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METHOD OF STRUCTURE IDENTIFICATION FOR INTERVAL DIFFERENCE OPERATOR BASED ON THE PRINCIPLES OF HONEY BEE COLONY FUNCTIONING

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Abstract: In the article, the problem of structure identification of the interval difference operator (IDO) as a model of distributed parameters object is considered. A new method of structure identification of the IDO based on the foraging behavior of a honey bee colony has been proposed and verified. In addition, a neural-like computational scheme of the implementation of the method has been developed. The effectiveness of using the proposed method and its computational scheme are shown on the example of building a macromodel for the prediction of humidity distribution on a drywall sheet in the process of its drying.

Key words: structure identification, interval difference operator, artificial bee colony algorithm, interval data.

1. Introduction

When solving management tasks, studying and investigating new processes, the most important tool is a mathematical model. For synthesis of an object's mathematical model, first and foremost, it is necessary to form a structure of the model (*structure identification*), and then set its parameters (*parametric identification*) [1,2].

The problem of structure identification of a mathematical model is well known to belong to NP-complete problems. This makes it extremely difficult in terms of solving and requires the use of stochastic optimization methods and principles of the theory of self-organization [1,3]. As a rule, in the majority of the works dealing with the process of mathematical modelling, a model structure is specified empirically by a researcher (based on the previously acquired experience) and is accurate within a set of unknown parameters which are objects of study (problem of parametric identification). This approach has the right to exist and yet it confirms the importance of the search for a universal method for solving the problem of structure identification of a mathematical model, using just a minimum of a priori information. The most significant results in studying the problem of structure identification of mathematical models were achieved by scientific schools headed by such Ukrainian and foreign scientists as Y. Tsypkin, A. Ivakhnenko, H. Akaike, D. Graupe, L. Ljung, R. Haber.

There exist two main approaches to the synthesis of a mathematical model structure: deductive and inductive [1]. Using the deductive approach, the structure of mathematical model is chosen on the basis of physical consideration. The application of such an approach requires thorough studies of physical characteristics of the modeled process and, in certain cases, is unacceptable due to the fact that some elements of the target structure of the model have no adequate interpretation from the mathematical point of view. There are some known methods for synthesis of the mathematical model structure in the form of a difference operator: "augmentation" or reduction of a mathematical model structure, combinatorial search methods etc., used in this approach. However, all of them, firstly, lead to over-complicating of the general form of the mathematical model, and, secondly, are characterized by high computational complexity.

In contrast to the deductive approach, the inductive modeling methods are often used. In this case, the mathematical model of the process is constructed in the form of a difference operator (DO) based on the analysis of experimental data obtained under the conditions of incomplete information. This approach is more acceptable both from the perspective of computational complexity, and in terms of costs minimization.

There are few publications dedicated to the problem of structure identification of a mathematical model in the form of a difference operator on the basis of interval data [4, 5]. But the approaches proposed in these articles are based on the genetic algorithms, which are heuristic, require to set a number of parameters, and are ineffective when physics of the process is poorly understood.

Paper [6] describes the basic principles of the method for structure identification of an interval difference operator (IDO), based on the principles of swarm intelligence and shows that the application of this approach to the development of mathematical models of real objects has several advantages over the methods based on the genetic algorithms (GA). In particular, the main advantages of the method of structure identification of the IDO based on the principles of honey bee colony functioning are the reduction of computational complexity and more “predictable behavior” of the procedures for generating improved variants of the IDO structures. Therefore, the goal of this work is to develop: a method for IDO structure identification based on the principles of swarm intelligence inherent in a bee colony and a computational scheme of its implementation.

2. Statement of problem

Consider the task of structure identification of a linear DO in standard form:

$$v_{i,j,h,k} = \vec{f}^T(v_{0,0,0,0},...,v_{i-1,j-1,h-1,k-1}, \vec{u}_{i,j,h,0},...,\vec{u}_{i,j,h,k})\cdot\vec{g}, \quad (1)$$

$$i=1,...,I,\ j=1,...,J,\ h=1,...,H,\ k=1,...,K,$$

where $\vec{f}^T(\bullet)$ is the vector of unknown basic functions, that defines the structure of DO; the symbol $(\bullet)$ means the set of basic functions in (1); $v_{i,j,h,k}$ represents the modeled characteristic at the point with the discrete coordinates i,j,h at the time discrete k; $\vec{u}_{i,j,h,0},...,\vec{u}_{i,j,h,k}$ are the vectors of input variables; $\vec{g}$ stands for the vector of unknown parameters of DO.

Note, that the standard form of DO (1) will be obtained based on the analysis of experimental data. The experimental data were obtained in the interval form under conditions of different values of influence factors.

The vector of estimated values $\hat{\vec{g}}$ of the parameters $\vec{g}$ and the vector of basic functions $\vec{f}^T(\bullet)$ in (1) can be obtained from the condition of holding a given precision of the model:

$$[\hat{v}_{i,j,h,k}] \in [z^-_{i,j,h,k}; z^+_{i,j,h,k}] \quad (2)$$

where $[z^-_{i,j,h,k}; z^+_{i,j,h,k}]$ is the interval of possible values of the modeled characteristic at the point with the discrete coordinates i,j,h at the time discrete k.

In (2) $[\hat{v}_{i,j,h,k}]$ means the estimated interval values of the modeled characteristic, which has to be calculated using the difference operator below:

$$[\hat{v}_{i,j,h,k}] = [\hat{v}^-_{i,j,h,k}; \hat{v}^+_{i,j,h,k}] = \vec{f}^T([\hat{v}_{0,0,0,0}],...,[\hat{v}_{i-1,0,0,0}],..., [\hat{v}_{0,j-1,0,0}],...,[\hat{v}_{i-1,j-1,h-1,k-1}], \vec{u}_{i,j,h,0},...,\vec{u}_{i,j,h,k})\cdot\vec{g} \quad (3)$$

All calculations in the DO (3) must be conducted using the rules of interval arithmetic, DO (3) is called an interval difference operator (IDO). The complexity of the problem of setting the IDO (3) is that not only its parameters are unknown, but also its general view, i.e. its structure.

In the first place, let us introduce some denotations that are necessary to reveal the essence of the formal problem statement. Let l_s denote the current structure of the IDO:

$$l_s = \{f_1^s(\bullet)\cdot g_1^s; f_2^s(\bullet)\cdot g_2^s; \mathbf{K}; f_{m_s}^s(\bullet)\cdot g_{m_s}^s\} \subset \Lambda, \quad (4)$$

where $\vec{f}^s = \{f_1^s(\bullet); f_2^s(\bullet); \mathbf{K}; f_{m_s}^s(\bullet)\} \subset F$ is the set of structure elements defining the current structure of the IDO; $m_s \in [I_{\min}; I_{\max}]$ is the number of elements in the current structure; $F = \{f_1(\bullet); \mathbf{K}; f_l(\bullet); \mathbf{K}; f_L(\bullet)\}$ is the set of all structure elements; $\vec{g}^s = \{g_1^s; g_2^s; \mathbf{K}, g_{m_s}^s\}$ is the vector of unknown parameter values to be estimated, for the current structure of the IDO, on the basis of random search methods [7]; Λ stands for the set of all possible IDO structures.

The problem of structure identification consists in finding the structure of the IDO l_0 in the form of (4) so that the IDO (5) formed on the basis of this structure

$$[v_{i,j,h,k}(l_0)] = [f_1^0(\bullet)]\cdot \hat{g}_1^0 + \mathbf{K} + [f_{m_0}^0(\bullet)]\cdot \hat{g}_{m_0}^0 \quad (5)$$

satisfies conditions (2), i.e. we should ensure the inclusion of interval estimates of the predicted values of the modeled characteristic into the intervals of possible values of the characteristic modeled on the basis of the set of all experimental points.

It should be noted that in this case, the parametric identification is the stage of structure identification of IDO. It is known that if input data are set in interval form, this stage implies forming a vector of basic functions (the current structure of a IDO l_s) and determining estimations of the IDO parameters by solving an interval system of nonlinear algebraic equations (ISNAE) [8]. However, solving the ISNAE is an extremely complicated computational task. That is why, instead of solving the ISNAE, some approximation to its solution is to be found. The quality (accuracy) of the current structure of the IDO l_s depends on the approximation.

Thus, the quality of the current structure of the IDO will be estimated on the basis of the quality indicator $d(l_s)$, which quantitatively determines the proximity of the current structure to a satisfactory one in terms of providing the condition (2). The value of the quality indicator $d(l_s)$ is calculated using the expressions obtained in article [8] based on the modification of the ISNAE:

$$d(l_s)=\max_{i=1,\ldots,I,\,j=1,\ldots,J,\,h=1,\ldots,H,\,k=1,\ldots,K}\{\left|mid(\vec{f}^{Ts}([\hat{v}_{0,0,0,0}],\ldots,[\hat{v}_{i-1,j-1,h-1,k-1}],\vec{u}_{i,j,h,0},\ldots,\vec{u}_{i,j,h,k})\cdot\vec{g}^{s})-mid([z_{i,j,h,k}])\right|\}$$
$$\text{if } [\hat{v}_{i,j,h,k}]\cap[z_{i,j,h,k}]=\varnothing,\ \exists i=1,\ldots,I,\ \exists h=1,\ldots,H,\ \exists k=1,\ldots,K; \quad (6)$$

$$d(l_s)=\max_{i=1,\ldots,I,\,j=1,\ldots,J,\,h=1,\ldots,H,\,k=1,\ldots,K}\{wid(\vec{f}^{Ts}([\hat{v}_{0,0,0,0}],\ldots,[\hat{v}_{1,j-1,0,0}],\ldots,[\hat{v}_{i-1,j-1,h-1,k-1}],\vec{u}_{i,j,h,0},\ldots,\vec{u}_{i,j,h,k})\cdot\vec{g}^{s})$$
$$-wid((\vec{f}^{Ts}([\hat{v}_{0,0,0,0}],\ldots,[\hat{v}_{0,0,h-1,0}],[\hat{v}_{i-1,0,0,0}],\ldots,[\hat{v}_{i-1,j-1,h-1,k-1}],\vec{u}_{i,j,h,0},\ldots,\vec{u}_{i,j,h,k})\cdot\vec{g}^{s}))\cap[z_{i,j,h,k}])\} \quad (7)$$
$$\text{if } [\hat{v}_{i,j,h,k}]\cap[z_{i,j,h,k}]\neq\varnothing\ \ \forall i=1,\ldots,I,\ \forall j=1,\ldots,J,\ \forall h=1,\ldots,H,\ \forall k=1,\ldots,K;$$

where $mid(\bullet), wid(\bullet)$ are the operation of determining the center and the width of the intervals, respectively.

The expression (6) describes the "proximity" of the current structure to a satisfactory one at the initial iterations while the equation (7), if $d(l_s)=0$, ensures the fulfillment of the condition (2).

Now the problem of structure identification of the IDO will be written formally as a problem of searching a minimum value of the function $d(l_s)$:

$$d(l_s)\xrightarrow{\vec{g}^{s},\,\vec{f}^{s}(\bullet)}\min,\ m_s\in[I_{\min};I_{\max}],\ \vec{f}^{s}(\bullet)\in F \quad (8)$$

From expressions (6) and (7) we see that for all the calculated values of the quality indicator of the structures l_s the inequality $d(l_s)\geq 0$ is correct under any conditions. Thus, the goal function $d(l_s)$ has a global extremum only at those points, for which the following equality holds: $d(l_s)=0$.

Based on the theory of multiple models [9], it is arguable that in the space of possible solutions to the problem of IDO structure identification, the function $d(l_s)$ has many global minimums.

The smaller value of the function $d(l_s)$ is, the "better" current structure of the IDO l_s is. If $d(l_s)=0$, then the current structure of the IDO ensures the development of an adequate model for which the interval estimates of the predictable characteristic belong to the intervals of possible values of the modeled characteristic.

3. Method of structure identification for interval difference operator

To solve the problem of structure identification of the model of a parameter-distributed object in form of IDO, article [6] proposes to apply the artificial bee colony algorithm (ABCA). The ABCA was proposed by the Turkish scientist Dervis Karaboga in 2005 [10]. The ABCA models the intelligent behavior of honey bees in search for nectar sources [11]. Let us consider the essence of the ABCA drawing certain analogies with the principles of organization of the IDO structure identification method. The algorithm is given below [11]:

Step 1. Initialization.

Step 2. Worker-bees phase (*worker-bees fly to the neighbourhood of known nectar sources and notify explorer-bees about the amount of the found nectar*).

Step 3. Explorer-bees phase (*explorer-bees stay in the hive and wait for information from the worker-bees, after that, they choose the nectar sources (depending on the amount of the nectar) in the neighbourhood they will fly to*).

Step 4. Scout-bees phase (*scout-bees fly in random directions to find new nectar sources, instead of the exhausted ones*).

Step 5. If the stopping criterion is not reached, go to Step 2; or memorize the best solution.

In the context of the problem of structure identification: *behavior of honey bee* while choosing a nectar source directly implements the algorithm of synthesis of the current structure of an IDO; *the current nectar source position* represents the current structure of an IDO; *the amount of nectar* means the quality of the current IDO structure l_s (the value $d(l_s)$).

To implement the method of IDO structure identification based on the principles of honey bee colony functioning, we set the following initial parameters:

- *MCN* – maximum number of algorithm iterations;
- *LIMIT* – maximum possible number of iterations of "immutability" of the structure, e.i. if the IDO structure does not provide any improvement after *LIMIT* iterations, then it is defined as "exhausted";
- *S* – initial number of IDO structures;
- $[I_{\min};I_{\max}]$ – the interval, where $I_{\min}$ and $I_{\max}$ are values of margin numbers of structure elements in the IDO structure l_s;
- F – the set of structure elements.

It should be noted that the convergence of the method of structure identification and the rapidity of the process of synthesis of mathematical model structure depend on the selection of modeling elements, so the set F should definitely include all elements of the sought IDO structure. Unfortunately, even by using the principles of self-organization theory, we cannot be certain that our software will be able to prepare a correct set F of the structure elements. That is why, the basic functions and order of the IDO should be set by a researcher empirically based on the analysis of the problem under investigation. So, in the implementation scheme of the structure identification method based on a bee colony functioning, it is recommended to form combinations from the elements of the set $\{v_{0,0,0,0},...,v_{0,0,h-1,0},...,v_{i-1,j-1,h-1,k-1}\}$ according to the order of the IDO. However, combinations of the elements of the set $\{\vec{u}_{i,j,h,0},...,\vec{u}_{i,j,h,k}\}$ should be generated based on the physical analysis of a real modeled process to satisfy the condition of reducing computational complexity in the process of solving the problem.

Based on the statement of the problem, by using the method of structure identification at *mcn-th* ($mcn \le MCN$) iteration, the structure of the IDO l_0 in the form (4), for which $d(l_0)=0$, should be found.

Fig. 1 shows a neural-like computation scheme of implementation of the method of IDO structure identification based on the principles of a bee colony functioning in the course of its search for rich food sources.

In the implementation scheme of the method of structure identification (Fig.1), the block "Initialization" means the initialization of initial parameters of the method. We specify the values of initial parameters: *MCN, LIMIT, S,* $[I_{\min};I_{\max}]$, and a set of structure elements *F*. Then, an initial set of the IDO structures with cardinal number *S* is randomly generated.

The initial set of the IDO structures Λ_0 is formed in the following sequence:

1. Choose randomly the number of structure elements m_s for each IDO structure l_s:

$$m_s = rand([I_{\min};I_{\max}]),\ s=1\ldots S. \qquad (8)$$

2. Using the operator $P_{init}(m_s,F)$, for each IDO structure l_s, generate a random vector of the basic functions $\vec{f}^s(\bullet)$,

$$\vec{f}^s(\bullet)=P_{init}(m_s,F),\ s=1\ldots S \qquad (9)$$

with the number m_s of elements in the random vector of the basic functions for the current IDO structure.

3. For each IDO structure l_s (with the already known vector of the basic functions $\vec{f}^s(\bullet)$), it is necessary to find a vector of unknown parameters $\vec{g}^s$. For this, we use the method of parametric identification based on random search procedures [7]. As a result of the IDO parametric identification phase, for each structure l_s, it is received a vector of known values of the parameters $\vec{g}^s$ and the calculated value of the quality indicator $d(l_s)$ for the structure l_s.

4. Initialize a counter of iterations *mcn*=1 and a counter of "exhaustion criterion" $limit_s$=0, where $l_s \in \Lambda_{mcn}$. If at least one structure of the IDO, for which $d(l_s)=0$, has been found at this step, go to the step ***"STOP"***.

In the implementation scheme for the method of structure identification (Fig.1), "Phase I" means the worker- bees phase. First step of "Phase I" is the synthesis of the set of the current IDO structures Λ'_{mcn}:

$$\Lambda'_{mcn}=P(\Lambda_{mcn},F) \qquad (10)$$

where the operator $P(\Lambda_{mcn},F)$ means the transformation of the set of IDO structures Λ_{mcn} into the set Λ'_{mcn}, by the way of random replacement of n_s elements of each structure by the elements from the set *F*. The number of the elements to be replaced is calculated as follows:

$$n_s=\begin{cases}\operatorname{int}\left(\left(1-\dfrac{\min\{d(l_s)|s=1\ldots S\}}{d(l_s)}\right)\cdot m_s\right),\\ \quad if\quad d(l_s)\ne\min\{d(l_s)|s=1\ldots S\}\\ \quad and\ n_s\ne 0;\\ \\ 1,\quad if\quad d(l_s)=\min\{d(l_s)|s=1\ldots S\}\\ \quad or\ n_s=0;\end{cases} \qquad (11)$$

It should be noted that in the article [6], to calculate the value of the variable n_s, there was proposed an expression based on the number of elements in the current IDO structure. However, this approach proved to be ineffective, because the number of elements in the current IDO structure is not constant, which follows from the equation (8). Therefore, for the value of n_s to be calculated, this article proposes expression (11), which does not take into account the number of the structure elements in the current IDO structure but relies only on the value of the quality indicator of the current IDO structure. We will calculate the number of structure elements n_s to be replaced, according to the principle: the smaller the value of the quality indicator of the IDO structure, the greater number of its structure elements requires replacing. However, for the "best" IDO structure one needs to replace only the minimum number of elements, i.e. one element. The need to replace the structure elements of the "best" IDO structure (in the current set of structures) is explained by the need for checking the "exhaustion criterion" for each of the formed IDO structures.

Notably, $|\Lambda_{mcn}|=|\Lambda'_{mcn}|=S$.

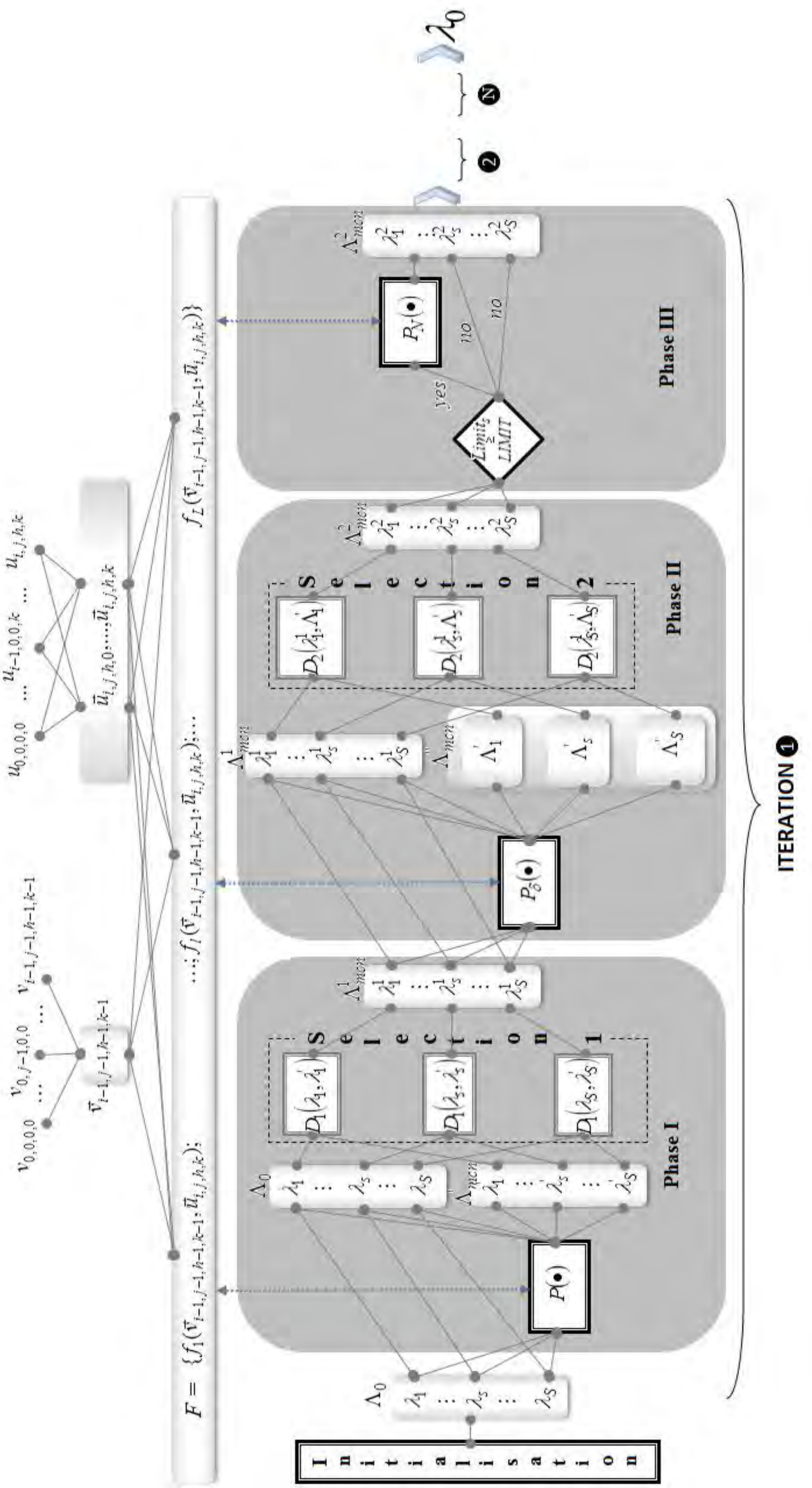
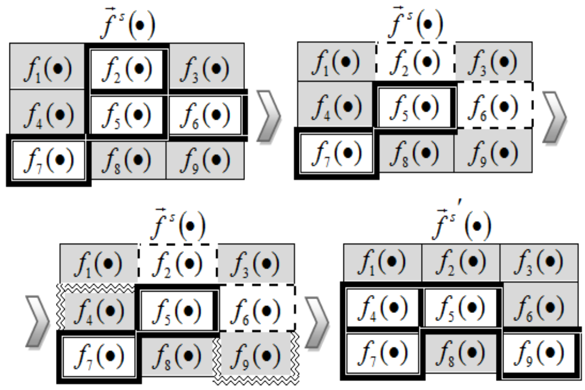


Fig. 1. Neural-like computational scheme of implementing the IDO structure identification method.

Fig. 2 schematically shows the example of the implementation of the operator $P(\Lambda_{mcn},F)$ (10).



– the structure elements from the set *F*, which are not included in the vector of basic functions of the current IDO structure;

– the structure elements from the set *F*, which are included in the vector of basic functions of the current IDO structure;

– the structure elements from the set *F*, which are included in the vector of basic functions of the current IDO structure and are selected to be replaced;

– the structure elements from the set *F*, which are not included in the vector of basic functions of the current IDO structure and are selected to replace the included ones.

Fig. 2. An example of using the operator $P(\Lambda_{mcn},F)$ *for the s-th IDO structure* $l_s \in \Lambda_{mcn}$*, where* $|F|=9, m_s=4, n_s=2$.

Fig. 2 shows the transformation mechanism of the current IDO structure l_s (from the set Λ_{mcn}), which is specified by the vector of basic functions made of the structure elements: $\{f_2(\bullet), f_5(\bullet), f_6(\bullet), f_7(\bullet)\}$, and for which the value $n_s=2$ was calculated; to the structure l'_s (from the set Λ'_{mcn}) by replacing the randomly selected structure elements $\{f_2(\bullet), f_6(\bullet)\}$ by the random elements $\{f_4(\bullet), f_9(\bullet)\}$ selected from the set F. As a result of the transformation, a new vector of the basic functions $\vec{f}^{s'}(\bullet)$ is obtained, which consists of the following structure elements $\{f_4(\bullet), f_5(\bullet), f_7(\bullet), f_4(\bullet)\}$. The vector of the basic functions $\vec{f}^{s'}(\bullet)$ uniquely determines the IDO structure l'_s.

The second step of "Phase I" is the pairwise selection of IDO structures and forming a set of the "best" IDO structures Λ^1_{mcn}. Fig. 1 shows the pairwise selection of IDO structures as the block "Selection 1". Inside the "Selection 1" block, the operator $D_1(l_s, l'_s)$ implements the synthesis of the set of the "best" IDO structures Λ^1_{mcn} on the basis of the current sets: Λ_{mcn}, Λ'_{mcn}. The operator $D_1(l_s, l'_s)$ implements the pairwise selection, for each pair of the IDO structures based on the values of quality indicator, using the expression given below:

$$l_s^1 = \begin{cases} l_s, IF(d(l_s) \le d(l'_s)), \\ l'_s, IF(d(l_s) > d(l'_s)), \end{cases} \quad (12)$$

where $l_s \in \Lambda_{mcn}$, $l'_s \in \Lambda'_{mcn}$, $l_s^1 \in \Lambda^1_{mcn}$ $s=1 \ldots S$.

Besides, if $d(l_s) \le d(l'_s)$, then $limit_s = \; = limit_s + 1$; but if $d(l_s) > d(l'_s)$, then $limit_s = 0$. If at least one IDO structure has been received at this step, for which $d(l_s^1)=0$, go to the step ***"STOP"***.

Thus, we shall get the set Λ^1_{mcn}, which is called a set of IDO structures of the first row formation (received at the *mcn-th* iteration of the method).

In the scheme of implementation of the method of structure identification (Fig.1), "Phase II" means the explorer-bees phase. The first step of "Phase II" is the synthesis of the set of the current IDO structures Λ''_{mcn} that is conducted taking into account their "quality".

$$\Lambda''_{mcn} = P_d(\Lambda^1_{mcn}, F), \quad (13)$$

$$\Lambda''_{mcn} = \{\Lambda'_1 \cup \Lambda'_2 \ldots \cup \ldots \Lambda'_s \ldots \cup \Lambda'_S\}, s = 1 \ldots S \quad (14)$$

where the operator $P_d(\Lambda^1_{mcn}, F)$ in the equation (12) means the transformation of the set Λ^1_{mcn} of the first row formation into the set Λ''_{mcn} of IDO structures. This operator means that we generate a set Λ'_s of IDO structures using the random replacement of the n_s elements (calculated by the expression (11)) of each structure l_s^1 by random elements of the set ***F***. However, in contrast to the actions of the operator $P(\Lambda_{mcn},F)$ in the equation (10), the operator in the equation (13) carries out the replacement only for those structures $l_s^1 \in \Lambda^1_{mcn}$ for which $R_s > 0$. The value of R_s for each of the structures $l_s^1 \in \Lambda^1_{mcn}$ is calculated using the expression given below:

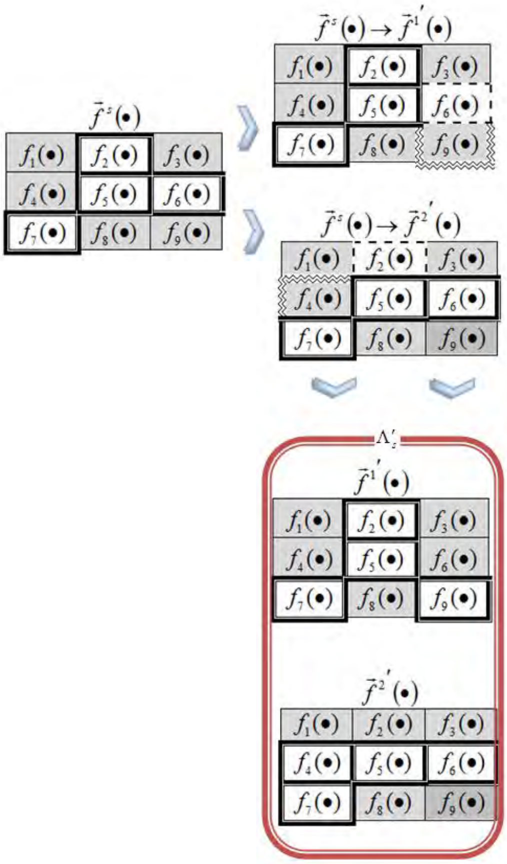
$$R_s = ToInt\left(S \cdot \left(2 \cdot \max\left\{d\left(l_s^1\right) \middle| i=1 \ldots S\right\} - d\left(l^1_s\right) - d\left(l^1_{s-1}\right)\right) \Big/ \sum_{s=1}^{S} \left(\max\left\{d\left(l_s^1\right) \middle| i=1 \ldots S\right\} - d\left(l^1_s\right) - R_{s-1}\right)\right) \quad (15)$$

$$s = 2 \ldots S$$

and $R_1 = 0$. The operation $ToInt(\bullet)$ means rounding to the nearest integer value. Note, that R_s means the number of structures that will be generated based on the structure l_s^1

(from the set $\Lambda^1{}_{mcn}$), where the elements of the set $\Lambda^1{}_{mcn}$ must be sorted by decreasing the value of the quality indicator. Thus, for each structure $l_s^1 \in \Lambda^1{}_{mcn}$, a set of structures Λ'_s, where $|\Lambda'_s| = R_s$, will be formed. That is, if $R_s \neq 0$, then $\Lambda'_s = \{l_1 \ldots l_r \ldots l_{Rs}\}$. Note that Λ'_s may be an empty set. The total number of the structures generated by the operator $P_d(\Lambda^1{}_{mcn}, F)$ is equal to S, i.e $\left|\Lambda^1{}_{mcn}\right| = |\Lambda''_{mcn}| = S$.

Fig. 3 schematically shows the example of the implementation of the operator $P_d(\Lambda^1{}_{mcn}, F)$ in the equation (13).



– the structure elements from the set *F*, which are not included in the vector of basic functions of the current IDO structure;

– the structure elements from the set *F*, which are included in the vector of basic functions of the current IDO structure;

– the structure elements from the set *F*, which are included in the vector of basic functions of the current IDO structure and are selected to be replaced;

– the structure elements from the set *F*, which are not included in the vector of basic functions of the current IDO structure and are selected to replace the included ones.

Fig. 3. An example of using the operator $P_d(\Lambda^1{}_{mcn}, F)$ *for the* s^{-th} *IDO structure* $l_s^1 \in \Lambda^1{}_{mcn}$, *where* $|F| = 9$, $m_s = 4$, $n_s = 1$, $R_s = 2$.

Fig. 3 shows the formation mechanism of the set Λ'_s, for the current IDO structure l_s^1 (from the set $\Lambda^1{}_{mcn}$). In the example, the current IDO structure l_s^1 is specified by the vector of basic functions formed from the structure elements: $\{f_2(\bullet), f_5(\bullet), f_6(\bullet), f_7(\bullet)\}$, and for which the values: $n_s = 1$, $R_s = 2$ were calculated. Thus, based on the current IDO structure l_s^1 a set of the IDO structures Λ'_s in the form – $\Lambda'_s = \{l_1, l_2\}$ is formed. The IDO structures l_1 and l_2 are specified by the vectors of basic functions formed from the structure elements: $\{f_2(\bullet), f_5(\bullet),, f_7(\bullet), f_9(\bullet)\}$ $\{f_4(\bullet), f_5(\bullet), f_6(\bullet), f_7(\bullet)\}$, respect-tively.

The second step of "Phase II" is the group selection of IDO structures and forming a set of the "best" IDO structures. Fig. 1 shows the group selection of IDO structures as the block "Selection 2". Inside the "Selection 2" block, the operator $D_2(l_s, \Lambda'_s)$ implements the synthesis of the set of the "best" IDO structures $\Lambda^2{}_{mcn}$ from the current sets: $\Lambda^1{}_{mcn}$, Λ''_{mcn}. It should be noted that the operator $D_2(l_s, \Lambda'_s)$ implements the selection of the "best" structures based on the quality indicator of the structure, using the following expression:

$$l_s^2 = \begin{cases} l_s^1, & IF(R_s = 0), \\ l_s^1, & IF((d(l_s^1) \le d(l_r)) \wedge (R_s \neq 0)), \\ & \forall l_r \in \Lambda'_s, r = 1 \ldots R_s, \\ l_r^s, & IF((d(l_s^1) > d(l_r)) \wedge (R_s \neq 0)), \\ & \exists l_r \in \Lambda'_s, r = 1 \ldots R_s. \end{cases} \quad (16)$$

Besides, if $R_s = 0$ or $((d(l_s^1) \le d(l_r)) \wedge (R_s \neq 0))$ then set*:* $limit_s = limit_s + 1$; but if $((d(l_s^1) > d(l_r)) \wedge (R_s \neq 0))$, then set: $limit_s = 0$. If at least one structure, for which $d(l_s^2) = 0$, has been received at this step, go to the step ***"STOP"***.

In the scheme of implementing the method of structure identification (Fig.1), "Phase III" means the scout-bees phase. The implementation of "Phase III" is as follows: checking the "exhaustion criterion" (bees leave the exhausted food sources).

If $limit_s \geq LIMIT$, then for all the IDO structures $l_s^2 \in \Lambda^2_{mcn}$, for which this condition is fulfilled, the equation given below is used:

$$l_s^2 = P_N(F, I_{\min}, I_{\max}) \tag{17}$$

and $limit_s = 0$.

The operator $P_N(F, I_{\min}, I_{\max})$ means random generation of the "new" structure l_s^2 using the set *F*. For each "new" structure l_s^2 we calculate the value of the quality indicator $d\left(l_s^2\right)$. If at least one structure, for which $d\left(l_s^2\right) = 0$, has been received at this step, go to the step ***"STOP"***, otherwise return to **Step 2.**

Step "STOP". Output of the optimum IDO structure, for which the quality indicator equals to 0.

4. An illustrative example

Let us consider the process of producing standard drywall sheets: 9.5 mm (thickness) by 2500 mm (length) by 1200 mm (width). It is known that humidity measuring devices have accuracy within 5%. That is why, it is necessary to ensure that interval humidity estimates are within the tolerable error at all points on the surface of a drywall sheet. Accordingly, for this field to be approximated, it is convenient to use an IDO. The permissible limits of relative humidity on the surface of drywall sheets to ensure the quality of product should be between 0,6% and 0,9%. Otherwise, the products are discarded.

The results of humidity measurements under given conditions (temperature in a drying chamber: $u_{1,0} = 120°$, $u_{1,k=1} = 125°$; velocity of the drywall sheet while its moving in a drying chamber: $u_{2,0} = 0,25$ m/min, $u_{2,k=1} = 0,28$ m/min) of the process are shown in article [7].

Let us perform the procedure of structure identification for a macromodel of humidity distribution on the drywall sheet surface at the drying stage in the form of the IDO using these data sets.

For the IDO structure synthesis by using the method of structure identification based on the ABCA, a finite set of structure elements (basic functions) *F* with $L = 80$ elements has been generated. The set of structure elements contains polynomial functions of not higher than the second degree for the IDO of not higher than the second order.

As a result, we have got Table 1 – an ordered set of structure elements.

Table 1

The ranked set *F* of structure elements

№	Structure element
1	$v_{i-1,j} \cdot (u_{1,0} \cdot u_{2,k} / u_{2,0} \cdot u_{1,k})$
…	…
6	$v_{i,j-1} \cdot v_{i-1,j} \cdot (u_{1,0} \cdot u_{2,k} / u_{2,0} \cdot u_{1,k})$
…	…
11	$v_{i-1,j} \cdot v_{i-1,j-1} \cdot (u_{1,0} \cdot u_{2,k} / u_{2,0} \cdot u_{1,k})$
…	…
16	$v_{i,j-1} \cdot v_{i-1,j}$
…	…
21	$v_{i-1,j} \cdot v_{i-1,j-1}$
…	…
26	$v_{i-1,j}$
…	…
31	$v_{i-1,j}^2$
…	…
36	$v_{i-1,j} \cdot (u_{1,0} / u_{2,0})$
…	…
41	$v_{i,j-1} \cdot v_{i-1,j} \cdot (u_{1,0} / u_{2,0})$
…	…
46	$v_{i-1,j} \cdot v_{i-1,j-1} \cdot (u_{1,0} / u_{2,0})$
…	…
51	$v_{i-1,j} \cdot (u_{1,k} / u_{2,k})$
…	…
56	$v_{i,j-1} \cdot v_{i-1,j} \cdot (u_{1,k} / u_{2,k})$
…	…
61	$v_{i-1,j} \cdot v_{i-1,j-1} \cdot (u_{1,k} / u_{2,k})$
…	…
66	$v_{i-1,j}^2 (u_{1,0} \cdot u_{2,k} / u_{2,0} \cdot u_{1,k})$
…	…
71	$v_{i-1,j}^2 \cdot (u_{1,0} / u_{2,0})$
…	…
76	$v_{i-1,j}^2 \cdot (u_{1,k} / u_{2,k})$
…	…
80	$v_{i-1,j-2}^2 \cdot (u_{1,k} / u_{2,k})$

The initial parameters of the computational scheme have been set as follows: *MCN=100*, *LIMIT=4*, *S=10*, $[I_{\min}; I_{\max}] = [4;10]$. Further, according to the computational scheme of the implementation of the method of structure identification for a macromodel based on the principles of bee colony functioning, an initial set of the IDO structures Λ_0 has been randomly generated. Also, for every structure l_s, the value of the quality indicator $d(l_s)$ and the number n_s of elements to be replaced have been calculated. As a result, we have got Table 2 – an initial set of IDO structures.

Table 2

The initial set of IDO structures Λ_0

№	The sequence numbers of the structure elements out of the set *F*, that define the IDO structures: $l_s \in \Lambda_0$	$d(l_s)$	n_s	$Limit_s$
1	2, 40, 27, 29, 24, 30	0,1307	1	0
2	11, 25, 31, 64, 3, 51, 36, 32	0,1518	3	0
3	61, 48, 31, 37	0,2049	2	0
4	10, 29, 16, 38	0,1175	1	0
5	10, 39, 41, 37	0,0935	1	0
6	7, 39, 20, 37	0,3217	2	0
7	7, 40, 26, 6, 53	0,1587	2	0
8	7, 40, 25, 6, 27	0,1565	2	0
9	7, 40, 25, 6, 27, 28, 29	0,1272	1	0
10	2, 40, 25, 1, 27, 29	0,1170	1	0

Next, we implement “Phase I” (*the worker-bees phase*). For this purpose, a set of the IDO structures $\Lambda'_{mcn=1}$ is formed using the expression (11). After that, we calculate the value of the quality indicator $d(l'_s)$ for all the structures $l'_s \in \Lambda'_1$. The results that we have got after the implementation of this stage of “Phase I” are shown in Table 3.

Table 3

The set of IDO structures Λ'_1 and calculated values of the quality indicator $d(l'_s)$

№	The sequence numbers of the structure elements out of the set *F*, that define the IDO structures: $\Lambda'_{mcn=1}$ $l'_s \in \Lambda'_1$	$d(l'_s)$	m'_s
1	2, 26, 27, 29, 24, 30	0.7383	6
2	11, 29, 31, 26, 3, 51, 36, 53	0.1260	8
3	1, 48, 31, 19	0.1616	4
4	10, 2, 16, 38	0.1145	4
5	10, 39, 41, 29	0.0649	4
6	7, 39, 52, 63	0.1420	4
7	7, 40, 26, 27, 58	0.1650	5
8	7, 50, 25, 6, 19	0.1094	5
9	7, 40, 35, 6, 27, 28, 29	0.1176	7
10	2, 40, 79, 1, 27, 29	0.3250	6

Then, we implement the pairwise selection of IDO structures from the sets Λ_0 and Λ'_1, based on the value of the quality indicator, using the expression (12). After the implementation of this stage of “Phase I”, we have got a set $\Lambda^1_{mcn=1}$ of IDO structures of the first row formation.

The results are shown in Table 4.

Table 4

The set $\Lambda^1_{mcn=1}$ of IDO structures of the first row formation

№	The sequence numbers of the structure elements out of the set *F*, $l^1_s \in \Lambda^1_{mcn=1}$	$d(l^1_s)$	$limit_s$
3	1, 48, 31, 19	0,1616	0
7	7, 40, 26, 6, 53	0,1587	1
6	7, 39, 52, 63	0,1420	0
1	2, 40, 27, 29, 24, 30	0,1307	1
2	11, 29, 31, 26, 3, 51, 36, 53	0,1260	0
9	7, 40, 35, 6, 27, 28, 29	0,1176	0
10	2, 40, 25, 1, 27, 29	0,1170	1
4	10, 2, 16, 38	0,1145	0
8	7, 50, 25, 6, 19	0,1094	0
5	10, 39, 41, 29	0,0649	0

Further, we implement “Phase II” (*the explorer-bees phase*). For this purpose, we form a set $\Lambda''_{mcn=1}$ of IDO structures, using the equation (13) (previously for each structure $l^1_s \in \Lambda^1_{mcn=1}$ the cardinal number R_s of the set Λ'_s has been calculated using the expression (15)). Note, the set $\Lambda''_{mcn=1}$ is equal to the union of the sets: $\Lambda''_{mcn=1} = \{\Lambda'_1 \cup \Lambda'_2 \mathbf{K} \cup \mathbf{K} \Lambda'_s \mathbf{K} \cup \Lambda'_S\}$. After that, the value of the quality indicator $d(l'_r)$ is calculated, for all the structures $l'_r \in \Lambda'_s$. The results that we have got after implementing this stage of “Phase II” are shown in Table 5.

Table 5

The set of IDO structures $\Lambda^1_{mcn=1}$ of the first row formation

№	The sequence numbers of the structure elements out of the set *F*, that define the IDO structures: $l^1_s \in \Lambda^1_{mcn=1}$	R_s	The sequence numbers of the structure elements out of the set *F*, that define the IDO structures: $l_r \in \Lambda'_s$	$d(l_r)$
3	1, 48, 31, 19	0	∅	-
7	7, 40, 26, 6, 53	0	∅	-
6	7, 39, 52, 63	1	7, 66, 77, 63	0.1687
1	2, 40, 27, 29, 24, 30	1	3, 40, 27, 16, 53, 30	0.1403
2	11, 29, 31, 26, 3, 51, 36, 53	1	11, 27, 31, 26, 60, 51, 36, 70	0.0787
9	7, 40, 35, 6, 27, 28, 29	1	7, 66, 35, 25, 27, 2, 29	0.2769
10	2, 40, 25, 1, 27, 29	1	2, 36, 25, 67, 27, 29	0.0870
4	10, 2, 16, 38	1	10, 2, 16, 29	0.051
8	7, 50, 25, 6, 19	1	7, 80, 25, 6, 32	0.0472
5	10, 39, 41, 29	3	10, 45, 41, 29	0.0816
			10, 39, 41, 27	0.0854
			10, 3, 41, 29	0.0439

Further, we implement the group selection of IDO structures from the sets: $\Lambda^1_{mcn=1}$ and $\Lambda''_{mcn=1}$ based on the value of the quality indicator using the equations (16). After the implementation of this stage of "Phase II", we have got a set $\Lambda^2{}_{mcn=1}$ of the IDO structures of the second row formation.

The results are shown in Table 6.

Table 6

The set of IDO structures $\Lambda^2{}_{mcn=1}$ of the second row formation

№	The sequence numbers of the structure elements out of the set *F*, that define the IDO structures: $l_s^2 \in \Lambda^2_{mcn=1}$	$d(l_s^2)$	$Limit_s$
3	1, 48, 31, 19	0.1616	1
7	7, 40, 26, 6, 53	0.1582	2
6	7, 39, 52, 63	0.1420	1
1	2, 40, 27, 29, 24, 30	0.1307	2
2	11, 27, 31, 26, 60, 51, 36, 70	0.0787	0
9	7, 40, 35, 6, 27, 28, 29	0.1176	1
10	2, 36, 25, 67, 27, 29	0.0870	0
4	10, 2, 16, 29	0.051	0
8	7, 80, 25, 6, 32	0.0472	0
5	10, 3, 41, 29	0.0439	0

Next, we implement "Phase III" (*the scout-bees phase*), that means the following: checking the "exhaustion criterion" (*bees leave the exhausted food sources*). As we can see from Table 6, for neither IDO structures of the second row formation l_s^2 the condition: $limit_s \geq LIMIT$ is not fulfilled, and hence, the operator $P_N(F, I_{\min}, I_{\max})$ will not run for none of the IDO structures l_s^2 on the first iteration of the method. Accordingly, Table 6 defines a current set of the IDO structures $\Lambda_{mcn=2}$. It is the set we shall use for the implementation of the second iteration of the method of structure identification.

During the synthesis, we have performed 3 iterations of the method of IDO structure identification based on the ABCA, and on the 3[th] iteration we have found the IDO structure in the following form:

$$
\begin{aligned}
&[\hat{v}^-_{i,j,k};\hat{v}^+_{i,j,k}] = 0,2269 - \\
&-0,0553\cdot(u_{1,0}\cdot u_{2,k}/u_{2,0}\cdot u_{1,k})\cdot[\hat{v}^-_{i,j-1,k};\hat{v}^+_{i,j-1,k}] - \\
&-0,3643\cdot[\hat{v}^-_{i-1,j-2,k};\hat{v}^+_{i-1,j-2,k}] + \\
&+0,1214\cdot(u_{1,0}\cdot u_{2,k}/u_{2,0}\cdot u_{1,k})\cdot[\hat{v}^-_{i-1,j,k};\hat{v}^+_{i-1,j,k}] + \\
&+1,0005\cdot[\hat{v}^-_{i,j-1,k};\hat{v}^+_{i,j-1,k}],
\end{aligned}
\qquad (18)
$$

where

$$
\begin{aligned}
&[\hat{v}^-_{i,j,k};\hat{v}^+_{i,j,k}] = (u_{1,0}\cdot u_{2,k}/u_{2,0}\cdot u_{1,k})\cdot \\
&\cdot[\hat{v}^-_{i,j,k=0};\hat{v}^+_{i,j,k=0}] \subset [z^-_{i,j,k=0};z^+_{i,j,k=0}] = \\
&= [z_{i,j,k=0} - z_{i,j,k=0}\cdot 0,01; z_{i,j,k=0} + z_{i,j,k=0}\cdot 0,01],
\end{aligned}
$$

{i=0,…,3; j=0,1}, {i=0; j=0,…,7} are the given initial conditions; $u_{1,0}, u_{1,k}$ are the temperature in the drying chamber corresponding to the given test dataset and the predicted k-value of the temperature, respectively; $u_{2,0}, u_{2,k}$ are the velocity of the drywall sheet in the drying chamber corresponding to the given test dataset and the predicted k value of the temperature, respectively.

In addition, for the synthesis of a mathematical model structure for humidity distribution on a drywall sheet surface at the stage of drying the experiment has been also held using the method of structure identification based on the genetic algorithms. The method was proposed in article [4].The experimental conditions were the same (*initial conditions, initial parameters of the computational scheme*). Using the method, the IDO structure has been obtained in the following form:

$$
\begin{aligned}
&[\hat{v}^-_{i,j,k};\hat{v}^+_{i,j,k}] = 0,2941 - \\
&-0.2286\cdot(u_{1,0}\cdot u_{2,k}/u_{2,0}\cdot u_{1,k})\cdot[\hat{v}^-_{i-1,j,k};\hat{v}^+_{i-1,j,k}] - \\
&-0.2836\cdot[\hat{v}^-_{i-1,j-1,k};\hat{v}^+_{i-1,j-1,k}]\cdot[\hat{v}^-_{i,j-1,k};\hat{v}^+_{i,j-1,k}] + \\
&+0.9213\cdot[\hat{v}^-_{i,j-1,k};\hat{v}^+_{i,j-1,k}] - 0.4575\cdot[\hat{v}^-_{i,j-2,k};\hat{v}^+_{i,j-2,k}] + \\
&+0.7267\cdot(u_{1,0}\cdot u_{2,k}/u_{2,0}\cdot u_{1,k})\cdot \\
&\cdot[\hat{v}^-_{i-1,j,k};\hat{v}^+_{i-1,j,k}]\cdot[\hat{v}^-_{i,j-1,k};\hat{v}^+_{i,j-1,k}],
\end{aligned}
\qquad (19)
$$

where

$$
\begin{aligned}
&[\hat{v}^-_{i,j,k};\hat{v}^+_{i,j,k}] = (u_{1,0}\cdot u_{2,k}/u_{2,0}\cdot u_{1,k})\cdot \\
&\cdot[\hat{v}^-_{i,j,k=0};\hat{v}^+_{i,j,k=0}] \subset [z^-_{i,j,k=0};z^+_{i,j,k=0}] = \\
&= [z_{i,j,k=0} - z_{i,j,k=0}\cdot 0,01; z_{i,j,k=0} + z_{i,j,k=0}\cdot 0,01],
\end{aligned}
$$

{i=0,…,3; j=0,1}, {i=0; j=0,…,7} are the given initial conditions; $u_{1,0}, u_{1,k}$ are the temperature in the drying chamber corresponding to the given test dataset and the predicted k-value of the temperature, respectively; $u_{2,0}, u_{2,k}$ are the velocity of the drywall sheet in the drying chamber corresponding to the given test dataset and the predicted k value of the temperature, respectively.

Should we compare the mathematical models in the equations (18) and (19), we can see that they are alike (*some structure elements are the same).* The reason is that the experimental conditions were the same for the implementation of both methods. However, the IDO structure received by the method of structure identification based on the ABCA (18) is simpler than the IDO structure received by the method of structure identification based on the GA (19).

In particular, from the perspective of computational complexity, the IDO structure (18) is simpler because it contains 4 structure elements and for one predicted point requires performing 12 multiplications and 4 summations, while the IDO structure (19) contains 5 structure elements and for the one predicted point requires performing 15 multiplications and 5 summations.

5. Conclusion

The problem of structure identification of an interval difference operator as the model of an object with distributed parameters has been considered. It is shown that this problem is a discrete optimization problem and its solving algorithms are NP-complete. Thus, we have obtained the following new scientific and practical results:

– the method for IDO structure identification has been proposed and validated, which unlike the existing one is based on the principles of bee colony functioning. The new method is based on the behavior of the bee colony while searching for rich food sources;

– using the new method (in contrast to using the known one based on the GA) reduces the computational complexity of implementation of the developed method and provides the use of strictly formalized procedures of generating better variants of IDO structures;

– a neural-like computational scheme of the implementation of the method of IDO structure identification has been proposed and validated. This scheme ensures the convergence of the implementation of the method, and - in contrast to the existing methods - it gives the possibility of obtaining simpler IDO structures with specified prognostic properties;

– effectiveness of using the proposed method and its computational scheme have been shown on the example of building a macromodel in the form of interval difference operator to predict the distribution of humidity in drywall sheets in the process of drying.

– it has been shown that the use of the proposed method (in contrast to the use of the known one based on the GA) gives a simpler model's structure of humidity distribution in drywall sheets in the process of drying, without impairment of its predictive properties;

– it has been shown that computational complexity of the implementation of the proposed method of structure identification is 18% less in comparison with the implementation of the known method based on the GA.

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МЕТОД СТРУКТУРНОЇ ІДЕНТИФІКАЦІЇ ІНТЕРВАЛЬНОГО РІЗНИЦЕВОГО ОПЕРАТОРА НА ОСНОВІ ПРИНЦИПІВ ФУНКЦІОНУВАННЯ КОЛОНІЇ МЕДОНОСНИХ БДЖІЛ

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Розглянуто задачу структурної ідентифікації інтервального різницевого оператора (ІРО) як моделі об'єкта з розподіленими параметрами. Запропоновано та обґрунтовано новий метод структурної ідентифікації ІРО на основі харчової поведінки колонії медоносних бджіл. Крім того, розроблено нейроподібну схему реалізації зазначеного методу. Ефективність застосування запропонованого методу та його обчислювальної схеми проілюстровано на прикладі побудови макромоделі процесу розподілу вологості на поверхні листа гіпсокартону на стадії його сушіння.

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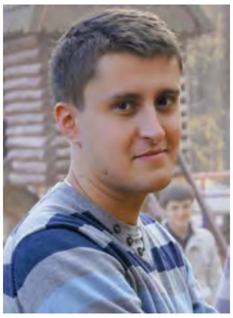

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