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ANALYSIS OF THE TASKS FOR DRYING PROCESS CONTROL IN DRYING ROLL-RIBBON UNITS ON THE SET OF FUNCTIONING CONDITIONS

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Abstract: The paper presents the general and specific tasks of control over drying processes aimed at the improvement of the product quality. It is proposed to solve the tasks of control over drying process using the approach of complete analysis of optimal control on the set of functioning conditions; to achieve this the analysis of the set of possible situations is carried out; five classes with the algorithmic support of data management system for drying roll ribbon units are identified.

One of the primary goals of the modern industry is the improvement of product quality to provide its competitiveness. An important reserve of quality improvement and productivity increase is the use of information control systems (**ICS**) for technological objects. Take for instance the Drying Roll-Ribbon Units (**DRU**).

The desired quality is achieved through the different modes of drying. However, the common task of drying process management (and some special problems) can be outlined with regard for the particular object.

The general problem of the drying process control is formulated as follows:

– *f*-operator lets you specify the value of the vector components of the output variables $y = (y_1, ..., y_Z)$ depends on the vector of control values $u = (u_1, ..., u_P)$ and vector of disturbances $x = (x_1, ..., x_H)$ in different situations of the operation

$$\mathcal{S} = \left\{ s_l(\cdot),\ l = \overline{1, L} \right\}, \qquad (1)$$

f- operator conditions:

$$f : \mathcal{U} \times \mathcal{X} \times \mathcal{S} \to \mathcal{Y}, \qquad (1a)$$

where $\mathcal{U}$, $\mathcal{X}$, $\mathcal{Y}$, $\mathcal{S}$ is the set of control and disturbance actions of output and situations changing variables correspondingly; l is the number of situation; L is the amount of possible situations; Z, P, H is the dimensionality of vectors y, u and x correspondingly;

– restrictions of input variables y and control values u:

$$y_z \in Y_z^{\text{perm}}, \quad z = \overline{1, Z}; \tag{2}$$

$$u_p \in U_p^{\text{perm}}, \quad p = \overline{1, P}, \tag{3}$$

where Y_z^{perm}, U_p^{perm} are feasible regions of y_z and u_p correspondingly;

– optimality criterion, which characterizes the quality Qu and performance Pe of the object, like

$$Q = Q(\Delta\text{Qu}, \Delta\text{Pe}, u) \to \min_u, \tag{4}$$

where ΔQu, ΔPe are the losses caused by the reduced end-product quality and the performance of the dryer, respectively.

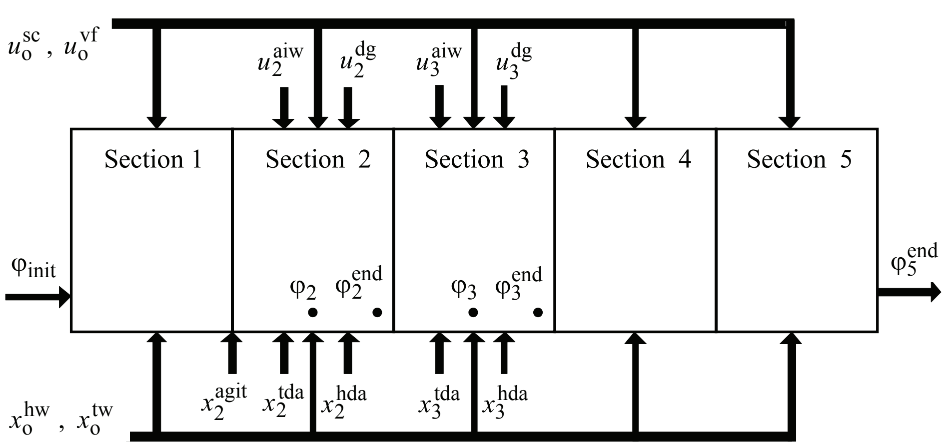
It's required to determine the value of control action u^*, under which the constraints (2), (3), and criterion (4) follows to its minimum.

The components of output vector y in the problem (1a) – (4) are values of material moisture on the outputs of limiting sections and at the end of the dryer. For the five section dryer (Figure) it is humidity at the end of second φ_2^{end}, third φ_3^{end} and fifth φ_5^{end} sections, and the vectors of control and disturbance actions can be written as

$$u = (u_{\text{o}}^{\text{sc}}, u_2^{\text{aiw}}, u_2^{\text{dg}}, u_3^{\text{aiw}}, u_3^{\text{dg}}, u_{\text{o}}^{\text{vf}}); \tag{5}$$

$$x = (\varphi_{\text{init}}, \varphi_2^{\text{end}}, x_2^{\text{tda}}, x_2^{\text{hda}}, x_2^{\text{agit}}, x_3^{\text{tda}}, x_3^{\text{hda}}, x_{\text{o}}^{\text{tw}}, x_{\text{o}}^{\text{hw}}), \tag{6}$$

where u_2^{aiw}, u_2^{dg}, u_3^{aiw}, u_3^{dg} are control variables of air intake windows and dumping gates of second and third sections correspondingly; u_{o}^{vf} is the control of the ventilation fan;



Structure of DRU as an object of management

u_o^{sc} is the speed control of belt conveyor; φ_{init} is the initial content of moisture in the material; x_2^{tda}, x_2^{hda} is the temperature and humidity of drying agents in the second section correspondingly; x_2^{agit} is the presence or absence of agitator at the inlet of the second section; x_3^{tda}, x_3^{hda} is the temperature and humidity of drying agents in the third section correspondingly; x_o^{tw}, x_o^{hw} is the temperature and humidity in the workshop.

The main component of the vector control actions *u* is the speed of the conveyor belt. It is also possible to use the air intake windows and dumping gates of relevant sections, if necessary.

Considering the relation of function of the productivity loss ΔPe of control *u*, that is similar to linear function, and relation of quality loss function ΔQu of control *u*, that is similar to parabolic function; criterion Q can be represented as follows:

$$Q = c_1\left(b_0 + b_1 u^2\right) + c_2(a_0 + a_1 u) \to \min_u, \quad (7)$$

where c_1, c_2 are the weights; b_0, b_1 are the parameters of the loss function of final product quality; a_0, a_1 are the parameters of the loss function of productivity.

The components of the set of situations S are the possible trajectories $s(\cdot)$ of changes of humidity along the length of the dryer: $s(\cdot) = \left(\varphi_2, \varphi_3, \varphi_5^{end}\right)$.

Particular control tasks of the drying process are considered in relation to individual lots of material that is in the limiting sections. The first specific problem is solved on the basis of information about quality of the material in the center of the second section and on the values of control and disturbance actions. The solution to the second problem is based on the information about quality of material in the center of the second and third sections, considering the values of corrective and disturbance actions.

The first specific problem for *m*-th lot can be mathematically represented as:

– model for determining the humidity in the second section of the dryer

$$\varphi_2(t_2^m) = f(u_2, x_2, A_2), \quad (8)$$

where t_2^m is the time required to determine the humidity of *m*-th lot of material in the second section; A_2 is an array of the parameters of model for humidity in the second section center; vectors of control u_2 and disturbance x_2 actions consists of :

$$u_2 = (u_o^{sc},\ u_2^{aiw},\ u_2^{dg},\ u_o^{vf}); \quad (9)$$

$$x_2 = (\varphi_{init},\ x_2^{tda},\ x_2^{hda},\ x_2^{agit},\ x_o^{tw},\ x_o^{hw}); \quad (10)$$

– restrictions on the change of control actions u_2 and output variable φ_2 :

$$u_2 \in U_2^{perm}; \quad (11)$$

$$\varphi_2 \in Y_2^{perm}, \quad (12)$$

where U_2^{perm} is the region of permissible values of control actions in the second section; Y_2^{perm} is the region of permissible values of humidity in the second section of dryer;

– functional to minimize

$$Q_2 = c_1 \Delta \mathrm{Qu}(u_2) + c_2 \Delta \mathrm{Pe}(u_2) \to \min_{u_2}. \qquad (13)$$

It's required to find the humidity using (8), when the m-th lot of material is in the second (limiting) section. And if the humidity is beyond the limits (12), the corrective action should be defined

$$u_2^* = \arg\min_{u_2} Q_m(\Delta \mathrm{Qu}, \Delta \mathrm{Pe}, c_1, c_2, u_2), \qquad (14)$$

The restriction (11) must be satisfied and the criterion (13) should reach its minimum.

An array of details is given to solve this problem

$$R = (A_2, x_2(t_m), u_2(t_m), U_2^{\mathrm{perm}}, Y_2^{\mathrm{perm}}, c_1, c_2). \qquad (15)$$

The second particular problem is formulated similarly. Data:

– model required to determine the humidity in the second and third sections of the dryer

$$f_m(A_2, A_3, \varphi_2(t_2^m), \varphi_3(t_3^m), \varphi_5^{\mathrm{end}}(t_\text{к}^m), u_2, u_3, x_2, x_3) = 0, \qquad (16)$$

where t_3^m, t_{end}^m is the time required to determine the humidity of m-th lot of material in the third and in the last sections; A_3 is the array of the parameters of model for humidity in the third section; vectors of control u_3 and disturbance x_3 actions consists of:

$$u_3 = (u_\text{o}^{\mathrm{sc}}, u_3^{\mathrm{aiw}}, u_3^{\mathrm{dg}}, u_\text{o}^{\mathrm{vf}}); \qquad (17)$$

$$x_3 = (\varphi_2, x_3^{\mathrm{tda}}, x_3^{\mathrm{hda}}, x_\text{o}^{\mathrm{tw}}, x_\text{o}^{\mathrm{hw}}); \qquad (18)$$

– restrictions on the change of control actions u_2, u_3 and output variables $\varphi_2, \varphi_3, \varphi_5^{\mathrm{end}}$:

$$u_2 \in U_2^{\mathrm{perm}}, \; u_3 \in U_3^{\mathrm{perm}}; \qquad (19)$$

$$\varphi_2 \in Y_2^{\mathrm{perm}}, \; \varphi_3 \in Y_3^{\mathrm{perm}}, \; \varphi_5^\text{к} \in Y_\text{к}^{\mathrm{perm}}, \qquad (20)$$

where U_3^{perm} is permissible values of control actions in the third section; Y_3^{perm}, $Y_\text{к}^{\mathrm{perm}}$ are the regions of permissible values of humidity in the third section and on the output of the dryer correspondingly;

– functional to minimize

$$Q_m(\Delta \mathrm{Qu}, \Delta \mathrm{Pe}, u_3) \to \min_{u_3}; \qquad (21)$$

– the array of changes of situations during operation of (1).

It's required to find out the humidity in the second, third and output sections using (16) when the m-th lot of material which goes through this (limiting) sections. And if the humidity is beyond the limits (20), the control action should be determined

$$u_3^* = \arg\min_{u_3} Q_m(\Delta \mathrm{Qu}, \Delta \mathrm{Pe}, u_3). \qquad (22)$$

The restriction (19) must be satisfied and the criterion (21) should reach its minimum.

The array of details is given to solve this problem:

$$R = \left(A_2, A_3, x_2(t_m), u_2(t_m), x_3(t_m), u_3(t_m), U_2^{\text{perm}}, U_3^{\text{perm}}, Y_2^{\text{perm}}, Y_3^{\text{perm}}, Y_{\text{end}}^{\text{perm}}, s_l(\cdot) \right). \tag{23}$$

As we can see from stated problems of control drying mode, their solutions can be reached using the models to determine the humidity in the center and the outputs of the second and third sections and in the output of fifth section of the dryer.

It is proposed to solve the problems of drying control, using the complete analysis of the optimal control on the set of the functioning states (**SFS**). According to the classification of systems on SFS, the DRU with its control device can be assigned to the third or fourth class [1], depending on the control task. In the third-class systems the variable of functioning states (situations changing variable) s may vary within a control time interval $T \in [t_0; t_{\text{end}}]$, but value s can be identified (known) in the current time $t \in T$. The model of the third class object represents a piecewise constant trajectory of change of the system operator. The switch points of the operator are random and correspond to the change of the value s on the trajectory. Usually, the models of such objects are differential equations with discontinuous right hand side.

Objects of the fourth class differ from the third so that the current values $s(t)$, $t \in T$ are unknown. It is considered the set of possible trajectories $\mathcal{S}$, on interval T starting at initial state $s(t_0)$ for simulation of such objects. It is considered the graph of changes of the functioning states as the operator of the system [1].

The basic assumption of this approach is shown on the example of five-section DRU. The vector of input variables is $y = \left(\varphi_2, \varphi_3, m(\varphi_5^{\text{end}}) \right)$. The deviations of humidity y_n of material in the centre of n-th section from required value $\bar{y}_n$ are considered as an elements of the set $\mathcal{S}$ (1) of possible trajectories of situation $s_l(\cdot)$ changing. In our case $\bar{y}_2 = 48$ %, and $\bar{y}_3 = 20$ %. The set $\mathcal{S}$ is convenient to define as the morphological table. It is assumed that l-th situation $s_l(\cdot) \in \mathcal{S}$ is determined by three components: $s_l(\cdot) = (s_{l2}, s_{l3}, s_{l5})$. Each component s_{l2}, s_{l3} can take five values, and component s_{l5} – three values:

$$s_{ln} = \begin{cases} s_{ln}^{\text{mbp}}, \text{ if } y_n < \left(\bar{y}_n - \delta_n^{(2)} \right); \\ s_{ln}^{\text{bp}}, \text{ if } y_n \in \left[\bar{y}_n - \delta_n^{(2)}, \bar{y}_n - \delta_n^{(1)} \right); \\ s_{ln}^{\text{p}}, \text{ if } y_n \in \left[\bar{y}_n - \delta_n^{(1)}, \bar{y}_n + \delta_n^{(1)} \right] = Y_n^{\text{perm}}; \\ s_{ln}^{\text{ap}}, \text{ if } y_n \in \left(\bar{y}_n + \delta_n^{(1)}, \bar{y}_n + \delta_n^{(2)} \right]; \\ s_{ln}^{\text{map}}, \text{ if } y_n > \left(\bar{y}_n + \delta_n^{(2)} \right), \; n = 2, 3; \end{cases}$$

$$s_{l5} = \begin{cases} s_{l5}^{\text{lw}}, \text{ if } y_5 < 0{,}65; \\ s_{l5}^{\text{md}}, \text{ if } y_5 \in [0{,}65;\ 0{,}8]; \\ s_{l5}^{\text{hg}}, \text{ if } y_5 > 0{,}8, \end{cases}$$

where $\delta_n^{(1)}$, $\delta_n^{(2)}$ are the set deviations y_n from $\bar{y}_n$, $\delta_n^{(1)} < \delta_n^{(2)}$; mbp – humidity is much below the permissible level; bp – humidity is below the permissible level; p – humidity is on permissible level; ap – humidity is above the permissible level; map – humidity is much above the permissible level; lw – low confidence-building measure; md – medium confidence-building measure; hg – high confidence-building measure.

In this case the set $\mathcal{S}$ consists of $L = 75$ different situations presented in Table 1. The strings of table are values of s'_{ln} for a single instant of time, and confidence-building measure of required humidity is determined for a second section of the DRU.

The table of situations $s_l^{\text{end}}(\cdot) = \left(s_{l2}^{\text{end}}, s_{l3}^{\text{end}}, s_{l5}\right)$, identifying by humidity in the outputs of second and third sections, constructs similarly. These situations correspond to the vector $y^{\text{end}} = \left(\varphi_2^{\text{end}}, \varphi_3^{\text{end}}, m(\varphi_5^{\text{end}})\right)$.

Table 1

The set of possible $\mathcal{S}$ for a single moment of time

Situation $s'_l(\cdot)$	States of elements set $\mathcal{S}$			Situation $s'_l(\cdot)$	States of elements set $\mathcal{S}$		
	$s_{l2}(t)$	$s_{l3}(t)$	$s_{l5}(t)$		$s_{l2}(t)$	$s_{l3}(t)$	$s_{l5}(t)$
1	2	3	4	1	2	3	4
$s'_1(\cdot)$	$s_{1,2}^{\text{mbp}}$	$s_{1,3}^{\text{mbp}}$	$s_{1,5}^{\text{lw}}$	$s'_{21}(\cdot)$	$s_{21,2}^{\text{mbp}}$	$s_{21,3}^{\text{map}}$	$s_{21,5}^{\text{lw}}$
$s'_2(\cdot)$	$s_{2,2}^{\text{bp}}$	$s_{2,3}^{\text{mbp}}$	$s_{2,5}^{\text{lw}}$	$s'_{22}(\cdot)$	$s_{22,2}^{\text{bp}}$	$s_{22,3}^{\text{map}}$	$s_{22,5}^{\text{lw}}$
$s'_3(\cdot)$	$s_{3,2}^{\text{p}}$	$s_{3,3}^{\text{mbp}}$	$s_{3,5}^{\text{lw}}$	$s'_{23}(\cdot)$	$s_{23,2}^{\text{p}}$	$s_{23,3}^{\text{map}}$	$s_{23,5}^{\text{lw}}$
$s'_4(\cdot)$	$s_{4,2}^{\text{ap}}$	$s_{4,3}^{\text{mbp}}$	$s_{4,5}^{\text{lw}}$	$s'_{24}(\cdot)$	$s_{24,2}^{\text{ap}}$	$s_{24,3}^{\text{map}}$	$s_{24,5}^{\text{lw}}$
$s'_5(\cdot)$	$s_{5,2}^{\text{map}}$	$s_{5,3}^{\text{mbp}}$	$s_{5,5}^{\text{lw}}$	$s'_{25}(\cdot)$	$s_{25,2}^{\text{map}}$	$s_{25,3}^{\text{map}}$	$s_{25,5}^{\text{lw}}$
$s'_6(\cdot)$	$s_{6,2}^{\text{mbp}}$	$s_{6,3}^{\text{bp}}$	$s_{6,5}^{\text{lw}}$	$s'_{26}(\cdot)$	$s_{26,2}^{\text{mbp}}$	$s_{26,3}^{\text{mbp}}$	$s_{26,5}^{\text{md}}$
$s'_7(\cdot)$	s_{72}^{bp}	s_{73}^{bp}	$s_{7,5}^{\text{lw}}$	$s'_{27}(\cdot)$	$s_{27,2}^{\text{bp}}$	$s_{27,3}^{\text{mbp}}$	$s_{27,5}^{\text{md}}$
$s'_8(\cdot)$	$s_{8,2}^{\text{p}}$	$s_{8,3}^{\text{bp}}$	$s_{8,5}^{\text{lw}}$	$s'_{28}(\cdot)$	$s_{28,2}^{\text{p}}$	$s_{28,3}^{\text{mbp}}$	$s_{28,5}^{\text{md}}$
$s'_9(\cdot)$	$s_{9,2}^{\text{ap}}$	$s_{9,3}^{\text{bp}}$	$s_{9,5}^{\text{lw}}$	$s'_{29}(\cdot)$	$s_{29,2}^{\text{ap}}$	$s_{29,3}^{\text{mbp}}$	$s_{29,5}^{\text{md}}$
$s'_{10}(\cdot)$	$s_{10,2}^{\text{map}}$	$s_{10,3}^{\text{bp}}$	$s_{10,5}^{\text{lw}}$	$s'_{30}(\cdot)$	$s_{30,2}^{\text{map}}$	$s_{30,3}^{\text{mbp}}$	$s_{30,5}^{\text{md}}$
$s'_{11}(\cdot)$	$s_{11,2}^{\text{mbp}}$	$s_{11,3}^{\text{p}}$	$s_{11,5}^{\text{lw}}$	$s'_{31}(\cdot)$	$s_{31,2}^{\text{mbp}}$	$s_{31,3}^{\text{bp}}$	$s_{31,5}^{\text{md}}$
$s'_{12}(\cdot)$	$s_{12,2}^{\text{bp}}$	$s_{12,3}^{\text{p}}$	$s_{12,5}^{\text{lw}}$	$s'_{32}(\cdot)$	$s_{32,2}^{\text{bp}}$	$s_{32,3}^{\text{bp}}$	$s_{32,5}^{\text{md}}$
$s'_{13}(\cdot)$	$s_{13,2}^{\text{p}}$	$s_{13,3}^{\text{p}}$	$s_{13,5}^{\text{lw}}$	$s'_{33}(\cdot)$	$s_{33,2}^{\text{p}}$	$s_{33,3}^{\text{bp}}$	$s_{33,5}^{\text{md}}$
$s'_{14}(\cdot)$	$s_{14,2}^{\text{ap}}$	$s_{14,3}^{\text{p}}$	$s_{14,5}^{\text{lw}}$	$s'_{34}(\cdot)$	$s_{34,2}^{\text{ap}}$	$s_{34,3}^{\text{bp}}$	$s_{34,5}^{\text{md}}$
$s'_{15}(\cdot)$	$s_{15,2}^{\text{map}}$	$s_{15,3}^{\text{p}}$	$s_{15,5}^{\text{lw}}$	$s'_{35}(\cdot)$	$s_{35,2}^{\text{map}}$	$s_{35,3}^{\text{bp}}$	$s_{35,5}^{\text{md}}$
$s'_{16}(\cdot)$	$s_{16,2}^{\text{mbp}}$	$s_{16,3}^{\text{ap}}$	$s_{16,5}^{\text{lw}}$	$s'_{36}(\cdot)$	$s_{36,2}^{\text{mbp}}$	$s_{36,3}^{\text{p}}$	$s_{36,5}^{\text{md}}$
$s'_{17}(\cdot)$	$s_{17,2}^{\text{bp}}$	$s_{17,3}^{\text{ap}}$	$s_{17,5}^{\text{lw}}$	$s'_{37}(\cdot)$	$s_{37,2}^{\text{bp}}$	$s_{37,3}^{\text{p}}$	$s_{37,5}^{\text{md}}$
$s'_{18}(\cdot)$	$s_{18,2}^{\text{p}}$	$s_{18,3}^{\text{ap}}$	$s_{18,5}^{\text{lw}}$	$s'_{38}(\cdot)$	$s_{38,2}^{\text{p}}$	$s_{38,3}^{\text{p}}$	$s_{38,5}^{\text{md}}$
$s'_{19}(\cdot)$	$s_{19,2}^{\text{ap}}$	$s_{19,3}^{\text{ap}}$	$s_{19,5}^{\text{lw}}$	$s'_{39}(\cdot)$	$s_{39,2}^{\text{ap}}$	$s_{39,3}^{\text{p}}$	$s_{39,5}^{\text{md}}$
$s'_{20}(\cdot)$	$s_{20,2}^{\text{map}}$	$s_{20,3}^{\text{ap}}$	$s_{20,5}^{\text{lw}}$	$s'_{40}(\cdot)$	$s_{40,2}^{\text{map}}$	$s_{40,3}^{\text{p}}$	$s_{40,5}^{\text{md}}$

Continued table 1

1	2	3	4	1	2	3	4
$s'_{41}(\cdot)$	$s^{\text{mbp}}_{41,2}$	$s^{\text{ap}}_{41,3}$	$s^{\text{md}}_{41,5}$	$s'_{59}(\cdot)$	$s^{\text{ap}}_{59,2}$	$s^{\text{bp}}_{59,3}$	$s^{\text{hg}}_{59,5}$
$s'_{42}(\cdot)$	$s^{\text{bp}}_{42,2}$	$s^{\text{ap}}_{42,3}$	$s^{\text{md}}_{42,5}$	$s'_{60}(\cdot)$	$s^{\text{map}}_{60,2}$	$s^{\text{bp}}_{60,3}$	$s^{\text{hg}}_{60,5}$
$s'_{43}(\cdot)$	$s^{\text{p}}_{43,2}$	$s^{\text{ap}}_{43,3}$	$s^{\text{md}}_{43,5}$	$s'_{61}(\cdot)$	s^{mbp}_{612}	s^{p}_{613}	$s^{\text{hg}}_{61,5}$
$s'_{44}(\cdot)$	$s^{\text{ap}}_{44,2}$	$s^{\text{ap}}_{44,3}$	$s^{\text{md}}_{44,5}$	$s'_{62}(\cdot)$	$s^{\text{bp}}_{62,2}$	$s^{\text{p}}_{62,3}$	$s^{\text{hg}}_{62,5}$
$s'_{45}(\cdot)$	$s^{\text{map}}_{45,2}$	$s^{\text{ap}}_{45,3}$	$s^{\text{md}}_{45,5}$	$s'_{63}(\cdot)$	$s^{\text{д}}_{63,2}$	$s^{\text{p}}_{63,3}$	$s^{\text{hg}}_{63,5}$
$s'_{46}(\cdot)$	$s^{\text{mbp}}_{46,2}$	$s^{\text{map}}_{46,3}$	$s^{\text{md}}_{46,5}$	$s'_{64}(\cdot)$	$s^{\text{ap}}_{64,2}$	$s^{\text{p}}_{64,3}$	$s^{\text{hg}}_{64,5}$
$s'_{47}(\cdot)$	$s^{\text{bp}}_{47,2}$	$s^{\text{map}}_{47,3}$	$s^{\text{md}}_{47,5}$	$s'_{65}(\cdot)$	$s^{\text{map}}_{65,2}$	$s^{\text{p}}_{65,3}$	$s^{\text{hg}}_{65,5}$
$s'_{48}(\cdot)$	$s^{\text{p}}_{48,2}$	$s^{\text{map}}_{48,3}$	$s^{\text{md}}_{48,5}$	$s'_{66}(\cdot)$	$s^{\text{mbp}}_{66,2}$	$s^{\text{ap}}_{66,3}$	$s^{\text{hg}}_{66,5}$
$s'_{49}(\cdot)$	$s^{\text{ap}}_{49,2}$	$s^{\text{map}}_{49,3}$	$s^{\text{md}}_{49,5}$	$s'_{67}(\cdot)$	$s^{\text{bp}}_{67,2}$	$s^{\text{ap}}_{67,3}$	$s^{\text{hg}}_{67,5}$
$s'_{50}(\cdot)$	$s^{\text{map}}_{50,2}$	$s^{\text{map}}_{50,3}$	$s^{\text{md}}_{50,5}$	$s'_{68}(\cdot)$	$s^{\text{p}}_{68,2}$	$s^{\text{ap}}_{68,3}$	$s^{\text{hg}}_{68,5}$
$s'_{51}(\cdot)$	$s^{\text{mbp}}_{51,2}$	$s^{\text{mbp}}_{51,3}$	$s^{\text{hg}}_{51,5}$	$s'_{69}(\cdot)$	$s^{\text{ap}}_{69,2}$	$s^{\text{ap}}_{69,3}$	$s^{\text{hg}}_{69,5}$
$s'_{52}(\cdot)$	$s^{\text{bp}}_{52,2}$	$s^{\text{mbp}}_{52,3}$	$s^{\text{hg}}_{52,5}$	$s'_{70}(\cdot)$	$s^{\text{map}}_{70,2}$	$s^{\text{ap}}_{70,3}$	$s^{\text{hg}}_{70,5}$
$s'_{53}(\cdot)$	$s^{\text{p}}_{53,2}$	$s^{\text{mbp}}_{53,3}$	$s^{\text{hg}}_{53,5}$	$s'_{71}(\cdot)$	$s^{\text{mbp}}_{71,2}$	$s^{\text{map}}_{71,3}$	$s^{\text{hg}}_{71,5}$
$s'_{54}(\cdot)$	$s^{\text{ap}}_{54,2}$	$s^{\text{mbp}}_{54,3}$	$s^{\text{hg}}_{54,5}$	$s'_{72}(\cdot)$	$s^{\text{bp}}_{72,2}$	$s^{\text{map}}_{72,3}$	$s^{\text{hg}}_{72,5}$
$s'_{55}(\cdot)$	$s^{\text{map}}_{55,2}$	$s^{\text{mbp}}_{55,3}$	$s^{\text{hg}}_{55,5}$	$s'_{73}(\cdot)$	$s^{\text{p}}_{73,2}$	$s^{\text{map}}_{73,3}$	$s^{\text{hg}}_{73,5}$
$s'_{56}(\cdot)$	$s^{\text{mbp}}_{56,2}$	$s^{\text{bp}}_{56,3}$	$s^{\text{hg}}_{56,5}$	$s'_{74}(\cdot)$	$s^{\text{ap}}_{74,2}$	$s^{\text{map}}_{74,3}$	$s^{\text{hg}}_{74,5}$
$s'_{57}(\cdot)$	$s^{\text{bp}}_{57,2}$	$s^{\text{bp}}_{57,3}$	$s^{\text{hg}}_{57,5}$	$s'_{75}(\cdot)$	$s^{\text{map}}_{75,2}$	$s^{\text{map}}_{75,3}$	$s^{\text{hg}}_{75,5}$
$s'_{58}(\cdot)$	$s^{\text{p}}_{58,2}$	$s^{\text{bp}}_{58,3}$	$s^{\text{hg}}_{58,5}$				

It is necessary to consider the situations $s_l(\cdot)$ identified by humidity in the second $\varphi_2(t)$ and in the third $\varphi_3(t)$ sections. And the measure of "trust" to achieve the desired quality is determined for the material in the third section at the moment t (Table 2).

According to the results of the set of possible situations in tables 1 and 2 the five classes that include different tasks of control the process of drying can be determined.

1. Class K_0. The humidity in the limiting sections is in the permissible range.

$$\left(\varphi_2 \in Y_2^{\text{per}}\right) \wedge \left(\varphi_3 \in Y_3^{\text{per}}\right).$$

This class includes the following situations:

$$K_0 = \{s_{28}(\cdot), s_{33}(\cdot), s_{36}(\cdot), s_{37}(\cdot), s_{38}(\cdot), s_{53}(\cdot), s_{58}(\cdot), s_{61}(\cdot), s_{62}(\cdot), s_{63}(\cdot), s'_{28}(\cdot), s'_{33}(\cdot), s'_{36}(\cdot), s'_{37}(\cdot), s'_{38}(\cdot)\}.$$

Table 2

The set of possible $\mathcal{S}$ for different moments of time

Situation $s_l(\cdot)$	States of elements set $\mathcal{S}$			Situation $s_l(\cdot)$	States of elements set $\mathcal{S}$		
	$s_{l2}(t)$	$s_{l3}(t)$	$s_{l5}(t)$		$s_{l2}(t)$	$s_{l3}(t)$	$s_{l5}(t)$
1	2	3	4	1	2	3	4
$s_1(\cdot)$	$s_{1,2}^{\text{mbp}}$	$s_{1,3}^{\text{mbp}}$	$s_{1,5}^{\text{lw}}$	$s_{25}(\cdot)$	$s_{25,2}^{\text{map}}$	$s_{25,3}^{\text{map}}$	$s_{25,5}^{\text{lw}}$
$s_2(\cdot)$	$s_{2,2}^{\text{bp}}$	$s_{2,3}^{\text{mbp}}$	$s_{2,5}^{\text{lw}}$	$s_{26}(\cdot)$	$s_{26,2}^{\text{mbp}}$	$s_{26,3}^{\text{mbp}}$	$s_{26,5}^{\text{md}}$
$s_3(\cdot)$	$s_{3,2}^{\text{p}}$	$s_{3,3}^{\text{mbp}}$	$s_{3,5}^{\text{lw}}$	$s_{27}(\cdot)$	$s_{27,2}^{\text{bp}}$	$s_{27,3}^{\text{mbp}}$	$s_{27,5}^{\text{md}}$
$s_4(\cdot)$	$s_{4,2}^{\text{ap}}$	$s_{4,3}^{\text{mbp}}$	$s_{4,5}^{\text{lw}}$	$s_{28}(\cdot)$	$s_{28,2}^{\text{p}}$	$s_{28,3}^{\text{mbp}}$	$s_{28,5}^{\text{md}}$
$s_5(\cdot)$	$s_{5,2}^{\text{map}}$	$s_{5,3}^{\text{mbp}}$	$s_{5,5}^{\text{lw}}$	$s_{29}(\cdot)$	$s_{29,2}^{\text{ap}}$	$s_{29,3}^{\text{mbp}}$	$s_{29,5}^{\text{md}}$
$s_6(\cdot)$	$s_{6,2}^{\text{mbp}}$	$s_{6,3}^{\text{bp}}$	$s_{6,5}^{\text{lw}}$	$s_{30}(\cdot)$	$s_{30,2}^{\text{map}}$	$s_{30,3}^{\text{mbp}}$	$s_{30,5}^{\text{md}}$
$s_7(\cdot)$	s_{72}^{bp}	s_{73}^{bp}	$s_{7,5}^{\text{lw}}$	$s_{31}(\cdot)$	$s_{31,2}^{\text{mbp}}$	$s_{31,3}^{\text{bp}}$	$s_{31,5}^{\text{md}}$
$s_8(\cdot)$	$s_{8,2}^{\text{p}}$	$s_{8,3}^{\text{bp}}$	$s_{8,5}^{\text{lw}}$	$s_{32}(\cdot)$	$s_{32,2}^{\text{bp}}$	$s_{32,3}^{\text{bp}}$	$s_{32,5}^{\text{md}}$
$s_9(\cdot)$	$s_{9,2}^{\text{ap}}$	$s_{9,3}^{\text{bp}}$	$s_{9,5}^{\text{lw}}$	$s_{33}(\cdot)$	$s_{33,2}^{\text{p}}$	$s_{33,3}^{\text{bp}}$	$s_{33,5}^{\text{md}}$
$s_{10}(\cdot)$	$s_{10,2}^{\text{map}}$	$s_{10,3}^{\text{bp}}$	$s_{10,5}^{\text{lw}}$	$s_{34}(\cdot)$	$s_{34,2}^{\text{ap}}$	$s_{34,3}^{\text{bp}}$	$s_{34,5}^{\text{md}}$
$s_{11}(\cdot)$	$s_{11,2}^{\text{mbp}}$	$s_{11,3}^{\text{p}}$	$s_{11,5}^{\text{lw}}$	$s_{35}(\cdot)$	$s_{35,2}^{\text{map}}$	$s_{35,3}^{\text{bp}}$	$s_{35,5}^{\text{md}}$
$s_{12}(\cdot)$	$s_{12,2}^{\text{bp}}$	$s_{12,3}^{\text{p}}$	$s_{12,5}^{\text{lw}}$	$s_{36}(\cdot)$	$s_{36,2}^{\text{mbp}}$	$s_{36,3}^{\text{p}}$	$s_{36,5}^{\text{md}}$
$s_{13}(\cdot)$	$s_{13,2}^{\text{p}}$	$s_{13,3}^{\text{p}}$	$s_{13,5}^{\text{lw}}$	$s_{37}(\cdot)$	$s_{37,2}^{\text{bp}}$	$s_{37,3}^{\text{p}}$	$s_{37,5}^{\text{md}}$
$s_{14}(\cdot)$	$s_{14,2}^{\text{ap}}$	$s_{14,3}^{\text{p}}$	$s_{14,5}^{\text{lw}}$	$s_{38}(\cdot)$	$s_{38,2}^{\text{p}}$	$s_{38,3}^{\text{p}}$	$s_{38,5}^{\text{md}}$
$s_{15}(\cdot)$	$s_{15,2}^{\text{map}}$	$s_{15,3}^{\text{p}}$	$s_{15,5}^{\text{lw}}$	$s_{39}(\cdot)$	$s_{39,2}^{\text{ap}}$	$s_{39,3}^{\text{p}}$	$s_{39,5}^{\text{md}}$
$s_{16}(\cdot)$	$s_{16,2}^{\text{mbp}}$	$s_{16,3}^{\text{ap}}$	$s_{16,5}^{\text{lw}}$	$s_{40}(\cdot)$	$s_{40,2}^{\text{map}}$	$s_{40,3}^{\text{p}}$	$s_{40,5}^{\text{md}}$
$s_{17}(\cdot)$	$s_{17,2}^{\text{bp}}$	$s_{17,3}^{\text{ap}}$	$s_{17,5}^{\text{lw}}$	$s_{41}(\cdot)$	$s_{41,2}^{\text{mbp}}$	$s_{41,3}^{\text{ap}}$	$s_{41,5}^{\text{md}}$
$s_{18}(\cdot)$	$s_{18,2}^{\text{p}}$	$s_{18,3}^{\text{ap}}$	$s_{18,5}^{\text{lw}}$	$s_{42}(\cdot)$	$s_{42,2}^{\text{bp}}$	$s_{42,3}^{\text{ap}}$	$s_{42,5}^{\text{md}}$
$s_{19}(\cdot)$	$s_{19,2}^{\text{ap}}$	$s_{19,3}^{\text{ap}}$	$s_{19,5}^{\text{lw}}$	$s_{43}(\cdot)$	$s_{43,2}^{\text{p}}$	$s_{43,3}^{\text{ap}}$	$s_{43,5}^{\text{md}}$
$s_{20}(\cdot)$	$s_{20,2}^{\text{map}}$	$s_{20,3}^{\text{ap}}$	$s_{20,5}^{\text{lw}}$	$s_{44}(\cdot)$	$s_{44,2}^{\text{ap}}$	$s_{44,3}^{\text{ap}}$	$s_{44,5}^{\text{md}}$
$s_{21}(\cdot)$	$s_{21,2}^{\text{mbp}}$	$s_{21,3}^{\text{map}}$	$s_{21,5}^{\text{lw}}$	$s_{45}(\cdot)$	$s_{45,2}^{\text{map}}$	$s_{45,3}^{\text{ap}}$	$s_{45,5}^{\text{md}}$
$s_{22}(\cdot)$	$s_{22,2}^{\text{bp}}$	$s_{22,3}^{\text{map}}$	$s_{22,5}^{\text{lw}}$	$s_{46}(\cdot)$	$s_{46,2}^{\text{mbp}}$	$s_{46,3}^{\text{map}}$	$s_{46,5}^{\text{md}}$
$s_{23}(\cdot)$	$s_{23,2}^{\text{p}}$	$s_{23,3}^{\text{map}}$	$s_{23,5}^{\text{lw}}$	$s_{47}(\cdot)$	$s_{47,2}^{\text{bp}}$	$s_{47,3}^{\text{map}}$	$s_{47,5}^{\text{md}}$
$s_{24}(\cdot)$	$s_{24,2}^{\text{ap}}$	$s_{24,3}^{\text{map}}$	$s_{24,5}^{\text{lw}}$	$s_{48}(\cdot)$	$s_{48,2}^{\text{p}}$	$s_{48,3}^{\text{map}}$	$s_{48,5}^{\text{md}}$

Continued table 2

1	2	3	4	1	2	3	4
$s_{49}(\cdot)$	$s_{49,2}^{\text{ap}}$	$s_{49,3}^{\text{map}}$	$s_{49,5}^{\text{md}}$	$s_{63}(\cdot)$	$s_{63,2}^{\text{p}}$	$s_{63,3}^{\text{p}}$	$s_{63,5}^{\text{hg}}$
$s_{50}(\cdot)$	$s_{50,2}^{\text{map}}$	$s_{50,3}^{\text{map}}$	$s_{50,5}^{\text{md}}$	$s_{64}(\cdot)$	$s_{64,2}^{\text{ap}}$	$s_{64,3}^{\text{p}}$	$s_{64,5}^{\text{hg}}$
$s_{51}(\cdot)$	$s_{51,2}^{\text{mbp}}$	$s_{51,3}^{\text{mbp}}$	$s_{51,5}^{\text{hg}}$	$s_{65}(\cdot)$	$s_{65,2}^{\text{map}}$	$s_{65,3}^{\text{p}}$	$s_{65,5}^{\text{hg}}$
$s_{52}(\cdot)$	$s_{52,2}^{\text{bp}}$	$s_{52,3}^{\text{mbp}}$	$s_{52,5}^{\text{hg}}$	$s_{66}(\cdot)$	$s_{66,2}^{\text{mbp}}$	$s_{66,3}^{\text{ap}}$	$s_{66,5}^{\text{hg}}$
$s_{53}(\cdot)$	$s_{53,2}^{\text{p}}$	$s_{53,3}^{\text{mbp}}$	$s_{53,5}^{\text{hg}}$	$s_{67}(\cdot)$	$s_{67,2}^{\text{bp}}$	$s_{67,3}^{\text{ap}}$	$s_{67,5}^{\text{hg}}$
$s_{54}(\cdot)$	$s_{54,2}^{\text{ap}}$	$s_{54,3}^{\text{mbp}}$	$s_{54,5}^{\text{hg}}$	$s_{68}(\cdot)$	$s_{68,2}^{\text{p}}$	$s_{68,3}^{\text{ap}}$	$s_{68,5}^{\text{hg}}$
$s_{55}(\cdot)$	$s_{55,2}^{\text{map}}$	$s_{55,3}^{\text{mbp}}$	$s_{55,5}^{\text{hg}}$	$s_{69}(\cdot)$	$s_{69,2}^{\text{ap}}$	$s_{69,3}^{\text{ap}}$	$s_{69,5}^{\text{hg}}$
$s_{56}(\cdot)$	$s_{56,2}^{\text{mbp}}$	$s_{56,3}^{\text{bp}}$	$s_{56,5}^{\text{hg}}$	$s_{70}(\cdot)$	$s_{70,2}^{\text{map}}$	$s_{70,3}^{\text{ap}}$	$s_{70,5}^{\text{hg}}$
$s_{57}(\cdot)$	$s_{57,2}^{\text{bp}}$	$s_{57,3}^{\text{bp}}$	$s_{57,5}^{\text{hg}}$	$s_{71}(\cdot)$	$s_{71,2}^{\text{mbp}}$	$s_{71,3}^{\text{map}}$	$s_{71,5}^{\text{hg}}$
$s_{58}(\cdot)$	$s_{58,2}^{\text{p}}$	$s_{58,3}^{\text{bp}}$	$s_{58,5}^{\text{hg}}$	$s_{72}(\cdot)$	$s_{72,2}^{\text{bp}}$	$s_{72,3}^{\text{map}}$	$s_{72,5}^{\text{hg}}$
$s_{59}(\cdot)$	$s_{59,2}^{\text{ap}}$	$s_{59,3}^{\text{bp}}$	$s_{59,5}^{\text{hg}}$	$s_{73}(\cdot)$	$s_{73,2}^{\text{p}}$	$s_{73,3}^{\text{map}}$	$s_{73,5}^{\text{hg}}$
$s_{60}(\cdot)$	$s_{60,2}^{\text{map}}$	$s_{60,3}^{\text{bp}}$	$s_{60,5}^{\text{hg}}$	$s_{74}(\cdot)$	$s_{74,2}^{\text{ap}}$	$s_{74,3}^{\text{map}}$	$s_{74,5}^{\text{hg}}$
$s_{61}(\cdot)$	$s_{61,2}^{\text{mbp}}$	$s_{61,3}^{\text{p}}$	$s_{61,5}^{\text{hg}}$	$s_{75}(\cdot)$	$s_{75,2}^{\text{map}}$	$s_{75,3}^{\text{map}}$	$s_{75,5}^{\text{hg}}$
$s_{62}(\cdot)$	$s_{62,2}^{\text{bp}}$	$s_{62,3}^{\text{p}}$	$s_{62,5}^{\text{hg}}$				

2. Class K_{Pe}. In this case s_{ln}^{bp} or s_{ln}^{mbp}, $\forall n \in \{2, 3\}$ and the performance of process can be improved without degradation of product quality. This class K_{Pe} consists of

$$K_{\text{Pe}} = \{ s_{26}(\cdot), s_{27}(\cdot), s_{31}(\cdot), s_{32}(\cdot), s_{51}(\cdot), s_{52}(\cdot), s_{56}(\cdot), s_{57}(\cdot), s'_{26}(\cdot), s'_{27}(\cdot), s'_{31}(\cdot), s'_{32}(\cdot)\}.$$

3. Class K_2. The value φ_2 is out of range

$$\left(y_2 > \bar{y}_2 + \delta_2^{(1)}\right) \wedge \left(y_3 < \bar{y}_3 + \delta_3^{(1)}\right).$$

This class includes the following situations

$$K_2 = \{ s_{39}(\cdot), s_{40}(\cdot), s_{64}(\cdot), s_{65}(\cdot), s'_{14}(\cdot), s'_{15}(\cdot)\}.$$

4. Class K_3. The value φ_3 is out of range

$$\left(y_3 > \bar{y}_3 + \delta_3^{(1)}\right) \wedge \left(y_2 < \bar{y}_2 + \delta_2^{(1)}\right).$$

This class includes the following situations

$$K_3 = \{ s_{18}(\cdot), s_{23}(\cdot), s'_{43}(\cdot), s'_{48}(\cdot)\}.$$

5. Class $K_{2,3}$. Deviation of φ_2 and φ_3

$$\left(y_2 > \bar{y}_2 + \delta_2^{(1)}\right) \wedge \left(y_3 > \bar{y}_3 + \delta_3^{(1)}\right).$$

Class $K_{2,3}$ includes the greatest number of possible situations.

$$K_{2,3} = \{ s_{16}(\cdot), s_{17}(\cdot), s_{19}(\cdot), s_{20}(\cdot), s_{21}(\cdot), s_{22}(\cdot), s_{24}(\cdot), s_{25}(\cdot), s_{29}(\cdot), s_{30}(\cdot), s_{34}(\cdot), s_{35}(\cdot), s_{54}(\cdot), s_{55}(\cdot), s_{59}(\cdot), s_{60}(\cdot), s'_4(\cdot), s'_5(\cdot), s'_9(\cdot), s'_{10}(\cdot), s'_{19}(\cdot), s'_{20}(\cdot), s'_{24}(\cdot), s'_{25}(\cdot), s'_{41}(\cdot), s'_{42}(\cdot), s'_{46}(\cdot), s'_{47}(\cdot)\}.$$

The condition of inclusion [2] plays the main role in the effective functioning of the third and fourth classes systems. The system is inclusive on the situation $s_l(\cdot) \in \mathcal{S}$, if the dryer control device generates the control function $u(s_l(\cdot))$, that provides the required product quality. That means $\varphi_5^{\text{end}} \in Y_5^{\text{perm}}$, within the time of material passage across all sections of the dryer. And the system is inclusive on SFS if the condition of inclusion $\forall s_l(\cdot) \in \mathcal{S}$ is performed.

The studies have shown that the condition of inclusion is performed for the classes K_0 and K_{Pe}. For the other classes it is required to generate control actions to ensure the best quality of the product.

The results of the full analysis are used in the development of ICS algorithmic software [3].

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Анализ задач управления процессом сушки в сушильных установках вальцеленточного типа на множестве состояний функционирования

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Ключевые слова и фразы: качество выпускаемой продукции; классы ситуаций функционирования; минимизируемый функционал; общая задача управления; ситуации функционирования; частные задачи управления.

Аннотация: Приведены постановки общей и частных задач управления процессами сушки с целью повышения качества выпускаемой продукции. Предложены решения задач управления процессом сушки с использованием подхода полного анализа оптимального управления на множестве состояний функционирования, для чего проведен анализ множества возможных ситуаций и выделены пять классов, согласно которым разрабатывается алгоритмическое обеспечение информационно-управляющей системы сушильных установок вальцеленточного типа.

Analyse der Aufgaben der Steuerung vom Trocknenprozess in den Trockenanlagen des walzenbandförmigen Typus auf der Menge der Funktionierungszustände

Zusammenfassung: Es werden die Stellungen der allgemeinen und einzelnen Aufgaben der Steuerung von den Trockenprozessen mit der Absicht der Erhöhung der Qualität der Produktion angeführt. Es wird vorgeschlagen, die Aufgaben der Steuerung vom Trockenprozess mit der Benutzung der vollen Analyse der Optimalsteuerung auf der Menge der Funktionierungszustände zu lösen. Es ist die Analyse der möglichen Situationen durchgeführt und sind fünf Klassen ausgezeichnet. Es wird die algorithmische Versorgung des informationsteuernden Systems der Trockenanlagen des walzenbandförmigen Typus entwickelt.

Analyse des problèmes de la commande du processus du séchage dans les séchoirs du type laminé à ruban sur une multitude d'états du fonctionnement

Résumé: Sont citées les mises en problèmes, général et particuliers, de la commande du processus du séchage dans le but de l'augmentation de la qualité des produits fabriqués. Est proposé de résoudre les problèmes de la commande du processus du séchage avec l'utilisation d'une approche de l'analyse optimale complète sur une multitude d'états du fonctionnement. Pour cela est réalisée une analyse d'un ensemble de situations possibles et sont déduites cinq classes selon lesquelles est élaborée la maintenance algorithmique du système informatique de commande d'un système des séchoirs du type laminé à ruban.

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