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Intellectualization of Decision Making Support in Tasks of Optimization of Complex Technical Systems based on Anfis Neuro-Fuzzy Network

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Abstract: The questions of multicriteria optimization of parameters of complex technical systems on an example of ecologically safe system electro-impulse processing of the root system of tomatoes are considered; the results of computational experiment with the use of polynomial models of the optimized object, methods of nonlinear optimization, minimax and medium degree convolution methods, and also neuro-fuzzy network ANFIS are given.
Keywords: multicriteria optimization, preference function, decision maker, ANFIS, mathematical models, electrical impulse, root system, tomatoes, computational experiment.

INTRODUCTION

One of the main features of parametric optimization task of complex technical systems is its multicriteria. When solving multicriteria optimization tasks in practice, two problems arise. First, most traditional scalarization methods for vector optimality criteria lead to modified optimality criteria that are not smooth. Under these conditions, the usual numerical optimization methods, calculated on smooth optimality criteria, are not effective due to the so-called «jamming» effect. Secondly, most scalarization methods for vector optimality criteria, such as, for example, convolution methods, require setting priorities (weighting coefficients) for each of the particular optimality criteria. In practice, setting priorities is not a trivial task and leads to a situation of uncertainty.

The main ways to overcome the first problem lies in the plane of solving ill-corrected tasks, for which regularization methods are developed [1]. The practical implementation of these methods encounters a number of difficulties due to the need for additional functional analysis, as well as relatively large computational costs. The solution to the second problem is possible by introducing the preference function (PF) of the decision maker (DM), with its subsequent approximation using various methods of the theory of artificial intelligence. The most effective such methods include fuzzy and neural network approximation methods [2, 3].

FORMULATION OF THE PROBLEM

Imagine a mathematical model of a complex technical system (CTS) in the following form:

$$y_i = f_i(x,a); \quad i = \overline{1,k}, \qquad (1)$$

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where y_i; $i=\overline{1,k}$, - CTS output parameters, playing the role of particular optimality criteria; $x=(x_1, x_2,..., x_n)$ - vector of functional-design parameters of the CTS; f_i; $i=\overline{1,k}$ - predefined functions; a - parameters of the CTS mathematical model, the values of which are known in advance.

As a rule, with parametric optimization of the CTS, the following restrictions are imposed on its parameters:

1) $y_i \geq t_i$; $y_j = t_j$; $y_l \leq t_l$ - functional restrictions on the output parameters that determine the health conditions of the CTS;

2) $x_{j\min} \leq x_j \leq x_{j\max}$; $j=\overline{1,n}$ - direct restrictions on the functional-design parameters of the CTS.

By rewriting the functional restrictions on the output parameters of the CTS in the form of $g(x) \leq 0$, the general deterministic decision-making problem for choosing the vector of functional-design parameters with optimal parametric synthesis of the CTS can be formalized as follows:

$$f_i(x,a) \rightarrow \min_{x \in \Omega_x};\ (i=\overline{1,k}), \qquad (2)$$

where $\Omega_x = \left\{ x \in R^n \left| g_i(x) \leq 0;\ i=\overline{1,k};\ x_{j\min} \leq x_j \leq x_{j\max};\ j=\overline{1,n} \right. \right\}$ - many acceptable solutions.

The assumption that each of the output parameters in expression (2) must be minimized does not limit the generality of the statement of the problem of parametric optimization of the CTS, since functional constraints $y_i \geq t_i$ can be replaced by the opposite $y_i \leq t_i$ by introducing inverse functions, or by multiplying both sides of the inequality by -1.

SOLUTION METHOD

The optimization task (2) is not standard due to the presence of the vector optimality criterion. Let us reduce the original task with the vector optimality criterion (2) to a single-criterion optimization problem based on a combination of maximin and medium degree convolution methods [4]. Finally, we obtain the scalar optimality criterion of the form:

$$F(x) = \sum_{i=1}^{k} \exp[-\gamma \cdot \varphi_i(x,a)] \rightarrow \min_{x \in D};\ \gamma = 1, 2... \qquad (3)$$

where D- set of feasible solutions defined by functional constraints on functional-design parameters; $\varphi_i(x,a) = \alpha_i\left[\left(t_i - f_i(x,a)\right)/\delta_i - 1\right] \geq 0$-margin, which is an estimate of the degree of fulfillment of functional restrictions on the output parameters of the CTS $y_i \leq t_i$, $i=\overline{1,k}$; δ_i - scattering estimate of the *i*-th output parameter; α_i - weighting coefficients, determining the relative significance of the individual output parameters of the CTS: $\alpha_i > 0$; $\sum_{i=1}^{k}\alpha_i = 1$; $\gamma = 1, 2, ...$ - an integer, used to control the convergence of the optimization procedure.

Functional restrictions on the control parameters in the set D can be obtained from direct restrictions on the same parameters in the set Ω_x using the corresponding replacement formulas [5]. For example, the formula $x_j = x_{j\max} + \left(x_{j\min} - x_{j\max}\right) * \sin^2(x_j^{'})$ can be used, where $x_j^{'}$ the

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value of the *j*-th variable parameter from the set Ω_x.

The practical application of the modified criterion (3) allows not only to scalarize the vector optimality criterion, but also to overcome the problem of «ravine» and, due to the boundedness and closeness of the set *D*, to obtain a unique solution using the simplest smooth optimization algorithms [6].

The main problem in solving task (3) is that the values $\alpha_i, i=\overline{1,k}$ may not be known in advance, which leads to uncertainties in priorities. In this case, the general statement of the multicriteria optimization task (2) can be formulated as follows. Let a vector function $\Psi(x,a) = (f_1(x,a), f_2(x,a),... f_k(x,a))$ be given, the components of which are particular optimality criteria and, which is defined on the set of alternatives W_x of the vector of variable parameters *x*. It is necessary to find such a solution on the set W_x, that minimizes all the components of the vector-function $\Psi(x,a)$.

For each fixed vector $A = (\alpha_1, \alpha_2, ..., \alpha_k)$, the combined convolution method reduces the solution of problem (3) to the solution of a single-criterion optimization task of the form:

$$\min_{x\in D} F(x,\mathrm{A}) = F(x^*,\mathrm{A}), \qquad (4)$$

whose solution, as shown above, exists.

We denote the attainability set of the task (the set into which the vector optimality criterion maps the set W_x) as Ω_Ψ; Pareto front of tasks - Ω^*_Ψ , $\Omega^*_\Psi \subset \Omega_\Psi$; Pareto set - Ω^*_x . If $x \in \Omega^*_x$, we assume that the vector x is a Pareto effective vector [7].

If for each $\mathrm{A} \in D_\mathrm{A} = \{\mathrm{A} | \alpha_i \le 0, \sum_{i=1}^{k} \alpha_i = 1\}$ the solution to task (4) is unique, then this means that each of the admissible vectors A corresponds to a single vector x^* and the corresponding values of particular optimality criteria $f_1(x,a), f_2(x,a),... f_k(x,a)$. Based on this, it is possible to construct some preference function $\zeta(\mathrm{A})$ of the decision maker defined on the set $D_\mathrm{A} : \zeta : \mathrm{A} \to R.$

Then the task of multicriteria optimization is reduced to choosing one $\mathrm{A}^* \in D_\mathrm{A}$, for which $\max_{\mathrm{A}\in D_\mathrm{A}} \zeta(\mathrm{A}) = \zeta(\mathrm{A}^*)$.

We assume that ζ it is a linguistic variable that takes e = 5 final values: «Very bad», «Bad»,…, «Very Well». The core of a fuzzy variable ζ is denoted by ζ^0 [8] and introduce the following correspondence: value ζ «Very bad» corresponds to $\zeta^0 = 1$, value ζ «bad» corresponds to $\zeta^0 = 2$, value ζ «Average» corresponds to $z^0 = 3$, value ζ «Well» corresponds to $z^0 = 4$ and value ζ «Very Well» corresponds to $z^0 = 5$.

Thus, the task of multicriteria optimization is reduced to finding a vector $\mathrm{A}^* \in D_\mathrm{A}$, that provides the maximum of a discrete function $\zeta(\mathrm{A})$:

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$$\max_{A \in D_A} \zeta(A) = \zeta(A^*), \tag{5}$$

those to approximate the preference function of the decision maker.

The general scheme for solving this problem is iterative in nature and has several stages [9].

At the first stage, *n* vectors A_1, A_2,..., A_m are randomly generated or in some other way generated. The procedure for the following steps is as follows.

1) The single-criterion task is solved:

$$\min_{x \in D} F(x, A_l) = F(x^*, A_l),\ l = \overline{1,m}\ . \tag{6}$$

2)Found values $x_l^*; l = \overline{1,m}$; $f_i(x_l^*);\ i = \overline{1,k}$ are displayed.

3) Estimated values $f_i(x_l^*);\ i = \overline{1,k};\ l = \overline{1,m}$ obtained and preference function values $z(A_l);\ l = \overline{1,m}$ are entered.

In the second step, based on the values A_1, A_2,…, A_m and ratings $z(A_l);\ l = \overline{1,m}$ the following actions are performed:

1) A function $\tilde{\zeta}_1(A)$ is constructed that approximates $\zeta(A)$ in a neighborhood of A_1, A_2,…, A_m;

2) The single-criterion task is solved

$$\max_{A \in D_A} \tilde{\zeta}_1(A) = \tilde{\zeta}(A_1^*); \tag{7}$$

3) The single-criterion task is solved $\min_{x \in D} F(x, A_1^*) = F(x^*, A_1^*)$;

4) Found values x^*; $f_i(x^*);\ i = \overline{1,k}$ are displayed ;

5) Estimated values obtained $f_i(x^*);\ i = \overline{1,k}$ and the value of the preference function $\zeta(A_1^*)$ is entered.

At the third stage, based on the available values of A_1, A_2, ..., A_m, A_1^* and the corresponding estimates of the preference function $\zeta(A_1), \zeta(A_2), ..., \zeta(A_k), \zeta(A_1^*)$, the function $\zeta(A)$ is approximated in the vicinity of points A_1, A_2, ..., A_m, A_1^* as a result of which the function $\tilde{\zeta}_2(A)$ is constructed.

Further, the procedure continues according to the scheme of the second stage until the decision-maker decides to terminate the calculations. At each iteration, a «return» is allowed in order to change the previously introduced estimates of its preference function.

When using the adaptive neuro-fuzzy ANFIS network to approximate the PF of the DM, the output system is functionally equivalent to the Sugeno fuzzy output system, which is performed in two steps [10]. At the first step, the formation of the knowledge base and the Sugeno fuzzy inference system is carried out, as well as a rough adjustment of the model $\zeta(A)$. The second step is fine-tuning the model $\zeta(A)$, consisting in the selection of such parameters of membership functions that minimize the difference between the physical values of the output variable and model values.

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Suppose that N experiments were performed to determine the values of a linguistic variable ζ, as a result of which in n_1 these experiments the variable ζ took on a value ζ_1, in n_2 experiments - a value ζ_2, etc. before n_e and ζ_e.

We denote the corresponding input vectors A as

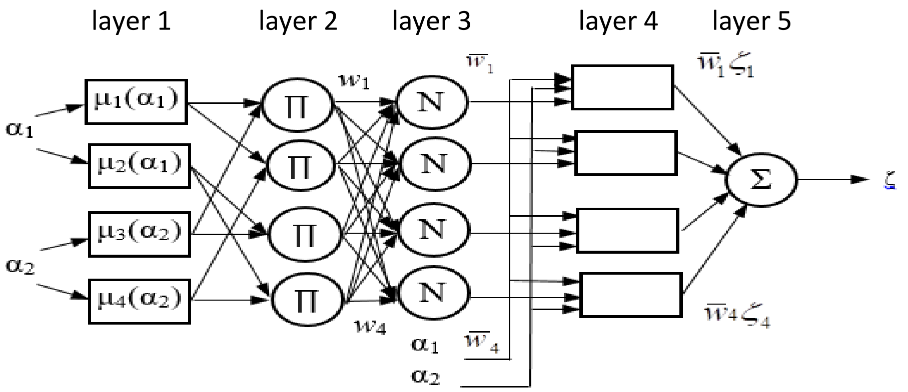
$\mathrm{A}_{i,j} = (\alpha_{i,j,1}, \alpha_{i,j,2}, ..., \alpha_{i,j,k}) \in D_A, \; i = \overline{1,e}, \; j = \overline{1,n_i}.$

We write the knowledge matrix $\{\alpha_{i,j,l}, \; i = \overline{1,e}, \; j = \overline{1,n_i}, \; l = \overline{1,k}\}$ as

$$\bigcup_{j=1}^{n_i} \left(\bigcap_{l=1}^{k} (\alpha_j = \alpha_{i,j,l}) \right) \rightarrow \zeta_i = a_{0i} + a_{1i}\alpha_1 + a_{2i}\alpha_2; \; i = \overline{1,e}. \tag{8}$$

The Sugeno knowledge base differs from the Mamdani knowledge base in that the conclusions of the rules are set not by fuzzy terms, but by a linear function of inputs.

When using the Sugeno algorithm, the first stage of its implementation as applied to the task of approximating a function $\zeta(\mathrm{A})$ coincides with the Mamdani derivation algorithm and includes the following operations: fuzzification, aggregation, activation, accumulation, defuzzification [10]. At the second stage, fine tuning of the model $\zeta(\mathrm{A})$, which consists in setting the parameters of the membership function based on the training set, is carried out using the neural network shown in Fig. 1.



$k = 2$

The purpose of the layers of the neural network is systematized in table 1

Table 1 **The purpose of the layers of the neural network ANFIS**

Layer number	The appointment of layer neurons	Layer output
1	Representation of terms of input variables	Values of membership functions $\mu_1(\alpha_1), \; \mu_2(\alpha_1), \; \mu_3(\alpha_2), \; \mu_4(\alpha_2)$
2	Antecedents of fuzzy rules	The degree of truth of the premises $w_1, \; w_2, \; w_3, \; w_4$ of the rules of the knowledge base of the system

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3	Normalization of the degree of compliance with the rules	The relationship of the degree of truth of the premises $\bar{w}_1, \bar{w}_2, \bar{w}_3, \bar{w}_4$ of the rules to the sum $\bar{w}_i = \frac{w_i}{\sum_{i=1}^{4} w_i}$ of the degrees of the premises of all the rules
4	Calculation of conclusions of rules	$\bar{w}_1\zeta_1,\ \bar{w}_2\zeta_2,\ \bar{w}_3\zeta_3,\ \bar{w}_4\zeta_4;\ \zeta_i = a_{0i} + a_{1i}\lambda_1 + a_{2i}\lambda_2;$ $\{a_{0i}, a_{1i}, a_{2i}\}$ - conclusion parameters
5	Aggregation of the result obtained according to various rules	Network output value ζ

Various methods are used in practice to train the ANFIS network: the back propagation method of the error, the hybrid method, and evolutionary algorithms [12].

To estimate the error of a fuzzy neural network, the error function is used

$$\Omega(a,b,a_0,a_1,a_2) = \frac{1}{N}\sum_{i=1}^{N}\left(\zeta(\mathrm{A}_i) - \bar{\zeta}(\mathrm{A}_i)\right)^2 \to \min_{a,b,A}, \qquad (9)$$

where $\zeta(\mathrm{A}_i)$, $\bar{\zeta}(\mathrm{A}_i)$ - the actual value of the output variable and the result of fuzzy inference at a point A_i; *a, b* - parameters of membership functions of the first layer of a fuzzy neural network; $A = \{a_0, a_1, a_2\}$ - many parameters of the fourth layer of the fuzzy neural network.

As the optimization task is solved, the ANFIS output system gains new knowledge, which leads to the need to change the topology of the fuzzy neural network. Modification of the topology of a fuzzy neural network can be carried out according to the technique proposed in the work [11].

PRACTICAL IMPLEMENTATION

The methodology described above for solving the multi-criteria optimization task was solved in relation to the technical system of ecologically safe protection of fruit plants from parasites. In particular, the technical system of electro-pulse processing of tomatoes to combat the root nematode is considered [3].

The mathematical model for the process of electro-pulse processing of tomatoes on a dimensionless scale has the following form:

$$\begin{aligned} y_1 &= 1.587 - 0.537 * x_1 - 0.460 * x_2 - 1.365 * x_3 + 0.299 * x_1{}^2 + 0.671 * x_2{}^2 + 1.551 * x_3{}^2; \\ y_2 &= 1400 + 50 * A_1^2 * A_2, \end{aligned} \qquad (10)$$

where $x_i = \frac{z_i - z_i^0}{\Delta z_i};\ i = \overline{1,3}$; $z_i^0 = \frac{(z_{\mathrm{i}\max} + z_{\mathrm{i}\min})}{2}$; $\Delta z_i = \frac{(z_{\mathrm{i}\max} - z_{\mathrm{i}\min})}{2}$; A_1=2500*x_1+3500; A_2=(936*x_3+1064)*10^{-10}; z_1 - transformer output voltage, V; z_2 - electric pulse duration, sec.; z_3 - capacitor capacitance, pF; y_1 - coefficient of necrosis, % ; y_2 - power consumed by the technical system, W.

The task of optimizing the process of processing plants by electric discharge has the following statement

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$$y_1(z) \to \min_{z \in \Omega_z};$$
$$y_2(z) \to \min_{z \in \Omega_z}, \qquad (11)$$

where $\Omega_z = \left\{ z \in R^n \middle| g_1(z) \leq 0;\ g_2(z) \leq 0;\ z_{j\min} \leq z_j \leq z_{j\max};\ j = \overline{1,3} \right\}$ - many acceptable solutions; $z_{j\min} \leq z_j \leq z_{j\max};\ j = \overline{1,3}$ - direct restrictions on the input parameters of the technical system; $g_1(z) \leq 0;\ g_2(z) \leq 0$ - functional limits on process output $y_1 - t_1 \leq 0;\ y_2 - t_2 \leq 0$; $t_1,\ t_2$ - setpoints.

When moving to a dimensionless scale, the set of feasible solutions is defined as

$$\text{W} = Y \text{ Ç } X = \{Y \text{ Î } R^k \,|\, y_1 \text{ £ } t_1;\ y_2 \text{ £ } t_2;\ t_1 = 1{,}5\ \%;\ t_2 = 1500\ \text{W};$$
$$X \text{ Î } R^n \,|\, -1.215 \text{ £ } x_i \text{ £ } 1.215;\ i = \overline{1,3}\}. \qquad (12)$$

Estimates of the scattering of the values of the output parameters were chosen as follows: by parameter $y_1(z)$ $d_1 = 0.01$, by parameter $y_2(z)$ $d_2 = 10$. The set of reachability is shown in

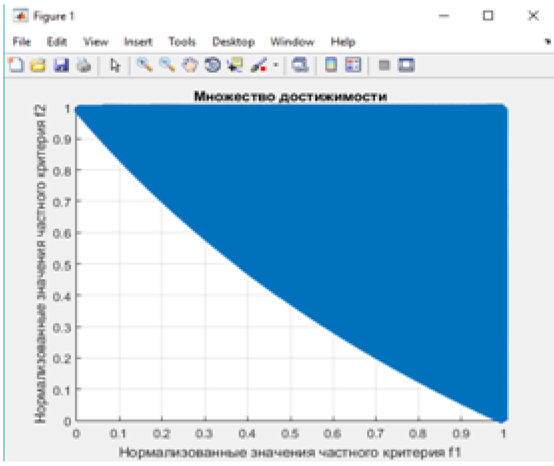

Fig. 2.

The optimization task in statement (3) was solved by the coordinate descent method, task (5), by determining the maximum value of the function $\zeta(\text{A})$, was solved by the golden section method.

The software implementation of the task of multi-criteria optimization of the process of electric pulse processing of tomatoes was carried out in the MATLAB 9.7.0 software environment on a personal computer with the DualCore Intel Pentium G4560 processor, 3500 MHz and 8 GB RAM.

The construction and training of the neuro-fuzzy network ANFIS was carried out in the following sequence.

Step 1. The number of «overclocking» solutions n equal to six was chosen: A1, A2,…, A6. Moreover, the extreme values of A1, A6 were chosen at the boundaries of the range of the weight coefficient $\alpha_1;\ \alpha_2 = 1 - \alpha_1$, and the average values of A2, A3, ..., A5 were randomly generated.

Step 2. The multicriteria optimization task was solved in the statement (3) at the generat-

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ed points. The results of solving the multicriteria optimization task are shown in table 2. According to the table. 2, the NTrain.dat file was formed, into which the data for training the ANFIS neuro-fuzzy network was placed.

Step 3. The ANFIS neural-fuzzy network editor is loaded with the anfisedit command and the training data sample is loaded from the NTrain.dat file. The opening editor window is shown in Fig. 3.

Table 2 The results of solving task (3) at the generated points

Iteration number	α_1	y_1	y_2	ζ
1	0	5.1047568443647364	1400.8827636960002	2
2	0.32	1.0750077064829138	1530.0137542173500	3
3	0.12	1.3958051053281146	1445.3261712921521	5
4	0.59	0.98763860425667394	1588.7361794377134	3
5	0.26	1.1235524778705630	1511.6352390201871	3
6	1	0.96672483777880258	1643.5552385593733	2

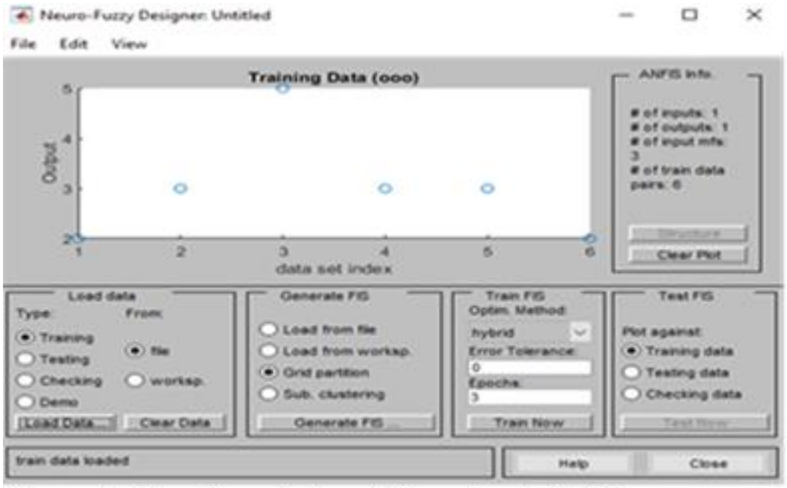

Figure 3- The editor window of the network ANFIS

Step 4. The generation of the structure of the FIS fuzzy inference system of the Sugeno type is carried out, which is performed after pressing the Generate FIS button. After that, a dialog box opens with an indication of the number and type of membership functions for individual terms of the input variables and the output variable shown in Fig. 4.

Step 5. The type of membership functions is selected, in our case gaussmf is the Gaussian distribution function. When you clicked the Structure button, the structure was visualized as a result of the FIS fuzzy inference system, which is shown in Fig. 5.

Step 6. A hybrid network training method is chosen, in our case hybrid is a combination of the least squares methods and the inverse gradient decrease. In this case, the learning error level - Error Tolerance is set to zero by default. The number of training cycles - Epochs is set equal to 40. After pressing the Train Now button, the progress of the training process is visualized in the window shown in Fig. 6.

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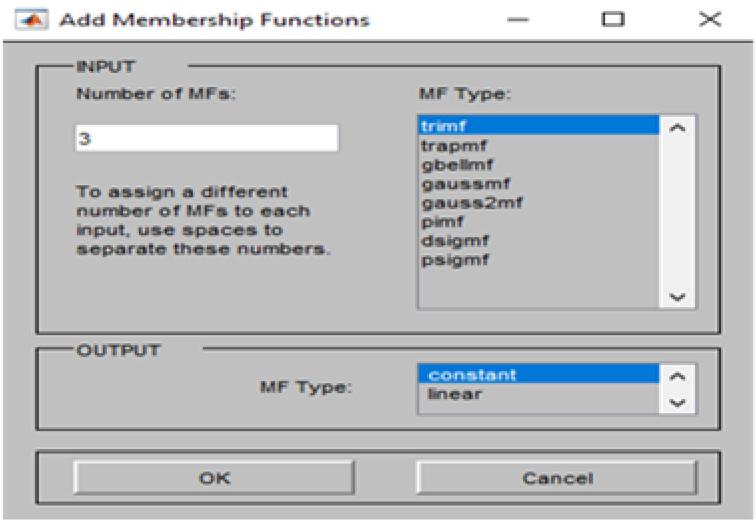

Figure 4- The editor window of the network ANFIS

At the same time, it becomes possible to access the FIS graphical editor, the graphical interface for viewing rules and the graphical interface for viewing the surface of the generated fuzzy inference system.

After three additional iterations, the final result was obtained, which is given in Table. 3.

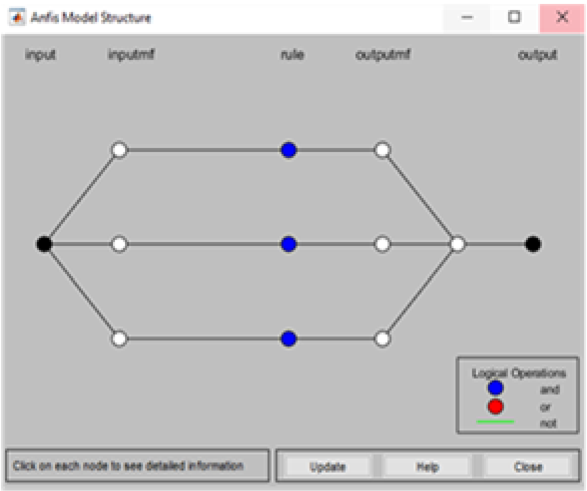

Figure 5 - The structure of the network ANFIS

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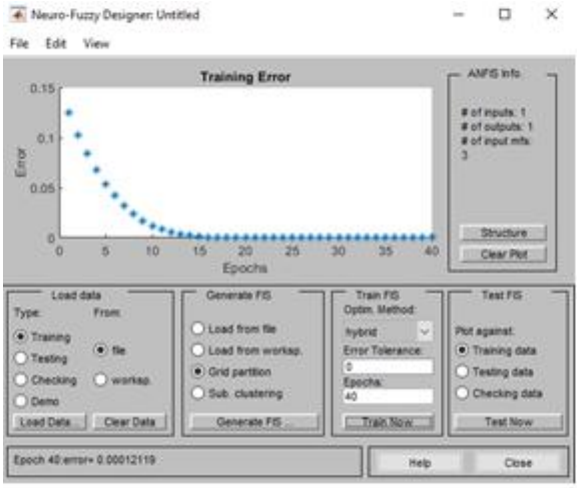

Figure 6 - Graphs of the learning process

Table 3 The results of solving the task (5)

Iteration number	α_1	y_1	y_2	ζ
1	0	5.1047568443647364	1400.8827636960002	2
2	0.32	1.0750077064829138	1530.0137542173500	3
3	0.12	1.3958051053281146	1445.3261712921521	5
4	0.59	0.98763860425667394	1588.7361794377134	3
5	0.26	1.1235524778705630	1511.6352390201871	3
6	1	0.96672483777880258	1643.5552385593733	2
7	0.110	1.4344381614368813	1449.2470500028558	5
8	0.115	1.4145439760325877	1451.8033668132491	5
9	0.102	1.4684684525152787	1445.1430662691575	5

The graphical interface for viewing the rules generated at the ninth step of iterations of the fuzzy inference system is shown in Fig. 7. The preference function of the decision maker at the ninth step of iterations after smoothing with a cubic spline is shown in Fig. 8.

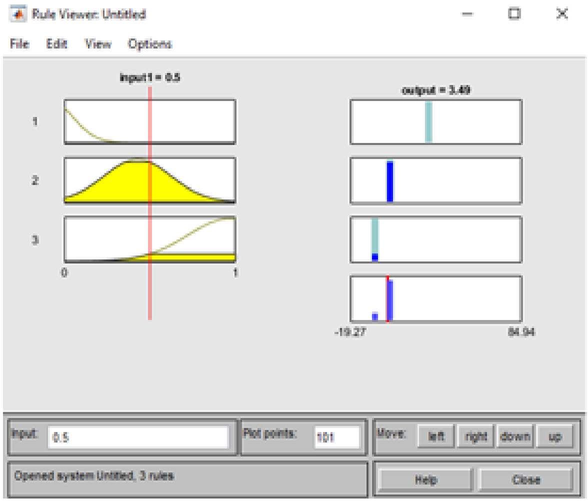

Figure 7- Graphical viewer rules generated on the ninth iteration step

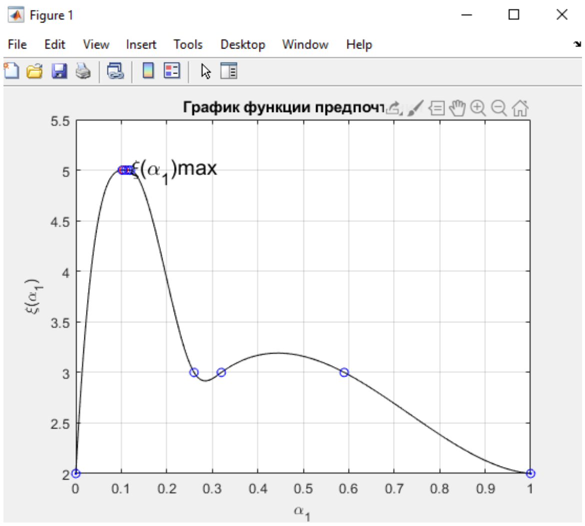

Figure 8 - Face preference function, decision maker on ninth step of iteration

The final result of solving the multicriteria optimization task of the electro-pulse processing of tomatoes is as follows: $\alpha_1 = 0.102$; $\alpha_2 = 0.898$; x_1=-0.4797; x_2=0.4285; x_3=0.4449; z_1=2540 V; z_2= 0.167 sec.; z_3= 1397 pF; y_1=1.46 % and y_2=1445 W.

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