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GENERAL PRINCIPLES OF FORMALIZATION OF TECHNOLOGICAL PROCESS CONTROL OF MINING PRODUCTION IN A DYNAMIC DISTRIBUTED SYSTEM

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ABSTRACT

Context. The problem of synthesis, modeling, and analysis of automated control of complex technological processes of mining production as a dynamic structure with distributed parameters.

Objective. On the example of the technological line of ore beneficiation, the general principles of formalization of control of mining production processes as a dynamic system with distributed parameters are considered.

Method. The modeling of interactions between individual components of the control system is carried out using the methods of coordinated distributed control. In accordance with this approach, the technological line is decomposed into a set of separate subsystems (technological units, enrichment cycles). Under these circumstances, the solution to the global optimization problem is also decomposed into a corresponding set of individual subproblems of optimizing the control of subsystems. To solve the global problem, this formulation uses a two-level structure with coordinating variables that are fed to the input of local control systems for technological units and cycles. At the lower level of control, sets of subtasks have independent solutions, coordinated by the coordinating variables formed at the upper level.

Results. The paper proposes a method for forming control of a distributed system of technological units of an ore dressing line based on the decomposition of the dynamics of the distributed system into time and space components. In the spatial domain, the control synthesis problem is solved as a sequence of approximation problems of a set of spatial components of the dynamics of the controlled system. In the time domain, the solution of the control synthesis problem is based on the methods of synthesizing control systems with concentrated parameters.

Conclusions. The use of the proposed approach to the formation of technological process management at mining enterprises of the Kryvyi Rih iron ore basin will improve the quality of iron ore concentrate supplied to metallurgical processing, increase the productivity of technological units and reduce energy consumption.

KEYWORDS: mining, automation, ore dressing, distributed control, process, system.

ABBREVIATIONS

DCSs is a design and implementation of distributed control systems;

ESRD is a system with Concentrated Input and Distributed Output Variables with Extrapolator; CCD is a system with Concentrated Input and Distributed Output Variable.

NOMENCLATURE

Q_n is a productivity of stages for the finished product;

Q_i^3 is a set performance values;

β_n is a content of a useful component in the product of the stage;

$\beta_i^{\min}$ is a limits of useful component content by stage;

β_{XB1} is a losses of useful component in the tailings by stages and in general at the outlet of the enrichment line;

$\beta_{XB1}^{\min}$ is a restrictions on tail losses;

ξ is a specific gravity for each technological type in ore;

Ω is a current, minimum and maximum amount of concentrate produced, respectively;

β is a current, minimum and maximum proportion of total iron in the concentrate, respectively;

E is a mass of ore that can be processed by the concentrator;

Q is a total volume of ore processing of all technological types;

$\beta^d(l,s)$ is an output variable of this system is equivalent to the output variable of a system with distributed input and distributed output;

$Q(\bar{p})$ is a productivity of the ore dressing line of finished product;

$\beta(\bar{p})$ is a content of a useful component in the finished product;

$\bar{p}$ is a vector of coordinating parameters of the second level of control, which form the conditions for solving the tasks of the first level;

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$\Theta H_i(\ell_i,k)$ is a distributed impulse function of the system;

$\Theta H_i(\ell,(k+\varepsilon)T)$ is a distributed impulse response transient function of a ESRD, consisting of a CCD and a zero-order extrapolator unit Hi;

$\Theta H_i(\ell_i,t)$ is a partially distributed output variable in the time domain at a point ℓ_i;

$\{\psi_i(k)\}_{i,k}$ is a sequences of input variables ESRD;

$\{\Theta H_i(\ell_j,k)\}_{i,j,k}$ are the values of discrete distributed impulse response functions;

q is a discrete transition time CCD;

$\Omega HR_i(\ell,\infty)$ is a constant values of the given transient characteristics of the distributed parameters of the technological line of beneficiation;

$B_i^d(\ell_i,\infty)$ are the approximation parameters;

$\breve{B}^d$ is a vector of optimal approximation;

$\left(\beta_i^d\right)^{\gamma}(\ell,k)$ is an approximation of the distributed output variables of the identified object;

$\Xi_i(\ell_i,s)$ is an appropriate transfer functions;

$K_i(z)$ is a robust regulators;

$\Omega HR_i(\ell,\infty)$ is a constant values of the given transient characteristics of the distributed parameters of the technological line of beneficiation;

$B_i^d(\ell_i,\infty)$ are the approximation parameters;

$\breve{B}^d=\left\{B_i^d(\ell_i,\infty)\,|\,i=\overline{1,n}\right\}$ is a vector of optimal approximation;

$\left(\beta_i^d\right)^{\gamma}(\ell,k)$ is an approximation of the distributed output variables of the identified object.

INTRODUCTION

The technological processes of mining production, namely the extraction and preparation of raw materials for metallurgical processing, are distributed in space, characterized by various dynamics, many interrelated variables and disturbing factors. An example of a corresponding diagram of the chain of devices built on the basis of a typical technological line of an ore processing plant with the indication of control points for the characteristics of ore material at different stages of iron ore processing is shown in Fig. 1.

A characteristic feature of technological complexes of concentration plants as control objects is the multistage nature of production processes implemented using many units, equipment, and transport links between them through a multi-circuit water-sludge circuit and/or belt conveyors. At the same time, positive technological feedback (re-cycle) is organized through the water-sludge circuit, both within and between the beneficiation stages.

Synthesis, modeling, and optimizati on of the management of such mining structures is still a problematic issue.

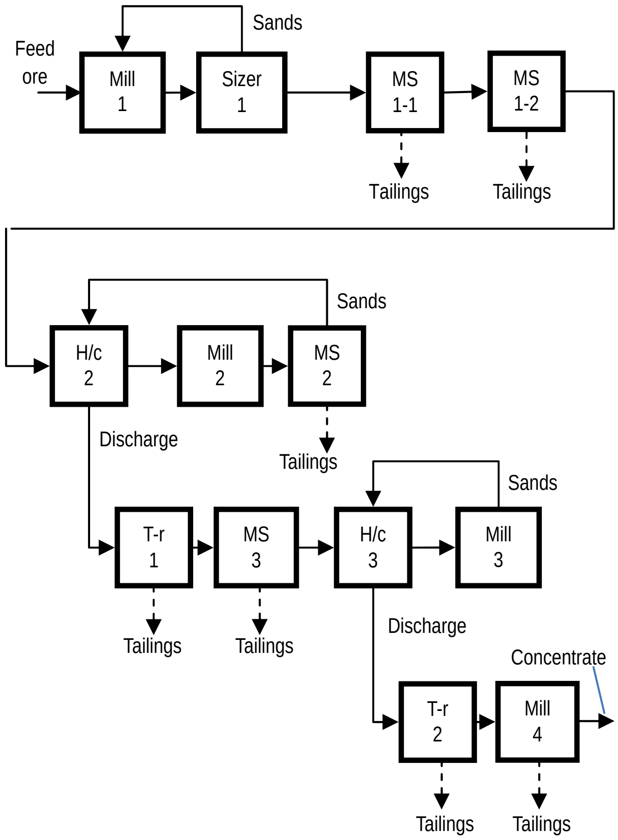

Figure 1 – Diagram of the chain of devices on the technological line of the ore dressing plant

The object of study is processes of automated control of the technological line of mining production in the conditions of changing characteristics of raw materials and the state of technological units/

The subject of study is the mathematical models, criteria and methods of distributed optimal control of interrelated processes of mining production based on a dynamic spatial and temporal structure

The purpose of the work of the research is to improve the energy efficiency and quality of automated control of the technological line for the preparation of ore for metallurgical processing, to increase the extraction of useful components into concentrate during the processing of iron ore by developing principles and approaches to distributed optimal control of interrelated mining processes based on a dynamic space-time model.

1 PROBLEM STATEMENT

Multi-criteria control structures formed on the basis of a complex indicator that includes the following goals are widely used in the automated control systems of concentrating production: maximizing ore processing productivity, maximizing concentrate quality, and minimizing losses of useful components in tailings [1].

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$$J = \begin{cases} Q \to \max; \\ \beta_k \to \max; \\ \beta_{\text{XB}} \to \min. \end{cases} \quad (1)$$

An expanded version of criterion (1), which comprehensively takes into account the performance indicators of individual stages of ore dressing, is proposed in [2].

$$J = \begin{cases} Q_1 \to \max(Q_1 \to Q_1^3);\ \beta_1^{\min} \le \beta_1 \le \beta_1^{\max};\ \beta_{XB1}^{\min} \le \beta_{XB1} \le \beta_{XB1}^{\max}; \\ Q_2 \to \max(Q_2 \to Q_2^3);\ \beta_2^{\min} \le \beta_2 \le \beta_2^{\max};\ \beta_{XB2}^{\min} \le \beta_{XB2} \le \beta_{XB2}^{\max}; \\ \ldots \\ Q_K \to \max(Q_K \to Q_K^3);\ \beta_K^{\min} \le \beta_K \le \beta_K^{\max};\ \beta_{XB}^{\min} \le \beta_{XB} \le \beta_{XB}^{\max}. \end{cases} \quad (2)$$

In the existing automated process control systems in the mining and metallurgical complex, one of the most important indicators along with technological indicators is the energy efficiency indicator [3–6]. Increasing the energy efficiency of the control of the technological process of beneficiation, as shown in [7], is achieved by applying a comprehensive criterion

$$\begin{cases} \left|\bar{\xi} - \bar{\xi}^*\right| \to \min; \\ \Omega_l \le \Omega \le \Omega_h; \\ \beta_l \le \beta \le \beta_h; \\ Q/E \to \max. \end{cases} \quad (3)$$

This criterion ensures that the processed ore maintains the optimal particle size distribution in terms of recovery of the useful component, taking into account the mass ratio of certain technological types, and that the concentrate of a given quality is produced at the maximum utilization rate of technological processing equipment.

The analysis of control systems for the technological process of iron ore beneficiation showed that the control object should be represented as a distributed system [8, 9–11] with a concentrated input and a distributed output. At the same time, the output variable of this system is equivalent to the output variable of a system with distributed input and distributed output $\beta^d(l,s)$ [12].

Based on the above results, it is advisable to use a global optimization criterion when forming the control of an ore dressing line as a dynamic system with distributed parameters, which is generally described by the system

$$\begin{cases} Q(\bar{p}) \to \max; \\ \beta_l \le \beta(\bar{p}) \le \beta_h. \end{cases} \quad (4)$$

2 REVIEW OF THE LITERATURE

The DCSs are associated with many challenging problems, including network-induced delays, time-varying topology or throughput, or increasing complexity [12]. The need to solve these problems has stimulated the development of methods for modeling, analyzing, and synthesizing RSCs [13, 14].

Paper [13] presents the proposed methodology for modeling and analyzing distributed control systems, consisting of three modules, each of which is divided into several submodules. The methodology includes steps for analyzing communication interfaces and computational processes, and also presents a method for creating models of DCSs components in the form of colored time Petri nets and finite state machines. The result of the applied methodology is the analysis of the DSC, such as prediction of the throughput and response of the system to various input factors.

Computational processes and communication networks in DCSs can be viewed as systems with discrete events, which can be conveniently modeled using a number of approaches, including finite state machines and Petri nets [15–17].

In [18], the study of distributed control systems is considered from the perspective of "network management", providing a snapshot of five control issues: sampling control, quantization control, network control, event-driven control, and security control.

A DCSs is characterized by a multi-level architecture consisting of numerous subsystems deployed in a distributed manner, where control functions are distributed among many controllers, and individual control levels are connected by different types of communication networks [19].

In many cases, these subsystems have three fundamental characteristics [20]. The first characteristic is autonomy. Subsystems are usually autonomous or semi-autonomous and can often exist and operate independently. The second characteristic is homogeneity. Subsystems regularly have similarities and play relatively equal roles. The last and most important characteristic is interactivity. Subsystems must be connected to the system topology collectively so that they can communicate by exchanging information or substance and cooperate with each other.

Paper [21] analyzes the functionality, requirements, and cost of installation and operation of industrial DCSs systems based on PLC logic controllers. Particular attention is paid to the distribution of individual system components by the corresponding layers contained in their structure.

Distributed control systems offer numerous advantages over traditional centralized control systems. The main advantages of DCSs usually include the following properties [22]:

– increased reliability: by distributing control functions among several controllers, the DCSs eliminates single points of failure;

– scalability: DCSs makes it easy to expand control systems as industrial operations grow;

– flexibility: The DCSs provides full integration with other control systems, such as PLCs and SCADA systems;

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– reduced operating costs: By automating complex processes, the DCSs can help industries reduce labor costs, minimize human error, and optimize resource utilization;

– security: cybersecurity and physical security of the system are ensured at the operator and engineer levels.

But, like other advanced technologies, the implementation of DCSs also has certain problems and limitations [22]:

– high initial investment: the implementation of a DCSs may involve the purchase and installation of many controllers, I/O modules, communication networks, and human-machine interfaces;

– complexity: designing and configuring a DCSs requires specialized knowledge and experience;

– maintenance and support: Like any complex system, a DCSs requires regular maintenance and troubleshooting to ensure optimal performance.

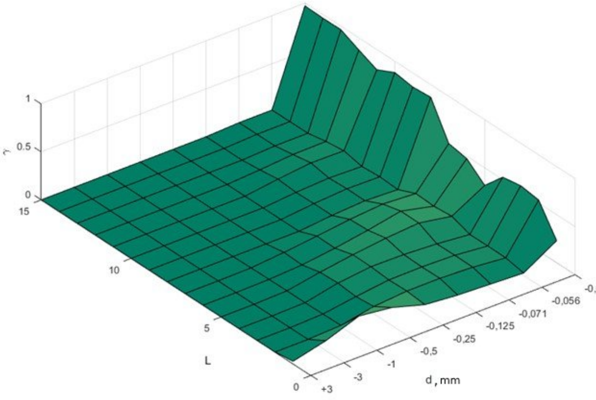
In the mining and ore processing industry, DCSs are effectively used to automate technological operations for reducing ore size [23–25], classifying grinding products [26–28], underground ore mining [29, 30], etc. The application of this approach is well coordinated with the systems of non-destructive non-contact control of the characteristics of raw materials and processed products as a means of information support for control processes [28, 31, 32].

The results of the analysis of studies on the use of distributed control systems for complex technological processes show that their use helps to increase production efficiency by providing centralized monitoring and control of distributed processes, allowing operators to make changes in real time to optimize performance [22]. In addition, RSCs use advanced control algorithms and data analytics to optimize processes, reduce energy consumption, and minimize waste.

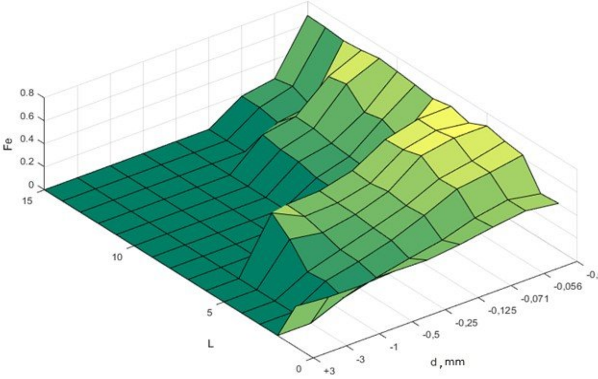
3 MATERIALS AND METHODS

The characteristics of iron ore raw materials in the process of multistage processing are presented as spatial and temporal variables distributed over an interval. The function of the distribution of the content of the useful component in the particle size classes of the ore material being processed is taken as the initial distributed variable [4].

After applying concentrated control actions to the system input, we obtain the system output signal as a distributed variable $\beta_i^d(\ell,t)$. An example of the realization of the output signal of the control object is, in this case, the output of size classes (Fig. 2a) and the iron content in size classes (Fig. 2b), distributed over the technological operations of the ore dressing line.



a



b

Figure 2 – Distributed along the technological line of beneficiation:
a) yield of solid of the pulp phase;
b) indicator of iron content content in the industrial product

The relationship between output and input variables is described by convolution [11].

$$\beta_i^d(\ell,t)=\Theta_i(\ell,t)*\psi_i(t). \qquad (5)$$

In the event that $\psi_i(t)$ is a single step function at the output of the system, we obtain a distributed transition function $\Omega_i(\ell,t)$. Similarly, we obtain the relationship between the individual input variables $\{\psi_i(t)\,|\,i=\overline{1,n}\}$ and the corresponding distributed output variables $\{\beta_i^d(\ell,t)\,|\,i=\overline{1,n}\}$. The total distributed function of the distribution of the content of the corrosive component by size classes is described by the expression

$$\beta^d(\ell,t)=\sum_{i=1}^{n}\Theta_i(\ell,t)*\psi_i(t). \qquad (6)$$

To increase the accuracy of identification of model parameters, it is advisable to measure the characteristics of ore material at the outlet of technological aggregates, which in the considered system correspond to points with

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coordinates $\ell_1,\ldots,\ell_n$, located near the points of application of controlling influences $\psi_1(t),\ldots,\psi_n(t)$, which can be, in particular [3, 4]: ore and water consumption in the mill, water consumption in the classifier, technological sump, hydrocyclone, magnetic separator, deslimer, etc. At these points, the output variables are partially distributed $\beta_1^d(\ell_1,t),\ldots,\beta_n^d(\ell_n,t)$, located on the respective surfaces of the distributed output variables $\beta_1^d(\ell,t),\ldots,\beta_n^d(\ell,t)$. Also, at the following locations $\ell_1,\ldots,\ell_n$ partial distributed impulse response functions are determined on the surfaces of individual distributed impulse response functions $\Theta_1(\ell_1,t),\ldots,\Theta_n(\ell_n,t)$. Using the relation (5), we obtain

$$\beta_i^d(\ell_i,t)=\Theta_i(\ell_i,t)*\psi_i(t), i=\overline{1,n}. \quad (7)$$

Taking into account the discrete input variables and the zero-order extrapolator {Hi} and the discrete outputs of the model of the ore dressing technological line are represented as a convolution

$$\beta_i^d(\ell,(k+\varepsilon)T)=\Theta H_i(\ell,(k+\varepsilon)T)*\psi_i(kT). \quad (8)$$

Let us assume T=1, ε=0. Then, according to formula (8), we obtain an expression for the function of the distribution of the useful component by fineness classes at the output of the ore dressing line

$$\beta_i^d(\ell,k)=\Theta H_i(\ell,k)*\psi_i(k), \quad i=\overline{1,n}. \quad (9)$$

Common distributed output variable $\beta^d(\ell,k)$ of the processing line as a control object with a concentrated input and distributed output with zero-order extrapolatorsy $\{H_i\}_i$, and will be written as

$$\beta^d(\ell,k)=\sum_{i=1}^{n}\Theta H_i(\ell,k)*\psi_i(k). \quad (10)$$

For points $\ell_1,\ldots,\ell_n$ located around concentrated input variables, partially distributed output variables can be obtained $\beta_1^d(\ell_1,k),\ldots,\beta_n^d(\ell_n,k)$ and consequently, partially distributed impulse transition functions $\Theta H_1(\ell_1,k),\ldots,\Theta H_n(\ell_n,k)$. In this case, the following convolutions are correct

$$\beta_i^d(\ell_i,k)=\Theta H_i(\ell_i,k)*\psi_i(k), \quad i=\overline{1,n}. \quad (11)$$

After applying the Laplace transform, moving to the domains, we obtain

$$\beta_i^d(\ell,s)=\Xi_i(\ell,s)\psi_i(s), \quad i=\overline{1,n}, \quad (12)$$

$$\beta^d(\ell,s)=\sum_{i=1}^{n}\Xi_i(\ell,s)\psi_i(s), \quad (13)$$

$$\beta_i^d(\ell_i,s)=\Xi_i(\ell_i,s)\psi_i(s), \; i=\overline{1,n}. \quad (14)$$

In the case when the action of the elements of the vector $\{\psi_i(t)\,|\,i=\overline{1,n}\}$ is added at points $\ell_1,\ldots,\ell_n$ at the outputs of the units $\Xi H_1(\ell_1,s),\ldots,\Xi H_n(\ell_n,s)$ Partially distributed output variables are formed $\beta_1^d(\ell_1,k),\ldots,\beta_n^d(\ell_n,k)$. Distributed output variables of blocks $\Xi H_1(\ell,s),\ldots,\Xi H_n(\ell,s)$: $\beta_1^d(\ell,k),\ldots,\beta_n^d(\ell,k)$ move along these trajectories. Thus, the total output variable of the technological line of ore dressing, as a distributed object, is given by the ratio:

$$\beta^d(\ell,k)=\sum_{i=1}^{n}\beta_i^d(\ell,k). \quad (15)$$

When a discrete representation is considered, the discrete dynamics of the system is given by a set of discrete distributed impulse response functions $\{\Theta H_i(\ell,k)\,|\,i=\overline{1,n}\}$. The given characteristics on this set are written as follows

$$\{\Theta HR_i(\ell,k)=\Theta H_i(\ell,k)/\Theta H_i(\ell_i,k)\,|\,i=\overline{1,n}\}. \quad (16)$$

This makes it possible to determine the output of the distributed control system of the processing line as follows

$$\beta_i^d(\ell,k)=\Theta H_i(\ell_i,k)\Theta HR_i(\ell,k)*\psi_i(k), \quad i=\overline{1,n}$$
$$i=\overline{1,n}. \quad (17)$$

The dynamics of the technological line of ore dressing, as a distributed object, is decomposed into a time component that depends on the continuous (t) or discrete (k) time at fixed values of i, $\ell_i:\{\Theta H_i(\ell_i,t)\}_{i,k}$, and the spatial component, which depends on a simple variable ℓ_i at fixed values of i, k: $\{\Theta HR_i(\ell,t)\}_{i,k}$.

Steady state of the function of distribution of the useful component by ore material size classes as distributed along the technological line of beneficiation of the initial $\beta^d(\ell,\infty)$ variable, in accordance with the theory proposed in [8, 12], can be described by means of a stable value of the transition function, $\{\Omega H_i(\ell,\infty)\,|\,i=\overline{1,n}\}$, that is obtained after applying a single stepwise impact $1(k)$ to each input $\{\psi_i(k)\,|\,k=\overline{1,n}\}$.

When forming the control, we use the following decomposition of the distributed dynamics of the system:

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time component $\{\Xi H_i(\ell_i, s) \mid i = \overline{1,n}\}$, spatial component $\{\Omega HR_i(\ell, \infty) \mid i = \overline{1,n}\}$.

As a result of spatial discretization of the model with discrete time of the ore dressing line, which has concentrated inputs (adjustable parameters of technological units and operations) and distributed output (content of the useful component classes) at the points $\{\ell_j \mid j = \overline{1,m}\}$ is obtained in scalar form

$$\left\{\beta^d(\ell_i,k) = \sum_{i=1}^{n} \Theta H_i(\ell_j,k) * \psi_i(k)\right\}_{j,k,i}. \tag{18}$$

Expression (14) is written in vector form as follows

$$\bar{\beta}^d(\ell_i,k) = \sum_{i=1}^{n} \Theta H_i(\ell_j,k) * \psi_i(k). \tag{19}$$

Considering that for a particular $i, j, r > q$ The following ratio is true: $\Theta H_i(\ell_j, r) = 0$, where q – discrete transition time CCD, expression (19) can be written as

$$\begin{bmatrix} \beta^d(\ell_1,k) \\ \dots \\ \beta^d(\ell_m,k) \end{bmatrix} = \sum_{i=1}^{n} \begin{bmatrix} \Theta H_i(\ell_1,0) & \dots & \Theta H_i(\ell_1,q) \\ \dots & \dots & \dots \\ \Theta H_i(\ell_m,0) & \dots & \Theta H_i(\ell_m,q) \end{bmatrix} \begin{bmatrix} \psi_i(k) \\ \dots \\ \psi_i(k-q) \end{bmatrix}. \tag{20}$$

In expression (16), the individual matrices correspond to the distributed discrete impulse transition functions of the considered distributed object of controlling the ore dressing process, which is represented by different mineralogical and technological varieties (Fig. 3): FDV – formers of distributed variables, EECV – executive elements of concentrated variables.

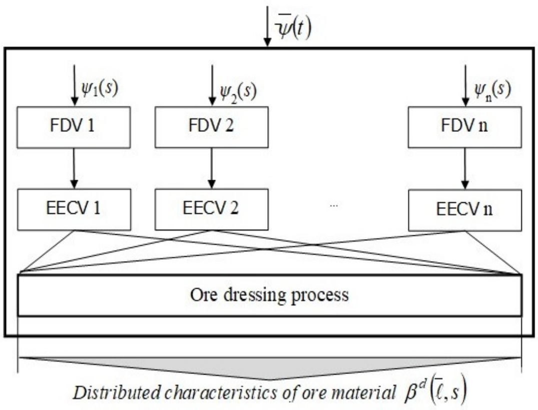

Figure 3 – Ore dressing process line as an object with concentrated inputs and distributed outputs

Taking into account the above, the global criterion for optimizing the control of the technological line of beneficiation as a dynamic object with concentrated inputs and distributed outputs is written as follows

$$\begin{cases} Q\left(\bar{p}, \bar{\psi}, \bar{\beta}^d\right) \to \max; \\ \beta_l \le \beta\left(\bar{p}, \bar{\psi}, \bar{\beta}^d\right) \le \beta_h. \end{cases} \tag{21}$$

The structure of a two-level coordinated distributed control system for a technological line for the beneficiation of iron ore raw materials as an object with concentrated inputs and distributed outputs is shown in Fig. 4.

At the upper level of system control (Fig. 4), the formation of coordinating variables is carried out $\bar{p}$, that affect the value of $\Delta\beta_i^d$ transformation of the function of distribution of the useful component by particle size classes of ore material at the *i*-th point, i.e., the load on the *i*-th technological unit of the concentration line.

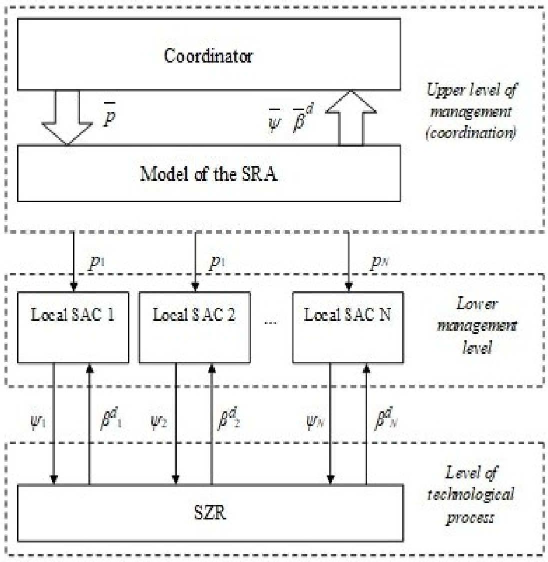

Figure 4 – System of two-level coordinated separated control of the technological line of enrichment

At the lower level of control, concentrated control influences are formed by local automatic control systems for individual technological units and cycles.

4 EXPERIMENTS

The control of a distributed system of technological units of an ore dressing line is formed on the basis of decomposition of the dynamics of a distributed system into time and space components [4]. In the spatial domain, the control synthesis problem is solved as a sequence of approximation problems of a set of spatial components of the dynamics of the controlled system. In the time domain, the solution of the control synthesis problem is based on the methods of synthesizing control systems with concentrated parameters. Thus, in the

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structure of the control system, blocks of spatial and temporal formation of control influences are distinguished (Fig. 5).

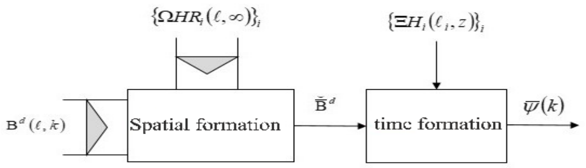

Figure 5 – Structure of the control system for the distributed ore dressing process

To form spatial control, the corresponding component is used $\left\{\Omega HR_i(\ell,\infty) \mid i=\overline{1,n}\right\}$, obtained as a result of decomposition of the distributed dynamics of the technological enrichment line. At the output of the spatial formation unit, a vector of concentrated variables is formed $\breve{\mathrm{B}}^d(\ell)$, which is the basis for the temporal formation of control taking into account the corresponding component $\left\{\Xi H_i(\ell_i,s) \mid i=\overline{1,n}\right\}$ distributed dynamics of the control object. The output of the time control formation unit is a vector of zoned control variables $\overline{\psi}(k)$ for local control systems of individual technical units.

In this case, the control task is to form the following sequence of control inputs $\overline{\psi}(k)$, which is in a steady state $k \to \infty$, ensure minimal control error at the quadratic norm

$$\left\|\varepsilon(\ell,\infty)\right\| = \left\|\mathrm{B}^d(\ell,\infty) - \beta^d(\ell,\infty)\right\| \to \min. \qquad (22)$$

The spatial control formation block (Fig. 5) solves the optimization problem of approximation

$$\left\|\mathrm{B}^d(\ell,\infty) - \sum_{i=1}^{n} \mathrm{B}_i^d(\ell_i,\infty)\Omega HR_i(\ell,\infty)\right\| \to \min. \qquad (23)$$

In [11], it was shown that the solution to the approximation problem (23) is guaranteed as a unique best approximation

$$\mathrm{B}^{d*}(\ell,\infty) = \sum_{i=1}^{n} \breve{\mathrm{B}}_i^d(\ell_i,\infty)\Omega HR_i(\ell,\infty). \qquad (24)$$

The control vector $\breve{\mathrm{B}}^d$ is fed to the input of the time shaping unit, which contains the corresponding number of single-channel control loops with concentrated parameters. Each of the control loops generates the corresponding element of the vector of concentrated control actions $\overline{\psi}(k)$ and consists of a regulator $\left\{\mathrm{K}_i(z) \mid i=\overline{1,n}\right\}$ and a control object with a zero-order extrapolator $\left\{\Xi H_i(\ell_i,z) \mid i=\overline{1,n}\right\}$. When forming the control, the individual components of the vector $\breve{\mathrm{B}}^d = \left\{\breve{\mathrm{B}}_i^d(\ell_i,\infty) \mid i=\overline{1,n}\right\}$ are inputs of separate control circuits $\left\{\mathrm{K}_i(z), \Xi H_i(\ell_i,z) \mid i=\overline{1,n}\right\}$.

Thus, the synthesis of control of an open system is carried out in two stages: temporal control – by forming control loops with concentrated parameters; spatial control – by solving the approximation problem.

Time components required for the formation of control of the technological line of ore dressing $\left\{\Xi H_i(\ell_i,s) \mid i=\overline{1,n}\right\}$ the distributed dynamics of the control object are determined from the matrix of distributed discrete impulse transition functions $\left\{\Theta H_i(\ell_j,k) \mid i=\overline{1,n},\ j=\overline{1,m}\right\}$. Multiple discrete reviews $\left\{\Theta H_i(\ell_j,k)\right\}$ correspond to the set of approximations $\left\{\Theta H_i'(\ell_j,k) \mid i=\overline{1,n},\ j=\overline{1,m}\right\}$. So, we get

$$\beta_i^d(\ell,k) = \Theta H_i'(\ell,k) * \psi_i(k),\ i=\overline{1,n}$$
$$\left(\beta^d\right)'(\ell,k) = \sum_{i=1}^{n} \Theta H_i'(\ell,k) * \psi_i(k) \qquad (25)$$
$$\left(\beta_i^d\right)'(\ell,k) = \Theta HR_i'(\ell,k)\Theta H_i'(\ell_i,k) * \psi_i(k).$$

Since $\beta^d(\ell,k)$ defined as a linear combination of elements of discrete distributional characteristics of the dynamics of the system under consideration $\left\{\Theta H_i(\ell,k)\right\}_{i,k}$ – The accuracy of the models depends on the accuracy of the approximation of these characteristics and the physical constraints imposed on a particular control variable $\psi_i^{\max}$. Therefore, to ensure the required accuracy of the model, the differential properties of the set of elements $\left\{\psi_i^{\max}\Theta H_i(\ell,k)\right\}_{i,k}$ should be determined using a set of discrete values $\left\{\Theta H_i(\ell_j,k)\right\}_{i,j,k}$. These discrete values are used to determine the discrete continuity modulus, as well as the difference norms, which are then generalized over the entire interval $\ell \in [0,L]$ in the corresponding functional spaces. Select the element that has the maximum value of the differential properties and mark it as $\psi_i^{\max}\Theta H^{\max}{}_i(\ell,k)$, setting the approximation accuracy χ = 5%, and defining the norm || ||, the problem will take the form

$$\left\|\left(\beta^d\right)(\ell,k) - \left(\beta^d\right)'(\ell,k)\right\| \le \chi. \qquad (26)$$

At the same time, it takes into account the limitations imposed on the control variables.

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5 RESULTS

The main internal controlling influences in the enrichment line, which is shown in Fig. 1, are water consumption in technological units [4]. Figs. 6–11 show examples of the obtained qualitative and quantitative dependencies that characterize the influence of this parameter on the course of the technological process.

The dependence of the mass fraction of the solid phase in the iron ore pulp on the water flow to the technological units distributed along the concentration line is shown in Fig. 6. The dependence of iron content in the –0.044 mm class and the yield of this class on water consumption is shown in Figs. 7, 8. The dependence of the mass fraction of iron in the by-product on the mass fraction of the solid phase of the pulp distributed along the concentration line is shown in Fig. 9. The dependence of the mass fraction of iron in the industrial product and the iron content in the –0.071 mm class is shown in Fig. 10. 11.

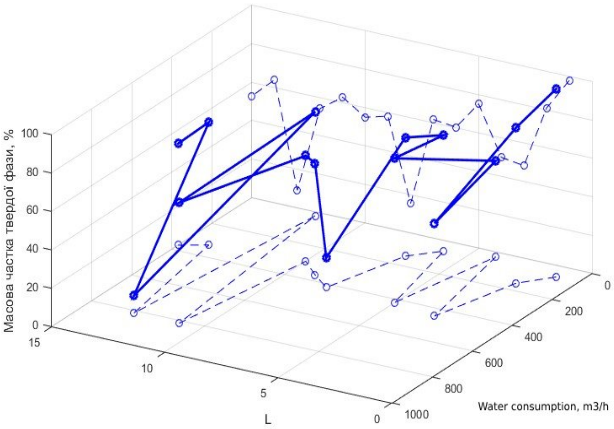

Figure 6 – Mass fraction of the solid phase in iron ore pulp depending on water flow to technological units:
“---” – distributed function; “- - -” – projections on coordinate planes

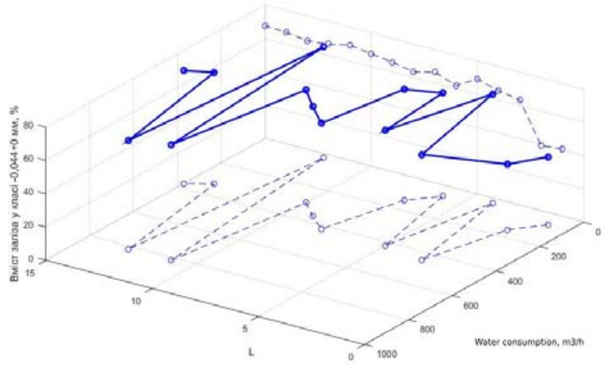

Figure 7 – Iron content in the class “–0.044 mm” depending on the water flow to the technological units:
“---” – distributed function; “- - -” – projections on coordinate planes

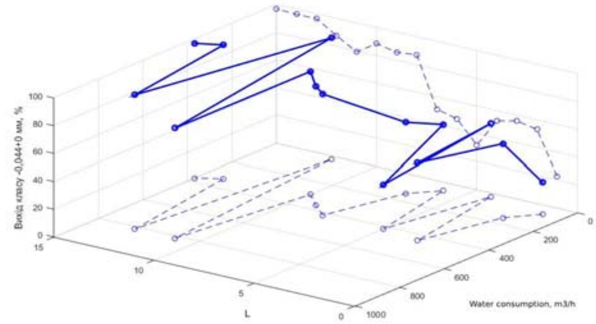

Figure 8 – The output of the size class “–0.044 mm” depending on the water flow to the technological units:
“---” – distributed function; “- - -” – projections on coordinate planes

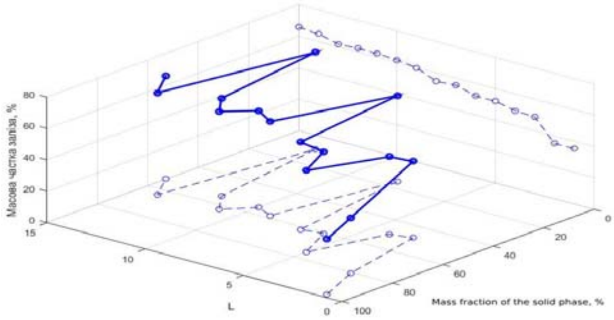

Figure 9 – Mass fraction of iron in the industrial product as a function of the mass fraction of the pulp solid phase:
“---” – distributed function; “- - -” – projections on coordinate planes

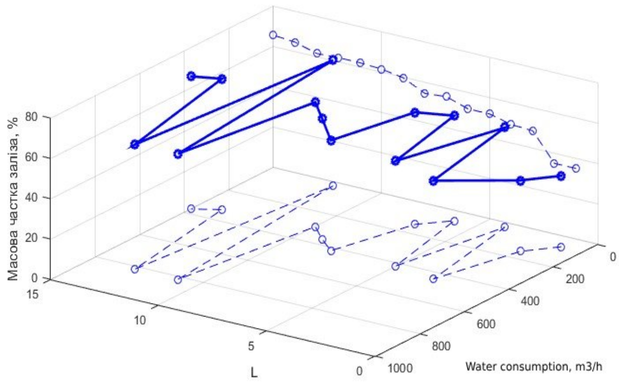

Figure 10 – Mass fraction of iron in industrial products as a function of water flow to technological units:
“---” – distributed function; “- - -” – projections on coordinate planes

6 DISCUSSION

Thus, the control of an ore dressing process line as an object with concentrated inputs and distributed outputs involves the synthesis of a spatially distributed control influence, on the basis of which a vector of corresponding time-dependent concentrated influences is formed.

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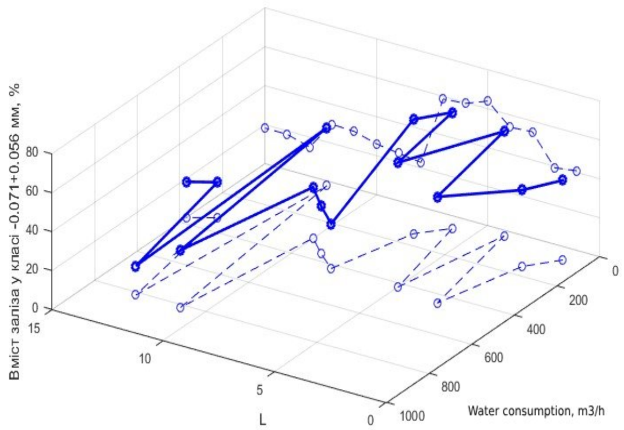

Figure 11 – Iron content in the –0.071 mm class depending on the water flow to the process units:
"---" – distributed function; "- - -" – projections on coordinate planes

The steady-state values of partial distributed transient characteristics are used to calculate the control system. The steady-state values of the transient characteristics are obtained on the basis of the finite value theorem [11, 12].

$$H_i(\ell,\infty) = \lim_{s\to\infty} s\left\{\Xi_i(\ell,s)\tfrac{1}{s}\right\} =$$
$$\lim_{s\to\infty} \Xi_i(\ell,s) = \lim_{s\to\infty} z\Xi H(\ell,z) = H_i(\ell,\infty),$$
$$H_i(\ell,\infty) = \Xi A_i(0)\Xi G_i(0)\int_0^L \Xi(\ell,\xi,0)T_i(\xi)d\xi. \quad (27)$$

Then the following feedback was given

$$HR_i(\ell,\infty) = \frac{H_i(\ell,\infty)}{H_i(\ell,\infty)} = \frac{H_i(\ell,\infty)}{H_i(\ell,\infty)} = HR_i(\ell,\infty). \quad (28)$$

The results of calculating the constant values are shown in Fig. 12.

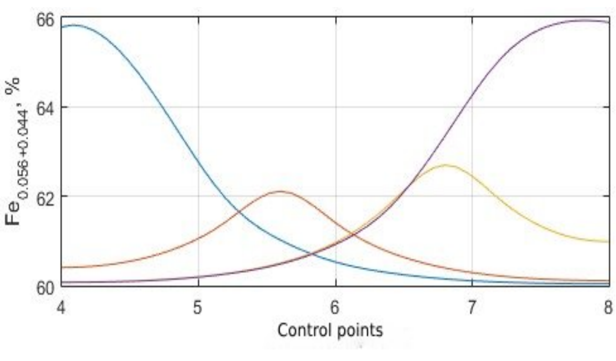

Figure 12 – Steady-state values of transient characteristics for individual inputs according to the control points of Fig. 1.

The given responses are determined as follows: first, the maximum functional values of the responses at the points $\{l_j\}_{j=1,11}$. Then the values at specific points $\{l_j\}_{j=1,11}$ divided by this value. The results of the reduction are shown in Fig. 13.

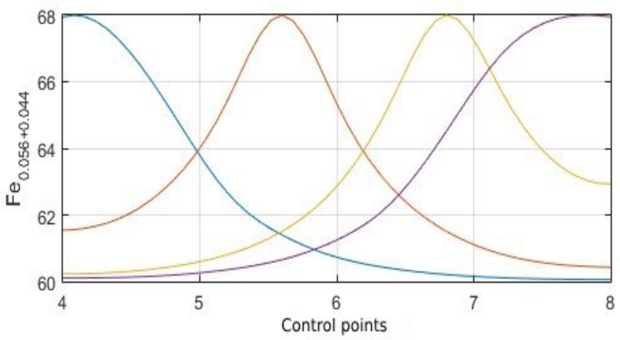

Figure 13 – Steady-state transient characteristics for individual inputs according to
to the control points of Fig. 1.

When forming a sequence of control actions $\psi_i(k)$ robust regulators used $K_i(z)$. The optimal parameters of the controllers were determined in accordance with the results obtained in [4].

The results obtained allow us to conclude that it is expedient to represent the technological line for the beneficiation of iron ore raw materials as a structure with concentrated inputs and distributed outputs and to use appropriate approaches to form the control of the system of technological units of mining production.

The testing of this approach in the formation of automated control of technological enrichment lines at ore dressing plants of the Kryvyi Rih iron ore basin shows that its application allows to reduce by 2–5% the fluctuations in the material composition of enrichment products, that go to the metallurgical processing, increase the content of useful component in the concentrate by 0.3–0.8%, maximize the productivity of technological units in conditions of variaty of static and dynamic characteristics of control objects and reduce by 0.2 – 0.9% of energy consumption.

CONCLUSIONS

The technological line of enrichment is decomposed into a set of separate subsystems (technological units, enrichment cycles). Under these circumstances, the solution of the global optimization problem is also decomposed into a corresponding set of individual subproblems of optimizing the control of subsystems.

The structure of the system of two-level coordinated distributed control of the technological line of iron ore beneficiation as an object with concentrated inputs and distributed outputs is proposed.

The formation of control of the distributed system of technological units of the ore dressing line is based on the decomposition of the dynamics of the distributed system into time and space components. In the spatial domain, the control synthesis problem is solved as a sequence of approximation problems on the set of spatial components of the modeled system dynamics. In the time domain, the solution of the control synthesis problem is based on the methods of synthesizing control systems with concentrated parameters.

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Using the proposed approach at mining enterprises in the Kryvyi Rih iron ore basin will improve the quality of iron ore concentrate supplied to metallurgical processing, increase the productivity of technological units and reduce energy consumption.

The scientific novelty. The paper proposes the structure of a two-level coordinated distributed control system for a technological line for the beneficiation of iron ore raw materials as an object with concentrated inputs and distributed outputs. The formation of the control of a distributed system of technological units of the ore dressing line is based on the decomposition of the dynamics of the distributed system into time and space components. In the spatial domain, the control synthesis problem is solved as a sequences of approximation problems on the set of spatial components of the dynamics of the controlled system. In the time domain, the solution of the control synthesis problem is based on the methods of synthesizing control systems with concentrated parameters.

The practical significance. Using the proposed approach at mining enterprises of the Kryvyi Rih iron ore basin will improve the quality of iron ore concentrate supplied to metallurgical processing, increase the productivity of technological units and reduce energy consumption

Prospects for further research. Prospects for further research are to study the possibility of using the proposed approach to solve a wide class of practical problems.

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ЗАГАЛЬНІ ПРИНЦИПИ ФОРМАЛІЗАЦІЇ КЕРУВАННЯ ТЕХНОЛОГІЧНИМИ ПРОЦЕСАМИ ГІРНИЧОГО ВИРОБНИЦТВА ЯК ДИНАМІЧНОЮ РОЗПОДІЛЕНОЮ СИСТЕМОЮ

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АНОТАЦІЯ

Актуальність. Проблема синтезу, моделювання та аналізу автоматизованого управління складними технологічними процесами гірничого виробництва як динамічної структури з розподіленими параметрами.

Мета роботи. На прикладі технологічної лінії збагачення руди розглянути загальні принципи формалізації управління процесами гірничого виробництва як динамічної системи з розподіленими параметрами.

Метод. Моделювання взаємодій між окремими компонентами системи керування здійснено з використанням методів скоординованого розподіленого керування. Відповідно до цього підходу технологічна лінія декомпозується на сукупність окремих підсистем (технологічних агрегатів, циклів збагачення). За таких умов розв'язання глобальної оптимізаційної задачі також декомпозується на відповідну множину окремих підзадач оптимізації управління підсистемами. Для вирішення глобальної задачі в цій постановці використовується дворівнева структура з координуючими змінними, які подаються на вхід локальних систем управління технологічними агрегатами і циклами. На нижньому рівні управління множини підзадач мають незалежні розв'язки, які координуються координуючими змінними, сформованими на верхньому рівні.

Результати. У статті запропоновано метод формування управління розподіленою системою технологічних агрегатів гірничо-збагачувальної лінії на основі декомпозиції динаміки розподіленої системи на часову та просторову складові. У просторовій області задача синтезу керування вирішується як послідовність задач апроксимації множини просторових складових динаміки керованої системи. У часовій області розв'язання задачі синтезу керування базується на методах синтезу систем керування із зосередженими параметрами.

Висновки. Використання запропонованого підходу до формування системи управління технологічним процесом на гірничодобувних підприємствах Криворізького залізорудного басейну дозволить підвищити якість залізорудного концентрату, що надходить на металургійну переробку, збільшити продуктивність технологічних агрегатів і знизити енергоспоживання.

КЛЮЧОВІ СЛОВА: видобуток, автоматизація, збагачення руди, розподілене управління, процес, система.

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