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THE ALGORITHM OF INTELLIGENT CONTROL FOR PASTY MATERIALS DRYING PROCESSES

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Abstract: Drying plants are common in the industry, but the complexity of their consideration as an object of control makes it very time-consuming to design real-time control systems based on the existing mathematical apparatus of the optimal control theory. The paper deals with the control algorithm based on the application of artificial intelligence methods to synthesize the optimal control, and to neutralize effects of process mode from acceptable values.

Introduction

Drying processes are quite widespread in modern industry. When you create a control system of a drying process, you should consider specific features of dryers as objects of control. These features include controlling by the large number of adjustable parameters, their distributivity, mutual influence of adjacent zones of each other (in multizones-dryers), the complexity of an optimality criterion, etc. In practice, to optimize the drying process, we often have to solve fairly complex systems of equations for heat and mass transfer, which greatly complicates the process of developing algorithms and software of control systems that provide a synthesis of optimal control actions in real-time.

Another possible approach is application of artificial intelligence methods in the development of mathematical and algorithmic support of control systems. The article deals with the designing of intelligent synthesis algorithm for the control information system for the paste materials drying process in dryer drum belt dryers using fuzzy logic methods and multi-agent approach.

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Formalization of the problem

Multistage **DDB** (Dryer Drum Belt) are widely used in industry for drying pasty materials [1]. For control problem, DDB can be considered as a multi-zone **MIMO**-object (Multi Input Multi Output).

There are two types of control in each zone that influence only in their own zone: u_i^{GA} – control of gates and air intake in the i-th zone; u_i^{SH} – control of heating by steam heater in the i-th zone. There are two other types of control, that influence every zone: u^{EF} – control of the exhaust fan and u^{BS} – control of the conveyor belt speed.

Vector of controls for DDB can be considered as

$$U(t) = (U_1(t), ..., U_n(t), U_0(t)), \quad t \in [t_0, t_{\mathrm{end}}];$$

$$U_i(t) = \left(u_i^{\mathrm{SH}}, u_i^{\mathrm{GA}}\right), \quad i = \overline{1, n}, \quad U_0(t) = \left(u^{\mathrm{BS}},\ u^{\mathrm{EF}}\right),$$

where $[t_0, t_{\mathrm{end}}]$ is time interval of control; n is number of zones.

The problem can be formulated as.

Input:

– the technological process is determined by valid ranges of temperature and humidity in dryer zones

$$T_i(t) \in \left[T_i^{\mathrm{l}},\ T_i^{\mathrm{h}}\right], \quad \varphi_i(t) \in \left[\varphi_i^{\mathrm{l}},\ \varphi_i^{\mathrm{h}}\right], \quad i = \overline{1, n}, \tag{1}$$

where T_i^{l}, T_i^{h} are lower and upper permissible values of material temperature in the i-th zone; φ_i^{l}, φ_i^{h} are lower and upper permissible values of material humidity in the i-th zone;

– restrictions on the components of vector of control at all times:

$$\begin{gathered} u_i^{\mathrm{SH}} \in \left[u_i^{\mathrm{SHl}}, u_i^{\mathrm{SHh}}\right],\ u_i^{\mathrm{GA}} \in \left[u_i^{\mathrm{GAl}}, u_i^{\mathrm{GAh}}\right], \\ u^{\mathrm{BS}} \in \left[u^{\mathrm{BSl}}, u^{\mathrm{BSh}}\right],\ u^{\mathrm{EF}} \in \left[u^{\mathrm{EFl}},\ u^{\mathrm{EFh}}\right], \quad i = \overline{1, n}, \end{gathered} \tag{2}$$

where u_i^{SHl}, u_i^{SHh}, u_i^{GAl}, u_i^{GAh} are boundary values of control actions for steam heater, gates and air intake in the i-th zone; u^{BSl}, u^{BSh} are boundary values of control actions for conveyor belt speed; u^{EFl}, u^{EFh} are boundary values of control actions for exhaust fan;

– the functional can be minimized

$$J_\Sigma = p_{\mathrm{e}} J_{\mathrm{e}} + p_{\mathrm{p}} J_{\mathrm{p}}, \tag{3}$$

where p_{e}, p_{p} are coefficients; J_{e} are a functional of minimum energy consumption; J_{p} – a functional of maximum performance.

We need to determine the vector of control actions

$$U^*(\cdot) = \left\{U_i^*(t), U_0^*(t),\ i = \overline{1, n},\ \ t \in [t_0, t_{\mathrm{end}}]\right\}, \tag{4}$$

that will provide for the maintenance of the required technological DDB mode (1) under the constraints (2) for optimum functional (3).

The algorithm of control actions synthesis

We consider the Multiagent approach to designing **ICS** (Information Control System) of drying process [3, 4]. The ICS for DDB includes following **CA** (Control Agents), that implement control actions: **BSCA** (Belt Speed Control Agent) $\left(u^{\mathrm{BS}}\right)$; **EFCA** (Exhaust Fan Control Agent)$\left(u^{\mathrm{EF}}\right)$; **SHCA** (Steam Heater Control Agent) for the *i*-th zone $\left(u_i^{\mathrm{SH}}\right)$; and **GACA** (Gates and Air intake Control Agent) for the *i*-th zone $\left(u_i^{\mathrm{GA}}\right)$. **AC** (Coordinator agent**)** is the basis of ICS. It coordinates control agents.

One of the most widespread types is a DDB with five-zones. In such dryers, maximum moisture removal occurs in second and third zones, so, in most cases, three humidity sensors (at ends of the second, third and fifth zones) are enough to monitoring the drying process. For evaluating the moisture content in real-time directly in the drying process we can apply intelligent sensors and information-measuring systems [4].

From the perspective of humidity sensors, a dryer drum belt can be divided into three areas:

1) first and second zones;
2) the third zone;
3) fourth and fifth zones.

Coordinator agent includes three observer agents (OA1-OA3). OA1 monitors and controls the first area of DDB (first and second sections), OA2 monitors and controls the second area (third zone), and OA3 monitors and controls the third zone (fourth and fifth sections). The main function of AC is a calculation of the necessary control and its distribution among the control agents.

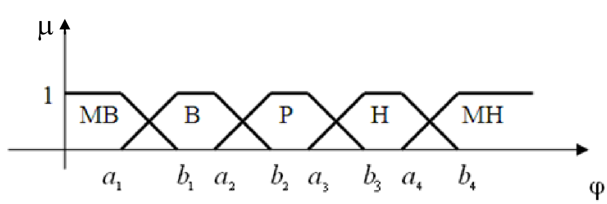
The array of control agent's parameters can be written as

$$R_{\mathrm{A}}^{j}=\left(u_{\mathrm{l}}^{j}, u_{\mathrm{h}}^{j}, \Delta u^{j}, P^{j}, W^{j}\right), \quad j=\overline{1,\ 12},$$

where u_{l}^{j}, u_{h}^{j} are minimum and maximum values of control actions for the *j*-th control agent; Δu^{j} is conversion factor for control; P^{j}, W^{j} is coefficients of influence on performance and power consumption.

The synthesis algorithm comprises four stages. The first stage is a fuzzification of the moisture content in the areas of maximum moisture removal (at the end of the second and third zones of DDB).

The proposed membership functions of the moisture content are shown in the figure. The presented membership functions are indicated by the following terms: **MB** (much below permitted), **B** (below permitted), **P** (permitted), **H** (higher permitted) and **MH** (much higher permitted).



Membership functions

Non-zero probabilities of terms can be calculated by the formula

$$\mu_i = \begin{cases} 1, \ \varphi_t^i \in \left[b_{j-1}^i; a_j^i\right], \\ \dfrac{\varphi_t^i - b_j^i}{a_j^i - b_j^i}, \ \varphi_t^i \in \left[a_j^i; b_j^i\right], \end{cases} \quad (5)$$

where $i = \overline{2, 3}$ is the number of DDB zone; $j = \overline{1, 4}$ is the number of segment on membership function (Figure).

The second stage is the calculation of the required control action.

This requires introduction of the array of coefficients affecting the performance $uv_{2,3}(j)$, elements, which quantitatively show the deviation degree of the current situation from the ideal drying process. Coefficients must take into account the fact that the length of the first zone is greater than the length of the second zone, in this example it is as twice long.

Application of fuzzy logic to identify the current situation enables to create complex non-linear relationship between the absolute deviation from the ideal process and the necessary control by configuring membership functions.

If exit moisture of the material at the end of the second zone is out of the permitted range (the probability of P term is less than 1) calculation of the control action requires bringing the process to acceptable values; OA1 is the general agent, OA2 provides short-time corrective control, and corrects humidity by the end of the third section.

Control actions for OA1 and OA2 calculated as follows

$$U_n^* = k\left(F^i\right) uv_i\left(F^i\right)\mu_i + k\left(F^i\right) uv_i\left(F^i + 1\right)(1 - \mu_i), \quad (6)$$

where n is number of OA, $i = \overline{2, 3}$ is the number of zone; F^i is the number of humidity term in the i-th section; k is coefficient determining the control character $k = \begin{cases} -1, \text{ when } F^i < 2, \\ 1, \text{ when } F^i \geq 3. \end{cases}$

Correction calculations for OA2 calculated as follows

$$U_2^k = r_{12} \frac{U_1^*}{1 - \dfrac{u_t^1 t}{l_j}}, \quad (7)$$

where t is time from the beginning of correction; u_t^1 is the current belt speed; r_{12} is ratio of the first and second areas lengths (in this case $r_{12} = 2$); l_j is length of the j-th zone.

The calculation of correction controls for OA2.

Thus, control calculated to correct the situation in the first area must be also applied to material passing into the second area (third zone), which leads to the increase in the selection of moisture in the third section, which should be taken into account in humidity measuring at the end of the second area. The added control in the second zone will reduce the moisture content at the end of the third section, but the system should not react to it, making allowance for corrective control.

When exit moisture of the material at the end of the third zone is out of permitted range, (the probability of P term is less than 1), calculation of the control action requires returning the process to acceptable values, OA2 is the general agent, OA3 provides short-time corrective control to correct humidity by the end of fifth zone. Calculation of OA2 control actions made by Formula (6).

Correction by OA3 agent is different from correction OA2 agent, because OA3 agent has at its disposal two zones (fourth and fifth), which reduces the excess drying of the material in the third zone now from the implementation of corrective control in the fourth section, before reach fifth section.

Correction calculations for AH3 in the fourth section are as follows

$$U_3^{k4} = r_{24} \frac{U_2^*}{1 - \frac{u_t^1 t}{l}}. \tag{8}$$

In our case, $r_{24} = 1$ as the length of the third zone is equal to the length of the forth one.

When implementation of all corrective actions in the fourth section is impossible, calculation of the OA3 correction in the fourth and fifth zones is as follows

$$U_3^k = r_{23} \frac{U_2^*}{1 - \frac{u_t^1 t}{l}}. \tag{9}$$

In our case, $r_{23} = 1/2$, as the length of the second area is half the length of the third one.

The third stage is the definition of agent priorities.

When calculating control, OA1 uses control agents which may affect the process in the first area, i.e. SHCA1, SHCA2, GACA1, GACA2, OA2 respectively uses SHCA3, GACA3, and OA3 uses SHCA4, SHCA5, GACA4, GACA5. BSCA and EFCA agents affect all sections simultaneously and controlled directly by the AC.

In combinations of situations when $F^2 \in \{1, 2\}$ and $F^3 \in \{1, 2\}$, that is, humidity at both sensors is below than permitted, AC controls with BSCA (to improve performance), realizing control $\min\left(\left|U_2^*\right|, \left|U_3^*\right|\right)$, after that there is implementation of unrealized control by OA.

In other cases, the implementation of control is in accordance with the calculated priorities.

The database stores parameters affecting the performance P^j and power consumption W^j. Therefore, in different situations, when there are several alternative embodiments of control, you must choose the best. To solve this optimization problem used settings of the current priority of system in the form of weights p_e and p_p.

Calculation agent priorities are performed as follows:

$$pr_i^j = p_e W^j + p_p P^j, \tag{10}$$

where pr_i^j is the priority of *j*-th agent to correct the humidity in the *i*-th area.

Accordingly, for the OA1 $j \subset \{3, 4, 8, 9\}$, for OA2 $j \subset \{5, 10\}$, for OA3 $j \subset \{6, 7, 11, 12\}$. For BSCA and EFCA priority is calculated using the same.

Next is the ranking of agent's numbers in groups in descending of priority. The result is the three vectors that contain numbers of CA for OA.

The fourth stage is the distribution of control between agents.

Database has parameters, which is the coefficient of transfer Δu_j control the transmitted CA in a control action specific for that type of CA. In this form of translation, with an excess of control, CA is able to convert unrealized control in abstract units and pass it back to the corresponding OA.

The distribution of control process can be described by the following step sequence.

1. Verifying the possibility of using BSCA.
2. Choosing a control area *n*.
3. OA of selected area sends optimal control, designed for the area U_n^* to the CA with the highest priority in this situation and settings (for $k = 1$ first agent has the number recorded in prr_n^1, in a second step has number in prr_n^2 and so on, for $k = -1$ it will be in reverse order, ie from the last element of priorities).
4. CA assesses control. If it is feasible, CA implements control and sends the appropriate signal to the OA ($U_{an}^* = 0$). If it is unrealizable, CA sends it back to the OA ($U_{an}^* = U_n^*$). If it is partially realizable by means of this CA, it implements it to the boundary values of acceptable control range and sends to AC surplus, calculated by the formula

$$U_{an}^* = U_n^* - \frac{\Delta U_n^j}{\Delta u_j}, \tag{11}$$

where ΔU_n^j is the part of the control in the *n*-th area, implemented by the current agent.

Stages 2, 3 repeated as long as the control is not fully implemented, i.e. $U_{an}^* = 0$ or all available CA will be checked.

5. Calculate the corrective control by (8) – (9).
6. Stages 1–4 are repeated for $n = \overline{1, 2}$.
7. If the OA cannot implement all control, the AC implements control with BSCA and EFCA in accordance with calculated priorities.

In implementing the excessive control by BSCA and EFCA they influence all areas, including those for which the control was realized.

Changing current control of BSCA or EFCA should be compensated by the corresponding correction in zones under OA; first, changes made in CA at stages 1–6. More details on this algorithm will be discussed by the example.

For BSCA, EFCA, SHCA1…SHCA5, GACA1…GACA5 agents, control function is implemented as follows.

1. Calculation of the current control

$$u_{\mathrm{t}}^{j}=u_{\mathrm{t}}^{j}+\Delta U_{i-1}^{j},\qquad \Delta U_{0}^{j}=0. \tag{12}$$

Recalculation of the current value is necessary for the proper observance of border control. It is necessary to take into account control, designed for the agent on the previous step of control and corrective control.

2. Calculation of the control growth

$$\Delta U_{i}^{j}=q(j)U_{i}^{*}u_{\mathrm{e}}^{j}, \tag{13}$$

where $q(j)$ is coefficient that indicates direction of control changes, $q(j)=\begin{cases}-1,\ j=1,\\ 1,\ j\neq 1.\end{cases}$

3. The calculation of projected CA state

$$u_{\mathrm{p}}^{j}=u_{\mathrm{t}}^{j}+\Delta U_{i}^{j}. \tag{14}$$

4. Determination of membership u_{p}^{j} in range of permissible values of control and message for OA can be made as follows:

$$\begin{cases}\Delta U_{n}^{j}=u_{\mathrm{l}}^{j}-u_{\mathrm{t}}^{j};\ U_{an}^{*}=\dfrac{u_{\mathrm{l}}^{j}-u_{\mathrm{p}}^{j}}{u_{e}^{j}},\ \text{when}\ u_{\mathrm{p}}^{j}<u_{\mathrm{l}}^{j};\\ \Delta U_{n}^{j}=\Delta U_{n}^{j};\ U_{an}^{*}=0,\ \text{when}\ u_{\mathrm{p}}^{j}\in[u_{\mathrm{l}}^{j};u_{\mathrm{h}}^{j}];\\ \Delta U_{n}^{j}=u_{\mathrm{h}}^{j}-u_{\mathrm{t}}^{j};\ U_{an}^{*}=\dfrac{u_{\mathrm{p}}^{j}-u_{\mathrm{h}}^{j}}{u_{\mathrm{e}}^{j}},\ \text{when}\ u_{\mathrm{p}}^{j}>u_{\mathrm{h}}^{j}.\end{cases} \tag{15}$$

Now consider the control functions for SHCA1, SHCA2, GACA1, GACA2.

For a more uniform load of these CA, control shared equally between them (in abstract units), and if one of them cannot perform control, it is transferred to another wholly or partially. If both agents cannot implement the necessary control, surplus transmitted to the OA.

Agents of these sections cannot be combined into a single agent in charge of two sections at once, because in different sections is different restrictions of the temperature, different values of coefficients, etc.

As a result, control functions of these agents implementing according to the following algorithm with $j = 3$ for SHCA and $j = 8$ for EFCA:

1) divide control into two parts

$$u_{1}=u_{2}=U_{n}^{*}/2, \tag{16}$$

where u_1 and u_2 is a partial controls;

2) calculation of the current value of control

$$\begin{cases} u_{\text{t}}^{j} = u_{\text{t}}^{j} + \Delta U_{i1}^{j},\ \Delta U_{0}^{j} = 0; \\ u_{\text{t}}^{j+1} = u_{\text{t}}^{j+1} + \Delta U_{i1}^{j+1},\ \Delta U_{0}^{j+1} = 0; \end{cases} \tag{17}$$

3) calculation of the control grows

$$\begin{cases} \Delta U_{i}^{j} = u_{1} u_{\text{e}}^{j}; \\ \Delta U_{i}^{j+1} = u_{2} u_{\text{e}}^{j+1}; \end{cases} \tag{18}$$

4) the calculation of projected CA state:

$$\begin{cases} u_{\text{p}}^{j} = u_{\text{t}}^{j} + \Delta U_{i}^{j}; \\ u_{\text{p}}^{j+1} = u_{\text{t}}^{j+1} + \Delta U_{i}^{j+1}. \end{cases} \tag{19}$$

5) determination of membership u_{p}^{j} in range of permissible values of control

$$\begin{cases} \Delta U_{i}^{j} = u_{\text{l}}^{j} u_{\text{t}}^{j};\ \ u_{1} = \dfrac{u_{\text{l}}^{j} u_{\text{p}}^{j}}{u_{\text{e}}},\ \text{when}\ u_{\text{p}}^{j} < u_{\text{l}}^{j}; \\ \Delta U_{i}^{j} = \Delta U_{i}^{j};\ \ u_{1} = 0,\ \text{when}\ u_{\text{p}}^{j} \in \left[u_{\text{l}}^{j}; u_{\text{h}}^{j}\right]; \\ \Delta U_{i}^{j} = u_{\text{h}}^{j} u_{\text{t}}^{j};\ \ u_{1} = \dfrac{u_{\text{p}}^{j} u_{\text{h}}^{j}}{u_{\text{e}}},\ \text{when}\ u_{\text{p}}^{j} > u_{\text{h}}^{j}; \\ \Delta U_{i}^{j+1} = u_{\text{l}}^{j+1} u_{\text{t}}^{j+1};\ \ u_{2} = \dfrac{u_{\text{l}}^{j+1} u_{\text{p}}^{j+1}}{u_{\text{e}}},\ \text{when}\ u_{\text{p}}^{j+1} < u_{\text{l}}^{j+1}; \\ \Delta U_{i}^{j+1} = \Delta U_{i}^{j+1};\ u_{2} = 0,\ \text{when}\ u_{\text{p}}^{j+1} \in \left[u_{\text{l}}^{j+1}; u_{\text{h}}^{j+1}\right]; \\ \Delta U_{i}^{j+1} = u_{\text{h}}^{j+1} u_{\text{t}}^{j+1};\ \ u_{2} = \dfrac{u_{\text{p}}^{j+1} u_{\text{h}}^{j+1}}{u_{\text{e}}},\ \text{when}\ u_{\text{p}}^{j+1} > u_{\text{h}}^{j+1}. \end{cases} \tag{20}$$

Next is the review of the implementation of control and, possibly, massage for OA

$$\begin{cases} U_{ai}^{*} = u_{1} + u_{2};\ \text{when}\ (u_{1} \neq 0) \cap (u_{2} \neq 0); \\ u_{1} = u_{2};\ \text{when}\ (u_{1} = 0) \cap (u_{2} \neq 0); \\ u_{2} = u_{1};\ \text{when}\ (u_{1} \neq 0) \cap (u_{2} = 0); \\ U_{ai}^{*} = 0;\ \text{when}\ (u_{1} = 0) \cap (u_{2} = 0). \end{cases} \tag{21}$$

If u_1 and u_2 both are equal or not equal to zero at the same time, you can send a message to OA. Otherwise unrealized control sent to the CA, who was able to implement all control, and the going to steps 2) – 5).

After that, it sends the answer to OA

$$U_{ai}^{*} = u_{1} + u_{2}. \tag{22}$$

Practical example

For practical example we use the following input

$$\{\varphi_{\mathrm{t}}^2 = 20,\ \varphi_{\mathrm{t}}^3 = 7,\ p_{\mathrm{p}} = 30,\ p_{\mathrm{e}} = 70,\ u_{\mathrm{t}}^1 = 3{,}2,\ u_{\mathrm{t}}^2 = 50,\ u_{\mathrm{t}}^3 = 95,\ u_{\mathrm{t}}^4 = 95,$$

$$u_{\mathrm{t}}^5 = 90,\ u_{\mathrm{t}}^6 = 65,\ u_{\mathrm{t}}^7 = 50,\ u_{\mathrm{t}}^8 = 95,\ u_{\mathrm{t}}^9 = 80,\ u_{\mathrm{t}}^{11} = 70,\ u_{\mathrm{t}}^{12} = 50\}.$$

Set of CA parameters in Table.
Parameters of membership functions given in vectors

$$a_j^2 = (16, 19, 21.5, 25, 100); \quad b_j^2 = (17, 20.5, 23, 30);$$

$$a_j^3 = (5, 7.5, 9.25, 12, 100); \quad b_j^2 = (6, 8.75, 11, 20).$$

Vectors of coefficients

$$uv_2 = (100, 60, 0, 60, 130); \quad uv_3 = (110, 70, 0, 70, 200).$$

Fuzzification

$$\mu_2 = \frac{20 - 20.5}{19 - 20.5} = 0.33; \quad \varphi_t^2 \in \left[a_2^2, b_2^2\right]; \quad \mu_3 = 1; \quad \varphi_t^3 \in \left[b_1^3, a_2^3\right].$$

Calculation of the required control action

$$U_1^* = -1 \cdot 60 \cdot 0.33 - 1 \cdot 0 \cdot 0.66 = -19.8; \quad U_2^* = -1 \cdot 70 \cdot 7 + 1 \cdot 0 \cdot 0 = -70;$$

$$U_2^k = 2\frac{-19.8}{1 - \frac{2t}{2}} = -\frac{39.6}{1-t}; \quad U_3^k = 1\frac{-70}{1 - \frac{2t}{2}} = -\frac{70}{1-t}.$$

Calculation of agents priorities:
– with probability 0,33 $F^2 = 2$ and with probability 1: $F^3 = 2$, BSCA has the highest priority

$$U = -\min(|-19.8|, |-70|) = -19.8; \quad U_3^* = -U = 19.8;$$

Set of CA parameters

<table>
<tr><th>j</th><th>u_{l}^j</th><th>u_{h}^j</th><th>u_{e}^j</th><th>P^j</th><th>W^j</th></tr>
<tr><td>1</td><td>2</td><td>4</td><td>0.01</td><td>100</td><td>100</td></tr>
<tr><td>2</td><td rowspan="5">30</td><td rowspan="2">105</td><td rowspan="5">0.25</td><td rowspan="2">25</td><td rowspan="5">20</td></tr>
<tr><td>3</td></tr>
<tr><td>4</td><td>100</td><td>20</td></tr>
<tr><td>5</td><td>95</td><td rowspan="2">15</td></tr>
<tr><td>6</td><td>75</td></tr>
<tr><td>7</td><td rowspan="6">0</td><td rowspan="6">100</td><td rowspan="6">0.2</td><td rowspan="2">25</td><td rowspan="3">35</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td><td>20</td></tr>
<tr><td>10</td><td rowspan="2">15</td><td rowspan="2">30</td></tr>
<tr><td>11</td></tr>
<tr><td>12</td><td>20</td><td>20</td></tr>
</table>

– priority vectors calculation is

$$pr_1 = (21.5,\ 21.85,\ 32,\ 32); \quad pr_2 = (20,\ 30.5);$$

$$pr_3 = (18.5,\ 18.5,\ 25.5,\ 25.5); \quad pr_{CA} = (100,\ 20);$$

– ranked vectors of CA numbers are $prr_1 = (8, 9, 3, 4)$; $prr_2 = (10, 5)$; $prr_3 = (11,\ 12, 6, 7)$; $prr_{AC} = (1, 2)$.

Distribution of control between agents:

– implementation of BSCA control, calculation of correction actions

$$\Delta U^1 = -19.8 \cdot 0.01 = 0.198; \qquad u_{\text{p}}^1 = 2 + 0.198 = 2.198;$$

$$2.198 \in [2; 4] \Rightarrow \Delta U_n^1 = 0.198; \qquad U_1^* = U_1^k = U_2^k = 0;$$

$$U_2^* = -70 - (-19.8) = -50.2; \quad U_4^k = 1\frac{-50.2}{1 - \frac{2.198t}{2}} = -\frac{50.2}{1 - 1.1t}; \quad T = 0.91h;$$

– ranked vector of numbers CA under OA2 is $prr_2 = (10,\ 5)$, so the situation can be corrected with the two agents (SHCA3 and GACA3). If the required actions are positive, the highest priority has agent number 10 (GACA3), in our case (required actions are negative) the highest priority has agent number 5 (SHCA3)

$$\Delta U_n^5 = -50.2 \cdot 0.25 = -11.64; \qquad u_{\text{p}}^5 = 90 - 11.64 = 78.36;$$

$$78.36 \in [30; 100] \Rightarrow \Delta U_n^5 = -11.64; \quad U_2^* = 0;$$

– ranked vector of numbers CA under OA3 is $prr_3 = (11,\ 12, 6, 7)$, so $U_3^* = 19.8 > 0$, and the highest priority is the CA with number 11, that is SHCA4

$$\Delta U_n^{11} = 19.8 \cdot 0.2 = 3.96\ \%; \qquad u_{\text{p}}^{11} = 70 + 3.96 = 73.96;$$

$$73.96 \in [0;\ 100] \Rightarrow \Delta U_n^{11} = 3.96\ \%.$$

Implementation of correction.

Correction in first and second areas is not needed, because $U_1^k = U_2^k = 0$.

For correction by OA3, we try implement correction in forth zone $U_4^k = -\frac{50.2}{1 - 1.1t}$, $t \in [0; 0.91]$.

Ranked vector of numbers CA under OA3 is $prr_3 = (11,\ 12, 6, 7)$, so in considering situation $(U_4^k < 0)$, the highest priority is the CA in forth zone (numbers 11 and 6) has agent with number 6 (SHCA4).

$$\Delta U_{\max}^6 = -49.2 \cdot 0.25 = -12.3\ ^\circ\text{C}; \qquad u_{\text{p}\,\max}^6 = 65 - 12.3 = 52.7\ ^\circ\text{C};$$

$$52.7 \in [30; 75] \Rightarrow \Delta U_n^{11} = -12.3\ ^\circ\text{C}; \qquad U_{\text{kor}}^6 = -\frac{12.3}{1 - 1.1t},\ t \in [0; 0.91].$$

Thus it was possible to implement the correction only by agents of the fourth zone.

Conclusion

In the article we considered the algorithm of intelligent control of drying process for paste materials in convective DDB dryers using fuzzy logic and the theory of multi-agent systems. The practical application of the algorithm in the ICS of the drying process will allow to synthesize control actions in real-time.

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Алгоритм интеллектуального управления процессами сушки пастообразных материалов

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Ключевые слова и фразы: интеллектуальное управление; мультиагентные системы; нечеткая логика; процессы сушки.

Аннотация: Процессы сушки широко распространены в промышленности, но сложность их рассмотрения в качестве объекта управления делает очень трудоемким разработку систем управления реального времени на основе существующего математического аппарата и теории оптимального управления. Рассмотрен алгоритм управления, основанный на использовании методов искусственного интеллекта, для синтеза оптимального управления, позволяющего частично устранить последствия выхода процесса за рамки допустимых значений.
