, a functional-technological scheme for facility management and technological process software was developed in real time using the curve fitting technique and loaded into the intelligent processor of the dryer **[5]**.

The use of artificial intelligence to accurately predict the convective drying process of fruits and vegetables has been discussed, which could provide opportunities for enhancing quality control and efficiency in the industry **[6]**.

Mathematical models of various fruits have also been developed using the curve approximation method and loaded them into the intelligent dryer's processor, while the drying process is taking place in real time **[7]**.

It has been noted that the seasonality of fruits and vegetables greatly influences the search for methods that extend the shelf life of this category of food. It is noted that as a result of continuous technological changes, changes can also be observed in the methods of studying and studying food, as well as in its microbiological aspects. It is worth noting that a new trend in the use of bioactive ingredients is also emerging, which is reflected in numerous attempts to maintain the high quality of these products for an extended period. New and modern methods are being sought in this area, with the primary goal of supporting drying processes and ensuring quality control during food processing **[8]**.

The experimental results were simulated using artificial neural networks. To forecast the drying parameters, a model was developed to predict the drying time, thanks to a innovative interface **[9]**.

Solar drying has been shown to improve energy efficiency, however, traditional sun drying has limited drying capacity and can cause significant losses in product quality. Greenhouse and indirect solar drying are advanced drying methods that improve product quality. The authors developed a natural convection greenhouse dryer and a natural convection indirect solar dryer to study the drying characteristics of date palm fruit (*Phoenix dactylifera* L.) in terms of moisture content and convective heat transfer coefficients **[10]**.

Freeze-drying is a method used for valuable and heat-sensitive products, ensuring that the product features are best protected. In this study, the pomelo fruit (Citrus maxima) peel samples were dried in two different thicknesses (5 × 1 × 1 cm and 5 × 1 × 0.5 cm) by freeze drying (FD) as well as forced convection (FCD) and microwave drying. According to the experimental results, it was observed that the thin sample dried in a shorter time in all drying methods **[11]**.

The controller automatically activates and deactivates the air flow blower fans and heating elements to ensure rapid drying while maintaining high product quality. It has been proven that the process's efficiency increases with an increase in drying speed **[12]**.

Based on the analysis of the existing scientific papers on the presented topic, it was found that the existing automatic control systems (ACS) for drying fruits are not able to ensure optimal control of the technological process, which should be expressed in reducing the energy consumption of the drying process and improving the quality of the product by maintaining the standard amount of residual moisture.

Scientific novelty

The novelty of this research is the first implementation of a NARMA L2 neural network in real-time control of conveyor-type fruit dryers.

Objectives

The research aim is to provide optimal control of dynamic objects, particularly to improve the quality of the transient characteristics of the automatic regulation system (ARS) of residual moisture of fruits at the outlet of the dehydrator through the synthesis of a fuzzy controller and a neural network regulator, which leads to a reduction in energy consumption during the drying process and an improvement in the quality of the product.

Scientific Hypothesis

We hypothesize that the dynamic mathematical model (transfer function) developed by approximating the transient characteristic obtained through the "fan rotation speed - relative humidity" channel provides a reliable prediction of the product moisture content and temperature distribution at the dryer outlet. The developed mathematical model will also allow us to control the range of changes in the residual moisture content of the fruit at the dryer outlet during unforeseen random disturbances in the drying process.

A computer model of the automatic regulation system (ARS) for the relative humidity of the drying agent will be developed in the MATLAB/Simulink system using a classical PID (Proportional-Integral-Derivative) controller, a PID-fuzzy controller, and a PID-Narma L2 neural network controller. The synthesis algorithm of the PID-fuzzy controller and the Narma L2 regulator of the object will be developed and implemented using the Neural Network Toolbox application in MATLAB. Simulating the system's computer model will be possible, and the research will determine the advantages of any given regulator.

MATERIAL AND METHODS

Samples

We selected ripe fruits suitable for drying, such as apricots, pears, blue plums, and apples, products with high moisture content, to achieve the set goal. These fruits were purchased from farms in Gori (Georgia). Their dehydration presents considerable challenges because each type of fruit has specific properties and varying compositions, depending on its origin, growing conditions, and degree of ripeness. These properties also determine the nutritional value and taste.

Samples were collected and temporarily stored at a temperature of 7°C.

Equipment

We estimated the parameters of the mathematical model of the fruit drying process for an industrial conveyor-type dryer, type G4-KSK-15 (Belgorod region, Shebekino, Russia), which is equipped with:

- Conveyor belt speed and fan speed sensors in the heaters;
- Steam pressure and temperature sensors in the heaters;
- Air temperature and relative humidity sensors of type EE211 on the last conveyor.

The instruments presented in Figure 1 are standard blocks of the applied MATLAB package for computer modeling.

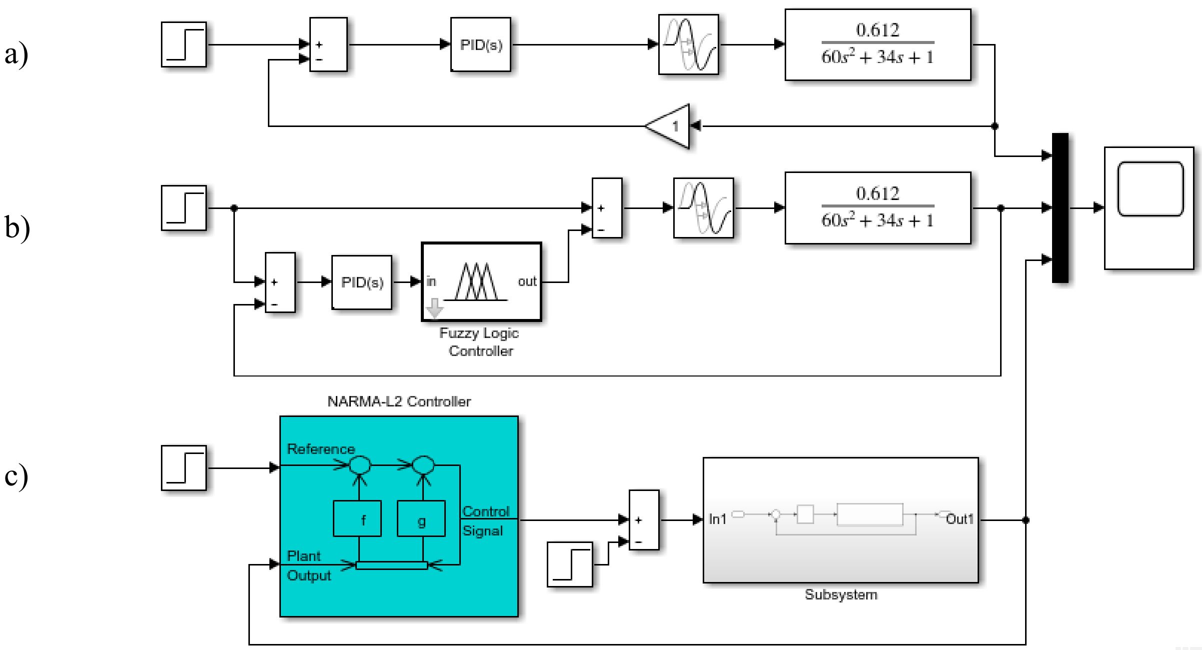


Figure 1 Structural block diagram of a computer model of an automatic regulation system for relative air humidity in a dryer.
Note: a) PID - classic controller; b) PID - fuzzy controller and c) PID-Narma L2 controller.

To ensure fulfillment of the goals stated in the paper, we offer fuzzy logic (fuzzy controller) and artificial neural network (ANN) control methods for intelligent control of systems. When building a smart control system of dynamic objects operating in real conditions, it is necessary to take into account the presence of uncorrelated disturbances in the system as well as the difference between the values of the modeled and the existing control system parameters **[13]**, **[14]**, **[15]**, and **[16]**.

The G4-KSK-15 conveyor-type convective drying unit is designed specifically for drying prunes**.** The detailed description and parameters of the device are presented in the scientific paper [**17**].

Laboratory Methods

The work utilized methods of convective drying, mathematical and computational modeling, and experimental research, which are based on determining drying and heat transfer coefficients, solving systems of differential equations, and describing the changes in relative humidity of the drying agent, temperature, and moisture content of the product at the drying outlet in real-time.

Changes in air temperature and relative humidity during drying were recorded synchronously using sensors mounted on the drying apparatus to measure humidity and air temperature. Experimental data were continuously recorded in real time for 200 s, and processed at 10 s intervals.

The residual moisture content of the dried product is controlled under industrial conditions through periodic sampling and laboratory analysis following the ISO 1446:2018 standard **[18]**.

We measured the moisture content of the product at both the inlet and outlet of the drying chamber through laboratory analysis of a sample.

Description of the Experiment

In our previous article, the experimental study of the conveyor dryer led to the development of dynamic (transient) characteristics of the fruit drying process, including the „steam pressure in the heater – relative humidity of the drying agent" channel. From this, it can be seen that the relative humidity of the air at the dryer outlet decreases with a certain inertia from 57.25% to 47.54% **[17]**, which in the presented paper was approximated by us **[19]**, **[20]**, **[21]**, **[22]** and **[23]** with a second-order polynomial (transfer function), the adequacy of which can be judged based on the research results with an accuracy of 95% to 98%.

The primary technological parameter is the residual moisture of the dried product, which is controlled under industrial conditions through periodic sampling and laboratory analysis, as specified in ISO 1446:2018 **[18]**.

Quality Assurance

Number of repeated analyses: Nine (three analyses repeated three times).

Number of experiment replications: Nine (three experiments, each repeated three times).

Calibration Characteristics of the Air Humidity Sensor:

- Measurement range: From 0 to 100% relative humidity;
- Measurement accuracy**:** ±0.1%
- Response time (signal stabilization): 17 s.

Reference materials: For the verification of laboratory equipment **[1]**, **[2]**, **[3]**, **[4]** methods **[5]**, **[6]**, **[7]**, **[8]** tests **[9]**, **[10]**, **[11]** and kits used **[12]**, **[13]**, **[14]**, **[15]**, **[16]** we have reviewed references.

Laboratory accreditation: The experiments were conducted in an industrial enterprise with a laboratory accredited to the international standard ISO 17025.

Data Access

The data supporting this study's results will be openly available at the Akaki Tsereteli State University Library (info@atsu.edu.ge) upon publication of the article.

Statistical Analysis

To analyze the test parameters of the product, a statistical analysis of the obtained data is conducted, and the reliability of the received data is evaluated using the T-test method of mathematical statistics, with the Windows IBM SPSS Statistics version 20.0 program (IBM, Armonk, New York, USA). We utilized the statistical functions for the arithmetic mean and the standard error to describe the ordered sample. We selected a reliability value of $p < 0.05$.

RESULTS AND DISCUSSION

Discuss the practical application of artificial intelligence as of a neural network model for the automatic control system of air relative humidity during the convective drying of fruits. When developing an automatic air relative humidity control system at the dryer outlet, based on FUZZY controllers and ANN, we must take into account that the precision of control over the dynamics of the controlled object depends on the selection of input data for the network signals, the number of hidden layers, and the neurons they contain **[24]**.

A comprehensive study is presented on the application of phase proportional-integral-derivative (FPID) controller to improve voltage regulation in automatic voltage regulator (AVR) systems. The conventional Proportional-Integral-Derivative (PID) control strategy is augmented with fuzzy logic (FL) to address the challenges associated with nonlinearities, uncertainties, and dynamic variations in power systems. This paper delves into the design process, including the selection of appropriate fuzzy sets, membership functions (MF), and rule base construction. Special emphasis is placed on the tuning of fuzzy parameters to optimize the controller's performance in voltage regulation tasks. Comparative studies are conducted to evaluate the FPID controller against traditional PID controllers, simple fuzzy controllers (FCs), and recent published literature to showcase its superior adaptability in scenarios where precise system models are challenging to obtain. Simulation results are obtained in MATLAB/SIMULINK to demonstrate the efficacy of the FPID controller in maintaining voltage stability, reducing settling time, overshooting, improving the transient response of the AVR system, and contributing to its robustness in the presence of changing system time constants **[25]**.

An in-depth review of the use of artificial intelligence (AI) using multilayer perceptron networks (MLPN) and other machine learning algorithms is proposed to effectively predict and classify the resulting vegetables and fruits during convection and spray drying. Artificial intelligence in food drying, particularly for entrepreneurs and researchers, presents a significant opportunity to accelerate development, reduce production costs, effectively control quality, and enhance production efficiency. Current scientific evidence confirms that the selection of appropriate parameters, including color, shape, texture, sound, initial volume, drying time, air temperature, air flow rate, area difference, moisture content, and final thickness, affects the yield as well as the quality of the resulting dried vegetables and fruits. Furthermore, scientific findings confirm that AI-supported fruit and vegetable drying technology offers an alternative for process optimization and quality control and can even indirectly extend the freshness of various nutrient-rich foods. The main challenge in the future will be to utilize AI in most production lines in real-time, to control process parameters, or to monitor the quality of raw materials obtained during the drying process **[8]**.

The thermal characteristics of drying equipment were studied in terms of energy efficiency. The higher convective heat transfer coefficient of the greenhouse dryer reduced the drying time and achieved the energy efficiency of indirect solar drying. The experimental data were fitted to various drying models, with the Lewis model yielding the best fit. The experimental errors were analyzed in terms of percentage uncertainty. Drying units can be a sustainable method for drying produce, especially in rural areas where advanced drying mechanisms are not yet available **[10]**.

The shortest drying time of pomelo (Citrus maxima) peel samples was recorded using the microwave drying method. The experimental results were modeled using artificial neural networks, a machine learning approach. Two different models were developed to predict drying parameters. The first model predicts mass-dependent parameters (sample mass, moisture content, and moisture ratio). The second model was developed for predicting drying times. At the same time, it is intended that users can quickly and easily expect the specified parameters thanks to the smart interface developed, **[11]**.

In the dryer, the air relative humidity model is represented using a computer model with a PID (Proportional-Integral-Derivative) classical regulator, a FUZZY controller block, and an NARMA (Nonlinear Autoregressive Moving Average) neural network regulator, as shown in Figure 1a.

The authors of this article, based on the experimental study presented in **[17]**, developed a dynamic mathematical model- transfer function of the channel "steam pressure in the heater - relative humidity".

$$W_0(s) = \frac{0.612}{60s^2+34s+1} \cdot e^{-14s} \quad (1)$$

Where: S - Ratio of the Laplace transform.

An improved neural network (INN) proportional-integral-derivative (PID) controller (INN-PID) has been developed. The dynamic performance of the PID, neural network PID (NN-PID) and INN-PID controllers was simulated with unit step signals as an input in MATLAB software. The simulation results show that the INN-PID controller outperforms the other two controllers in terms of control accuracy and regulation time **[15]**.

A three-dimensional numerical model is presented to study the effects of external vibration on the drying process of porous media. The model is based on a comparison of heat and mass transfer phenomena that arise during vibrating drying of unsaturated porous medium for two cases: triangular and sinusoidal external vibrations. The three-dimensional unstructured Control Volume Finite Element Method (CVFEM) is employed to simulate the vibrating drying. Numerical results of the time evolution of temperature, liquid saturation, pressure, and water content are compared and analyzed for the two cases **[29]**.

The simulation of a vacuum drying process using COMSOL Multiphysics software is presented, which is an effective tool for analyzing heat and mass transfer processes. This program allows you to monitor the temperature and humidity during the drying process and determine the optimal drying conditions **[30]**.

Mathematical modeling of a vector-controlled Permanent Magnet Synchronous Motor (PMSM) as an Electric Vehicle (EV) propulsion system using a Proportional Integral (PI) controller or a Proportional Integral Derivative (PID) controller is presented. The performance analysis of the drive is evaluated under transient conditions for settling time, rise time, steady state error of speed, and the vehicle's acceleration at the wheel axle for specifically designated values validated by MATLAB/Simulink **[31]**.

The PID controller is mathematically represented as follows **[13]**, **[30]**, and **[31]**.

$$y(t) = K_p \cdot \varepsilon(t) + K_I \int \varepsilon(t)dt + K_D \cdot \frac{d\varepsilon(t)}{dt} \quad (2)$$

Where: K_p- amplification factor; K_I - integral action time; K_D – derivative time; $\varepsilon(t)$- error signal, while:

$$x_1 \epsilon \left[-\frac{1}{P}, \frac{1}{P}\right],\ x_2 \epsilon \left[-\frac{1}{I}, \frac{1}{I}\right],\ x_3 \epsilon \left[-\frac{1}{D}, \frac{1}{D}\right] \quad (3)$$

Where: P, I, D – respectively, proportional, integral and differential components.

The transfer function parameters of the object during the convective drying of apples, the parameters and transient characteristics of the PID ($K_{P} = 4.75$; $K_I = 0.11$; $K_D = 43.22$) regulator of ARS, taking into account the stability condition, are determined using the pidtune function of the Matlab system and the Simulink *p*rogram's Control System Toolbox package with automatic control of the PID regulator in real-time mode **[13]**, **[17]**. The transient characteristic of the automatic regulation system of air relative humidity at the dryer outlet (with a PID – classical controller) is presented in Figure 4, Curve 1, from which the roughness of the system's performance indicators (in the paper, performance indicators are generally evaluated by Ts – regulation time, s overshoot, and σ – re-regulation, %) is visible. Based on the above, to improve the quality of the dryer's dynamic characteristics, we consider it advisable to develop an optimal control system for the fruit drying apparatus by synthesizing a FUZZY controller and NARMA-L2 neural network regulator.

In the paper, Alkahdery [19] presents an automatic control system PID, together with sensors, that allows the temperature and humidity of the drying chamber to be adjusted online to predefined parameters. The fan automatically changes its speed using pulse width modulation techniques for energy efficiency, depending on the required temperature of the drying chamber. The control system based on the Arduino

Uno board is built into the solar dryer, after which tests are carried out. According to experimental data, the system offers a flexible solution for various climatic zones and dried products, demonstrating its effectiveness in controlling the drying environment.

The authors of the article **[32]**, describe current problems of the residual moisture control loop of drying material in a dryer, for automation of drying processes and their solving utilizing fuzzy controller. The paper also presents the results of implementing an automatic control system with different configurations, as well as a comparative analysis of these configurations. The effectiveness of using fuzzy controllers is shown by an example of a drying apparatus control system.

1. Modeling and synthesis of the ACS of a drying machine with a fuzzy controller

Fuzzy control implies the application of a standard methodology based on the theory of fuzzy sets and the theory of fuzzy logic to solve control problems. It can be effective when there is no clear model for the control process or when the analytical mathematical model is very complex **[20]**.

A new Proportional-Integral-Derivative (PID)-type fuzzy logic controller (FLC) tuning strategy based on direct fuzzy relations is proposed to compute the PID constants. The motion control algorithm is composed by PID-type FLC and S-curve velocity profile, which is developed in C/C++ programming language**.** The experimental results were obtained on a linear platform integrated with a direct current (DC) motor, which was connected to an encoder to measure the position, **[33]**.

In the real system, the single-link manipulator was controlled using a stepper motor. The single-link manipulator is modeled with a stepper motor through a gearbox. The NARMA-L2 controller based on an artificial neural network (ANN) was preferred for controlling the stepper motor. The NARMA-L2 controller offers superior performance, especially in the control of nonlinear loads. Firstly, simulation of the single-link manipulator and the stepper motor, which also included resonance moments, was carried out in the MATLAB/Simulink environment. Then the training data of the NARMA-L2 controller was created and the training process was realized. Position control of the stepper motor was performed in a MATLAB/Simulink environment using a conventional control method and an NARMA-L2 controller. The simulation results were obtained at three different speeds and for different angle values **[34]**.

The block diagram of a computer model of the PID-Fuzzy controller control system, developed using Matlab/Simulink, is illustrated in Figure 1,b, which is a graphical environment for simulation modeling and allows building a dynamic model using a block diagram **[13]**, **[19]**, **[32]** and **[33]**. The dehydrator's fuzzy controller (Figure 1, b) was designed using the seven rules of the known algorithm, the rules of which are presented in Table 1. At that time, each subsequent phase at the inlet takes the value obtained at the previous stage **[13]**, **[20]**, **[25]** and **[33]**. In addition, we entered X1, X2, and X3 input variables and output <<Out>> variables. We constructed the membership functions for the terms of the used variables, (Figure 2). After that, these rules are formed in the fuzzy controller block of the drying machine's ACS (Figure 3).

Table 1 The rule for setting up the fuzzy controller of the ACS of the drying machine.

№	fuzzy controller rules
1	If (X1=good), then (Out=Z)
2	If (X1=low), then (Out=LP)
3	If (X1=high), then (Out=LN)
4	If (X1=good) and (X2=positive), then (Out=SP)
5	If (X1=good) and (X2=negative), then (Out=SN)
6	If (X1=good) and (X3=positive), then (Out=BP)
7	If (X1=good) and (X3=negative), then (Out=BN)

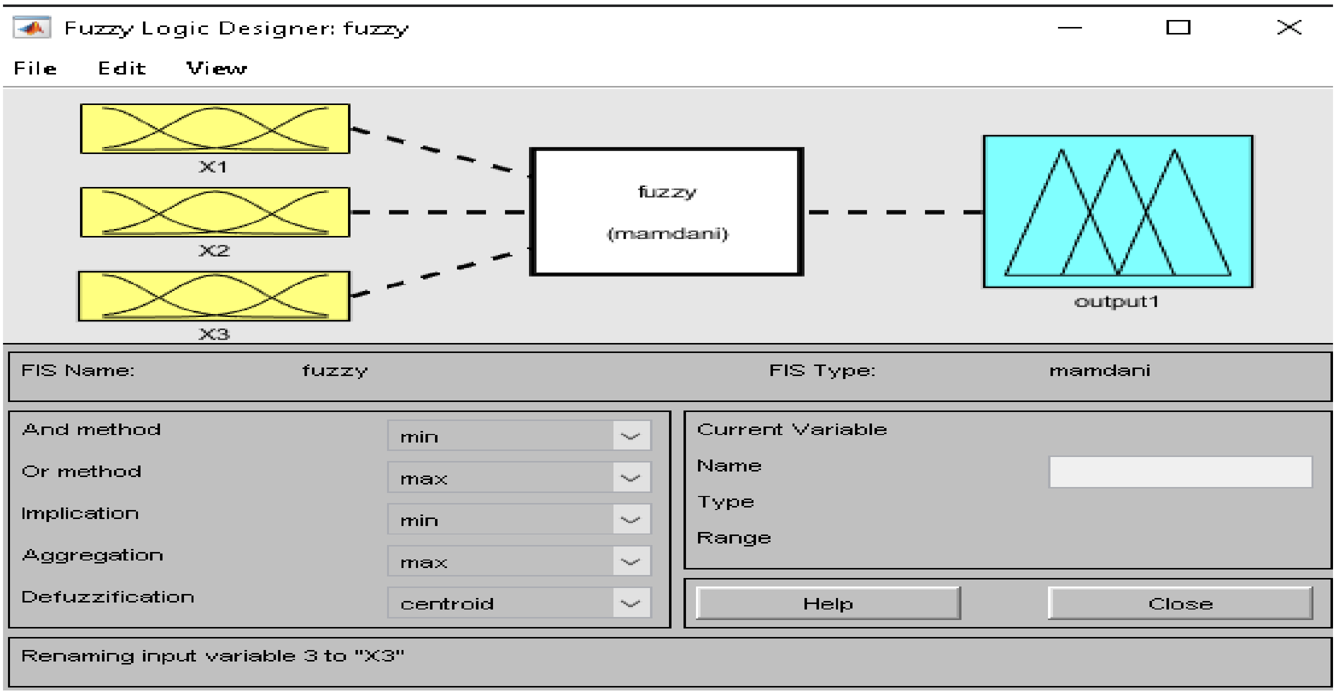


Figure 2 The input and output variables of the fuzzy controller block of the ACS of the drying machine.

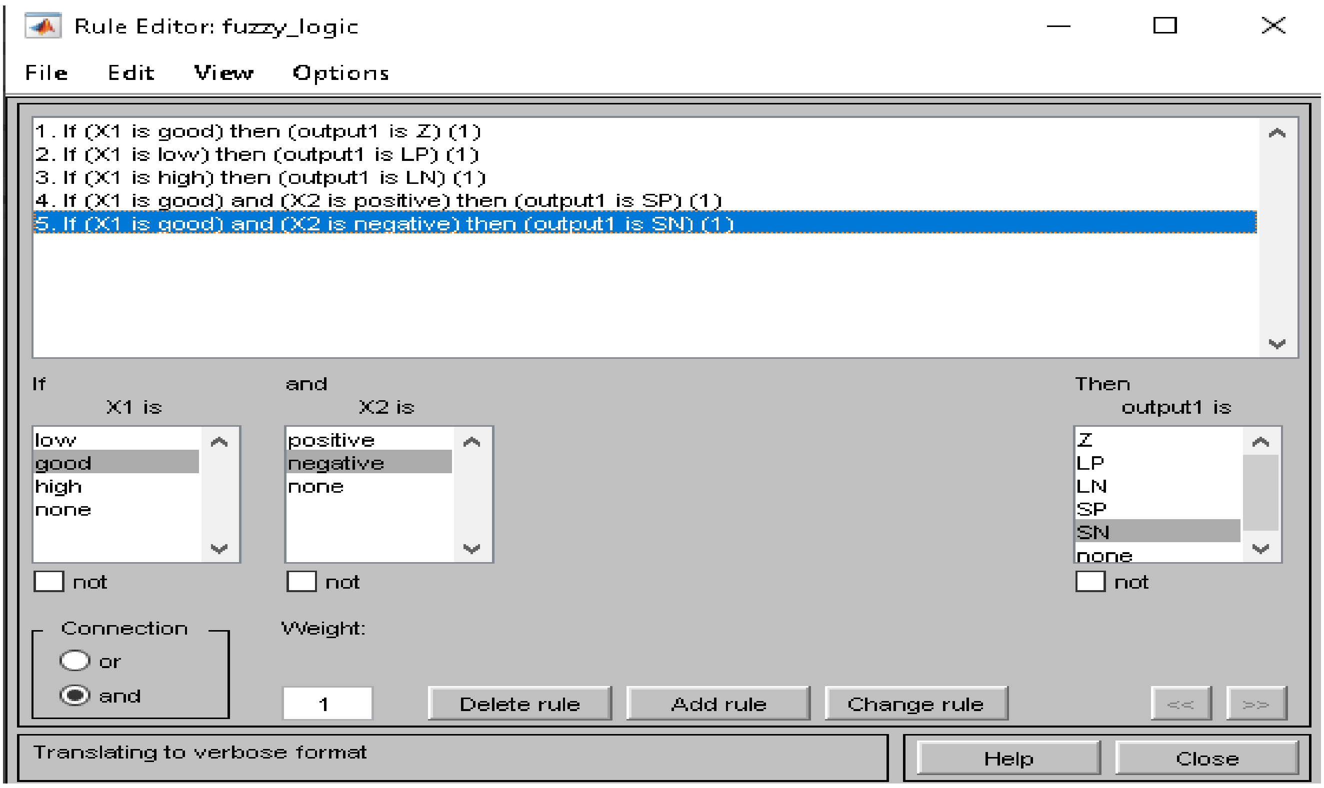


Figure 3 The block for setting up the fuzzy controller of the ACS of the drying machine.

Settings of the fuzzy controller of the ACS of the dehydrator are exported in the MatLab programming environment **[17]**, **[19]** and **[26]**. Then we connect settings to the fuzzy controller in the Simulink model. Finally, we obtain the ARS PID-fuzzy controller for air relative humidity at the dryer outlet, whose transient characteristics are shown in Figure 4, curve 2.

Although the phased controller improves performance compared to the classical PID, it remains more sensitive to poorly fitted rules and lacks the adaptive learning capabilities of neural networks.

Compared to the fuzzy PID implementation described by Garcia-Martinez et al. **[33]**, our model achieved 15% shorter settling times and reduced overshoot, highlighting the benefits of fuzzy adaptation in moisture-critical applications.

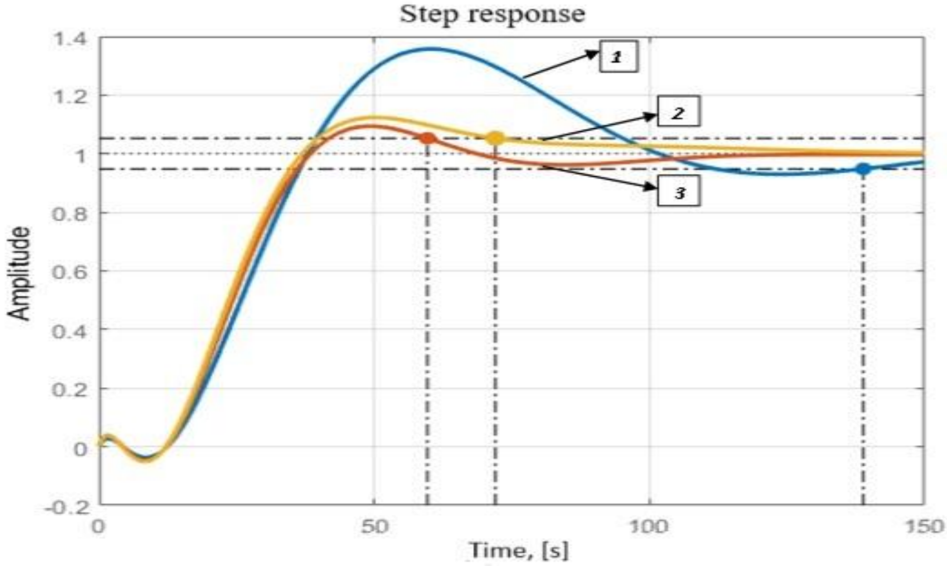


Figure 4 Transient characteristics obtained as a result of the study of the ACS of the drying machine during the drying of apples.
Note: 1. With a classic PID controller; 2. with a PID-fuzzy controller; and 3. with a PID-Narma L2 controller.

2. Modeling and synthesis of a drying machine with a Narma L2 neural network controller

There are neural network regulators of various architectures, among which Narma L2 is preferred, which is implemented with the Shallow Neural Network Toolbox package of the Matlab/Simulink utility. The regulator of this architecture (Figure 1c) is a modified neural network model of the control process, which is obtained during the autonomous identification stage and requires the least amount of computation. Real-time computations are only related to neural network implementations **[32]** and **[35]**.

The Narma L2 Controller synthesis files are located in the toolbox/net control directory of the Simulink system: Nncontrolutil, a support that provides access to private functions in Simulink; Sfunxy 2, a graph output function; and Nnident.m, a function used to identify the controlled object. The regulator's design process consists of two stages: the identification of the controlled object and the control law synthesis **[17]**, and **[34]**.

Examples of control theory systems implemented and solved in Matlab are presented in **[36]**. It discusses classical and modern control theory problems, including the analysis of first- and second-order systems, root locus techniques, controller design, pole placement, observer design, and the implementation of Simulink models, among others. These topics are discussed with many physical applications.

Replacing classical control with deep neural networks is a successful field in practical and medical fields, and is characterized by its ability to learn and train, as it is a field of machine learning and artificial intelligence. The results proved that the functioning of the neural networks and their performance is similar to classical control systems, with the advantage of simplicity and adaptability **[37]**.

Implementing the process of synthesis of the neuron controller begins with activating the Narma L2 controller block. The Plant Identification Narma-L2 window shown in Figure 5 will appear. The incident function is used to construct the window and implement the identification procedure.

The identification procedure requires settings for the architecture, training sequence, and teaching **[14]**.

When discussing the intellectualization of management systems, the need for intellectualization of a wide range of systems and management methods has been confirmed **[38]**. The hierarchy of levels of intelligent control, which is observed, is given and a comparative analysis of various artificial intelligence devices is given. The importance of addressing the challenges of goal-setting automation in control systems is recognized, as is the need to humanize anthropocentric systems, including those based on phase logic and case-based reasoning. Logical-linguistic and analytical phase controllers based on Zadeh's phase logic, Mamdani and Lukasevich implication are discussed. An overview of Mamdani-type controllers, which are based on the TS model, is provided. The conditions of optimality and stability of control systems with Mamdani phase controllers are analyzed. Sugeno dynamic models and ANFIS adaptive models are discussed, as well as learning methods developed based on fuzzy controllers.

Parameters given in the identification window shown in Figure 5 correspond to the neural network elements: the size of the covered layer S = 8, the number of delay elements at the inlet of the model N_i = 3, and the number of delay elements at the outlet of the model N_J = 2. Each subsequent element appears in a separate window when activating the previous element by double-clicking the mouse button **[38]**.

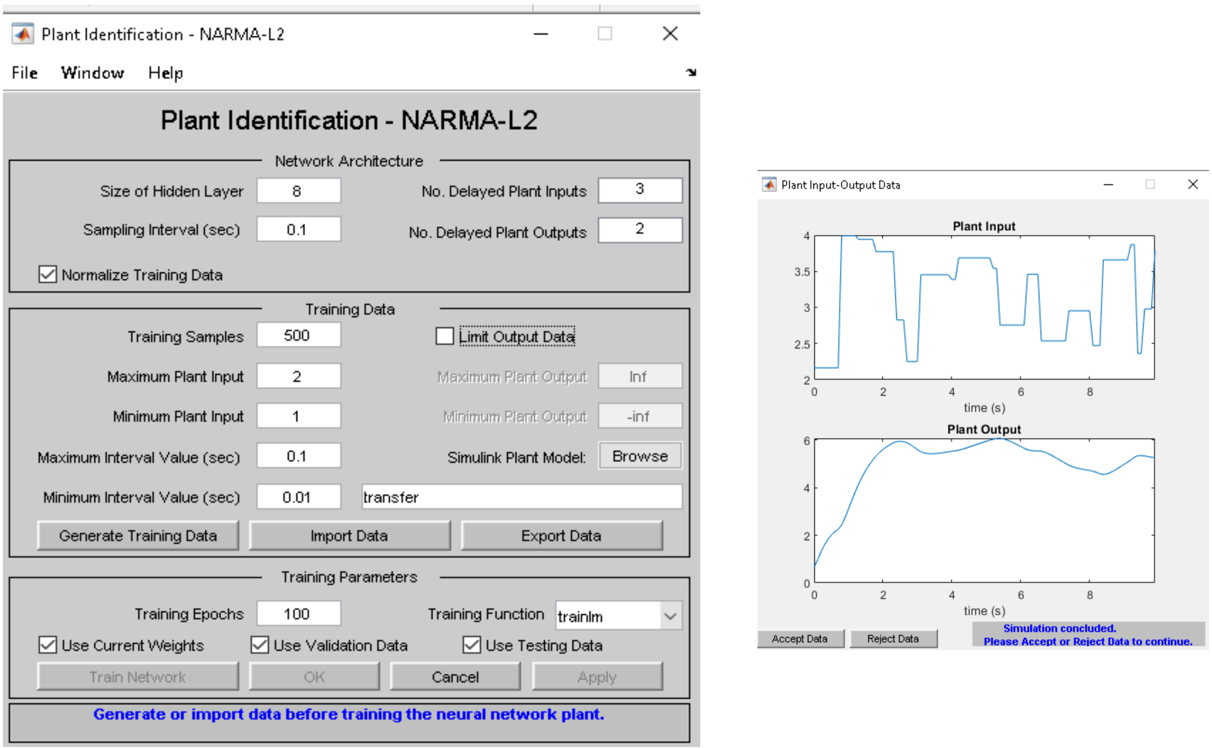
The control of a modular chain robot using an artificial neural network (ANN) allows it to navigate in different environments. The main contribution of this research is that it uses a software-defined radio (SDR) system, where the Wi-Fi channel with the best signal-to-noise ratio (SNR) is selected to transmit information about the simulated motion parameters received by the controller to the modular robot **[39]**. This allows for faster communication with fewer errors. In the event of a disconnection, these parameters are stored in the simulator, allowing them to be resent, thereby increasing the tolerance to communication failures. Additionally, the robot sends information about the average angular velocity, which is stored in the cloud. The errors in the ANN controller results, in terms of the traveled distance and time estimated by the simulator, are less than 6% of the real robot values.

Three types of phase systems are distinguished: Mamdani phase controllers, Takagi-Sugeno phase systems, and singleton-type phase systems. These characteristics indicate the historical background of each type of phase system and the main directions of its current research. However, the focus is on phase model-based approaches developed through the Lyapunov stability theorem and linear matrix inequality (LMI) formulations. Finally, the authors' personal views on the prospects and challenges of phase control research are discussed **[40]**.

The synthesis of neural network regulators and the analysis of the current state of intelligent control systems were carried out **[41]**. This paper presents stable synthesis algorithms for a multi-mode neural network controller based on methods for solving variational inequalities, ensuring the consistency of desired estimations and the high accuracy of the intelligent control system. Based on estimation theory, the regular algorithms have been proposed in combination with adaptive identification algorithms. These derived algorithms can provide consistency in desired estimations with convergence properties. They can be used in solving various problems related to system synthesis for controlling dynamic objects used for multiple functional purposes.

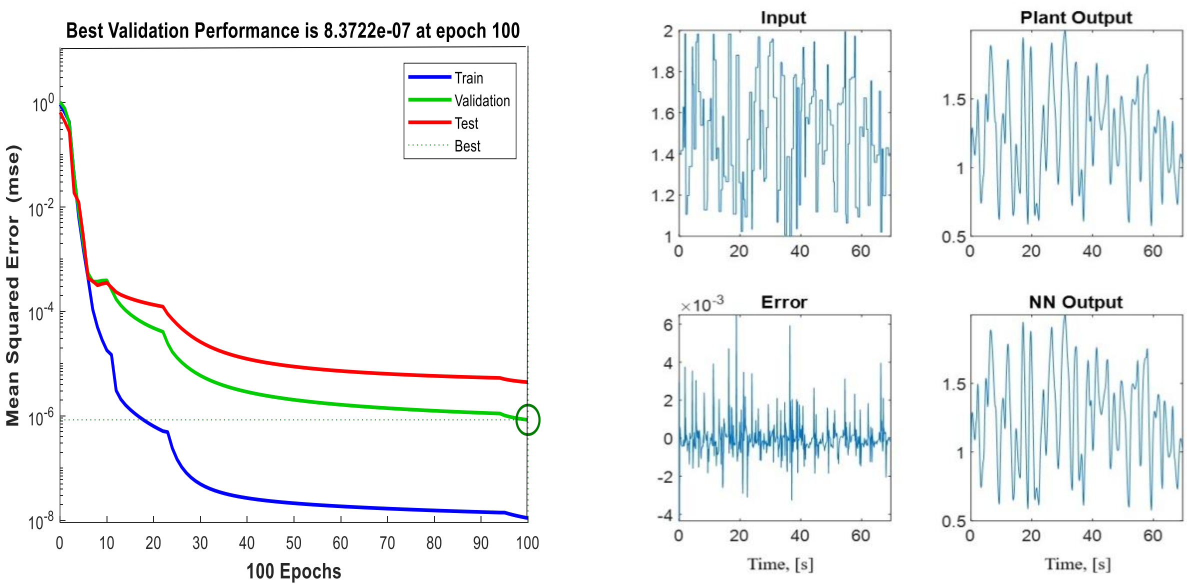
After creating the network, the process of teaching it is completed. The input vectors are a set of numeric arrays in double format, corresponding to the group representation of data. Teaching was performed using the Trainlm function, corresponding to the Levenberg-Marquardt algorithm **[42]**.

The focus is on the use of neural network technologies for the development of control systems **[43]**. The effectiveness of implementing neural network technologies in the business processes of three Russian companies is analyzed and the positive impact of using neural networks is confirmed according to several key parameters.The case analysis is supplemented by an analysis of the economic feasibility of implementing neural networks, which includes an assessment of the studied indicators, customer satisfaction, personnel control, and the effectiveness of each employee. Recommendations are given for the use of neural networks in an organization.



a) b)

Figure 5 Window for setting parameters of a Narma L2 Controller of the ACS of air relative humidity at the dryer outlet (a) and data generation (b).



a) b)

Figure 6 Results of teaching the Narma-L2 controller of ARS of air relative humidity at the dryer outlet Note: a) Graph of the change in mean squared error generated during the teaching process. b) Transient characteristics obtained as a result of testing.

During the data generation process of the Narma-L2 controller of fruit residual moisture, the mean square deviation of the root mean square error was removed, and the curves obtained as a result of checking in the control and test sets are presented in the windows shown in Figure 6. Figure 6a illustrates that the average value of the teaching error is 1,8 * 10 $^{-6}$, while the instantaneous errors between the training sets do not exceed 2,8 * 10 $^{-2}$.

After the teaching process, the numerical values of the weight matrix elements IW{1,1}, IW{3,2}, IW{5,3}, LW{2,1}, LW{4,3}, LW{5,4}, LW{6,5}, LW{6,2} and biases b{1}, b{2}, b{3}, b{4} are entered into the Narma-L2 controller block of the Simulink system.

The real-time test results of the air relative humidity at the dryer outlet shown in Figure 6, b with the Narma L2 controller ARS—the transient characteristic—are presented in Figure 4, curve 3.

The analysis of the curves presented in Figure 4 shows us that, the classic PID controller has the longest settling time and the highest deviation (Ts = 139 s, σ = 34%), consistent with its known limitations in handling nonlinearities and delays. The PID-Fuzzy controller showed improved performance (Ts = 72 s), leveraging rule-based adjustments. However, its fixed logic structure makes it less robust in dynamic environments. The NARMA L2 controller outperformed both, with a settling time of 59.7 s and minimal overshoot, highlighting the advantage of adaptive learning in regulating air humidity. These findings align with prior work by Gundogdu and Celikel **[34]**, who demonstrated the superior stability of NARMA L2 models in actuator control tasks.

When the object's parameters change during such teaching, the Narma L2 controller can reconfigure the PID regulator's parameters during the entire transition process, ensuring the system's stable operation and the required quality of the transient characteristic.

At the final stage of the research, we conducted a comparative analysis of the transient characteristics of the ACS that we developed, based on the curves shown in Figure 3. The quality indicators of the transient characteristic are presented in Table 2, from which it can be concluded that the quality indicators of the residual moisture during fruit dehydration with the fuzzy controller and the Narma L2 regulator ensure the quality of the dried product and the minimum amount of heat spent on drying. However, the quality indicators of the ACS with the Narma L2 controller are leading.

The superior performance of the NARMA L2 controller can be attributed to its ability to adaptively model the nonlinear dynamics of the drying process, reducing both response lag and overshoot under changing conditions.

To assess the improvement of energy efficiency in the automatic humidity control system, we compared the effectiveness of the classical PID and PID-NARMA L2 controllers based on the analysis of the regulation time (TS) of the transient characteristics presented in Figure 4. The comparative analysis reveals that the PID-NARMA L2 controller achieves faster regulation, resulting in increased energy efficiency for the system. The use of this controller reduces the duration of the transient process, which implies lower energy consumption during the regulation phase.

Table 2 The quality indicators of the optimal ARS for air relative humidity at the dryer outlet.

Automatic regulation system	Indicators of quality	
	T_s, [s]	σ, [%]
1. With a classic PID controller	139	34
2. With a PID-fuzzy controller	72	12
3. With a PID-Narma-L2 controller	59.7	9

The results of the conducted experimental research allow us to conclude that the developed Narma L2 regulator can become a prototype of PID, a classic industrial regulator of the configuration parameters for food industry drying machines.

CONCLUSION

This study developed a dynamic mathematical model of a conveyor-type fruit dryer by approximating its transient response using a second-order transfer function. Based on this model, three automatic control systems were implemented and compared: a conventional PID controller, a fuzzy logic-enhanced PID controller, and a PID-NARMA L2 controller using artificial neural networks. Simulations in MATLAB/Simulink demonstrated that the PID-NARMA L2 controller provided superior performance, with a 57% reduction in settling time and a 74% reduction in overshoot compared to the classical PID solution. The intelligent NARMA L2 controller also enabled more stable regulation of air relative humidity, directly contributing to improved control of the final fruit moisture content. Experimental validation confirmed that the proposed AI-driven regulation system reduced energy consumption for drying by up to 5% while preserving product quality. These findings highlight the effectiveness of integrating neural network-based control systems in industrial fruit dehydration processes, offering a replicable model for enhancing energy efficiency and automation in food processing technologies.

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