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OPTIMIZATION OF RESOURCE-INTENSIVE DYNAMIC SYSTEMS WITH A CONTINUOUS SUPPLY OF RAW MATERIALS ACCORDING TO THE CRITERION OF MINIMUM USE OF RESERVES

Igor Lutsenko
Corresponding author
Doctor of Technical Sciences, Professor*
E-mail: delo-do@i.ua
Svetlana Koval
PhD, Associate Professor*
Iryna Oksanych
Doctor of Technical Sciences, Professor*
Igor Shevchenko
Doctor of Technical Sciences, Professor*
*Department of Automation and Information Systems
Kremenchuk Mykhailo Ostrohradskyi National University
Pershotravneva str., 20, Kremenchuk, Ukraine, 39600

Optimization of production processes has always been one of the cornerstones for industrial enterprises seeking to improve productivity while minimizing the costs involved. A particularly difficult situation is when it is necessary to manage the process of the entire production chain with a continuous supply of raw materials. It is necessary to keep under control the actual production data, current production requirements, and adhere to the international strategy of energy saving.

This paper reports a devised optimal dynamic system with a continuous supply of raw materials, which automatically changes the control trajectory in order to reduce the amount of resources used. The theoretical scientific component is represented in the form of an interface model of the system, and the research results are represented in the form of time diagrams that show the verification of the proposed model.

The model provides for the interconnection of the chain of such developed dynamical systems, in which the continuity of the process is ensured by buffering systems, and the optimality of operation is enabled by adaptation mechanisms.

The time diagrams can demonstrate the interaction of systems and mechanisms that generate information signals through the port sections. At each subsequent control action, the process parameter changes were made within a set range. As a result of a targeted search for permissible controls, the system, driven by the adaptation mechanism, enabled a gradual reduction in the consumption of the energy product and stabilized the intensity of the target product being processed, which made it possible to subsequently avoid shutdowns and restarts of the production line and reduce overall production costs

Keywords: continuous production, product consumption, overall operation costs, modeling, structural-parametric optimization

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1. Introduction

When creating new or improving existing production lines with a continuous supply of raw materials, one often faces the problem of discrepancy between the intensity and amount of consumption of the target product in each subsequent subsystem of the converter class.

This fact imposes some restrictions on the control systems of such subsystems while minimizing the possibility of reaching the optimum of the entire production line.

When one tries to control one link, one converter system, the values of the input parameters of the subsequent ones are automatically changed, and, therefore, the process of setting up the entire chain must be started anew. This process is quite complex, time-consuming, and short-lived since the current situation in production can change at fairly short intervals while all adjustment procedures must be performed anew.

The current production situation can change due to a number of factors such as changing the number of orders, equipment breakdown, and redirection of the raw material flow. Changes in energy tariffs for enterprises, the purchase of new equipment with different modes of operation, and the consumption of resources are also sources of reconfiguration of the production line. All this destabilizes the operation of continuous production lines, which require the constancy of regimes.

Given that a fairly large percentage of production lines involve a continuous supply of raw materials, and understanding the complexity of monitoring and managing such processes, the task of optimizing continuous production according to the criterion of minimum costs is relevant.

2. Literature review and problem statement

Conducting an analysis of known technological advances to solve this problem, the review revealed that most papers over the past few years have addressed the optimization of processes through the transition from discrete-continuous to

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continuous production. This trend is observed, in particular, in the biotechnology industry.

The authors of paper [1] in this area note that it is important to reduce costs without neglecting the quality of the results of the process. Continuous processing, in their opinion, is the next step in the development of the process, leading to lower costs, increased productivity, and better quality control. The cited paper reports an economic comparison of existing stations for the processing of liquids and microfluidics with portion and continuous processing, where the financial advantage of the latter is proved. However, the cited paper does not show a strategy for managing a continuous process with many parameters, which would lead to the subsequent optimization of continuous processes.

Industrial resource-intensive production is a complex multi-criteria task where it is necessary to take into consideration a sufficiently large number of interrelated factors. In work [2], it is noted that one of the main problems related to managing the production of polypropylene fibrous filter elements is the control of the technological process. Given a large number of factors and parameters affecting the production process, as well as the need for optimal management, the authors argue that improving such a process is a complex scientific task. However, only mathematical models of the object were built in the cited paper, which depend on the parameters of the technological process. The management of the process and its path to the optimum was not shown.

On the other hand, the management of continuous production processes must be carried out in a single key with the transition of society to the rational use of resources. To achieve the goals of the Paris Climate Agreement, on the one hand, new, more energy-efficient approaches should be applied to industrial production. On the other hand, production must profit from these approaches by performing the process inexpensively and reliably [3].

Paper [4] tackles the issue of energy consumption control and indicates the importance of saving it. However, the authors propose only the automation of the process of collecting information about the current level of energy losses and do not consider the optimization of processes in the sources of these losses.

Reducing the use of energy resources is shown by the authors in article [5]. The optimization of the drying process and the dryer to increase energy efficiency is described. Thus, the authors propose to improve the technological system, which would subsequently increase the speed of obtaining a high-quality target product and thereby reduce the amount of energy resource used. However, that approach makes it possible to take only one step in the optimization of the process and does not reveal the possibility of subsequent optimization of the process by taking into consideration the current economic situation and production load for flexible management of drying parameters.

Article [6] examines the application of adaptive strategies for finding steepness in dynamic processes with double input and one output. That is, it is proposed to increase the degrees of freedom to increase the possibilities of management and search for an extreme path to the optimum. However, the purpose of the cited paper is to improve productivity, not to reduce the total costs of production. The authors also describe that with the help of a new approach in optimizing lipid productivity in continuous cultures of microalgae, input energy is also minimized. However, the process is seen as a closed system that does not provide a management option in the case of the interaction of several such sequentially operating systems.

The management of the technological process following the criterion of maximum income is also described in [7] where it is proposed to manage the pumping system. The purpose of the cited paper is the optimal management of continuous technological processes in a single production line according to the criterion of the minimum stocks used.

Optimization of the production line taking into consideration the current situation at the plant is considered in work [8]. However, the authors offer only a methodological basis for solving this issue through the introduction of instrumental and software innovative technologies, without describing what methods and algorithms would be used to optimize.

A new step in improving the management of resource-intensive dynamic systems is structural and parametric optimization [9], which radically increases the control capabilities by increasing the degrees of freedom of each subsystem and their practically independent management.

Structural innovations are associated with the addition of dual buffering systems between each system [10] and the division of technological mechanisms into sections. The proposed approach made it possible to obtain two degrees of freedom of control: the possibility of converting the sectional structure into self-stabilizing modular systems and changing the trajectory of the qualitative parameter of the channelized technological product within the production stage.

However, with increasing degrees of freedom, the number of possible variants of control modes has also increased exponentially [11]. Given that the situation can change unexpectedly and unevenly, moreover, given a large number of controlled parameters and resources used, this task is quite difficult. Thus, the rational selection of the necessary management option, taking into consideration the current situation and reducing resource costs at this stage of development of such a concept, is an important scientific task, and the topic of the article is relevant.

Summing up their analysis of literature data [1–11], we can conclude that the task of optimizing continuous processes is relevant. However, it is necessary to take into consideration the complexity of the resource-intensive production process with dynamically changing parameters and external economic factors. In addition, in accordance with the Paris Climate Agreement, new, more energy-efficient approaches should be applied to industrial production. And the problem must be solved not point-by-point for one continuous technological system but comprehensively, in the interaction of several such systems connected into one production line. From this point of view, this task cannot be considered fully solved today, and the need to solve it is justified and expedient.

3. The aim and objectives of the study

The aim of this opus is to develop and verify an automatic adaptive control system for resource-intensive dynamic systems with a continuous supply of raw materials. This will make it possible to reach the optimum of using the resources of the production line.

To accomplish the aim, the following tasks have been set:

– to devise an interface model of a resource-intensive dynamic optimal system with a continuous supply of raw materials, which involves a chain of such series-connected systems;

– to verify the proposed model and demonstrate the possibilities of reaching the optimum of using the resources of the production line.

4. The study materials and methods

To increase the degrees of freedom in the control over continuous processes, technological mechanisms are divided into technological sections. Sections make it possible to assemble independent modules, each of which has its subsystem for stabilizing the qualitative parameter of the technological product.

This approach makes it possible to set different trajectories for changing the qualitative parameters of a technological product within one production stage.

Thus, changing the structure of the technological mechanism (the number of modules) and the trajectory of changing the qualitative parameter of the channelized product makes it possible to change the total amount of energy consumption and wear of working mechanisms of the equipment.

Existing approach makes it possible to obtain two degrees of freedom of control: the possibility of changing the sectional structure into self-stabilizing modular systems and changing the trajectory of the qualitative parameter of the channelized technological product within the production stage.

Obtaining degrees of freedom of management, in turn, makes it possible to change the efficiency of using the resources of a continuous technological process and devise a method of structural and parametric optimization. As a criterion for optimization, an evaluation indicator is usually used, which has been verified for the possibility of its use as a criterion of efficiency. As a result of such actions, the optimization capabilities of management increase significantly.

The introduction of dual buffering systems (Fig. 1) makes serial technological subsystems with a continuous supply of raw materials more independent of each other. This makes it possible to increase the degree of freedom for each control subsystem and thereby improve the efficiency of finding the optimal mode of operation of the entire cybernetic system.

In Fig. 1, we adopted the following designations: $sSrcA1_{PD}$ – output of the source of cold liquid supply; $sSrcA1_{ZD}$ – input of the feed source; $sSrcP1_{PP}$ – output source of energy product supply; $sSrcP1_{ZPS}$ – input source of energy product supply; $sConvA1_{RD}$ – input; $sConvA1_{UD}$ – output; $sConvA1_{RP}$ – input; $sConvA1_{UPS}$ – output; $sConvA1_{ZP}$ – setting the intensity of the energy product supply; $sConvA1_{Z}$ – task signal for the production of a quality product; $sConvA1_{PD}$ – output product; $sConvA1_{ZD}$ – setting the volume of cold liquid supply; $sConvA1_{CL}$ – current level of loading of the heating mechanism buffer; $sConvA1_{TE}$ – ambient temperature; $sConvA1_{ET}$ – the specified value of the output product temperature; $sConvA1_{INT}$ – intensity of delivery of a quality product; $mBufA1_{RD}$ – buffering input; $mBufA1_{UCL}$ – current level; $mBufA1_{PD}$ – buffering output; $mBufA1_{SL}$ – entry level; $mBufA1_{RPS}$ – task for issuing the target product; $mCmpA1_{T}$ – controlled parameter; $mCmpA1_{S}$ – reference; $mCmpA1_{OUT}$ – output signal; $mCmpA2_{T}$ – reference; $mCmpA2_{S}$ – controlled parameter; $mCmpA2_{OUT}$ – output signal; $mFinA1_{IN}$ – input signal; $mFinA1_{OUT}$ – output signal; $mCrdB1_{IN}$ – input pulse signal; $mCrdB1_{CRD}$ – input transmitted signal; $mCrdB1_{OUT}$ – output signal; $mCrdB2_{IN}$ – input pulse signal; $mCrdB2_{CRD}$ – input transmitted signal; $mCrdB2_{OUT}$ – output signal; $mNoA1_{IN}$ – input; $mNoA1_{OUT}$ – output; $mOr2A1_{IN1}$ – first input signal; $mOr2A1_{IN2}$ – second input signal; $mOr2A1_{OUT}$ – output signal; $mMemA1_{IN}$ – input signal; $mMemA1_{OUT}$ – output signal; $mMemA1_{RES}$ – reset input signal; $mSelA1_{IN}$ – input pulse signal of the current amplitude; $mSelA1_{ET}$ – input pulse signal of reference amplitude; $mSelA1_{OUT}$ – output pulse signal with reference amplitude; $mRecA1_{U}$ – replenishment request; $mRecA1_{RD}$ – obtaining a special product; UP – section for receiving the signal of the task by the amount of intensity of the energy product supply; UHL – upper level of reserves; ULL – lower level of reserves; ZCL – current inventory level.

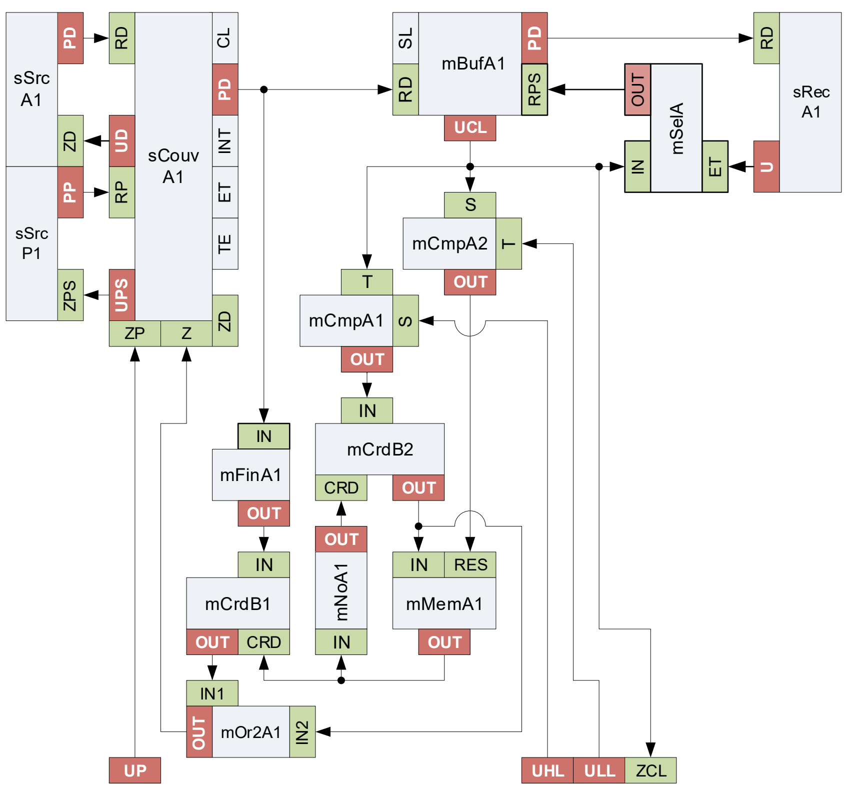

Fig. 1. Interface model of a dual buffering system for converter class production systems with a continuous supply of technological products

Verification of cybernetic estimated indicators of the use of reserves as criteria for the effectiveness of converter class systems with a continuous supply of a technological product was carried out in work [12]. A cybernetic model of operation with distributed parameters for continuous processes was built. The formulas for calculating the main estimated indicators of a continuous technological process were proposed and their verification was carried out at three different control trajectories, which showed the adequacy of the devised approach.

The final stage was the derivation of three variants of the stock efficiency formula for converter class systems with a continuous supply of the technological product, the calculation of which is made at specified points in time throughout the production cycle:

$$ELF = A / R, \tag{1}$$

$$ELF = \frac{\left[\left(\left(PE + PE^{*}\right) - \left(RE + FE\right)\right)\left(v_d - v_l\right)^2\right] / 2}{\sum_{v_0}^{v_l}\sum_{u_0}^{u}\sum_{w_0}^{w}\left(\left(re_n + fe_n\right) - \left(pe_n + pe_n^{*}\right)\right)}, \tag{2}$$

$$ELF = \frac{\int_{v_l}^{v_d}\int_{u_0}^{u}\int_{w_0}^{w}\left(pe_i(t) + pe_i^{*}(t) - \left(\left|re_i(t)\right| + \left|fe_i(t)\right|\right)\right)\mathrm{d}w\,\mathrm{d}u\,\mathrm{d}v}{\int_{v_0}^{v_l}\int_{u_0}^{u}\int_{w_0}^{w}\left(\left|re_i(t)\right| + \left|fe_i(t)\right| - \left(pe_i(t) + pe_i^{*}(t)\right)\right)\mathrm{d}w\,\mathrm{d}u\,\mathrm{d}v} = \begin{cases} v \geq v_i, v \in \left[v_l, v_d\right], \\ v \geq v_i, v \in \left[v_0, v_l\right], \end{cases} \tag{3}$$

where A is the potential effect of the operation; R – the value of the resource intensity of the operation; PE is a function of the results of the movement of the output products of the operation in cases where the distributed nature of the function pe_i can be neglected; PE^* is a function of the results of the movement of the output products of the operation when using fe_i in cases where the distributed nature of the function can be neglected; RE is a function of the results of the movement of the input products of the operation in cases where the distributed nature of the function re_i can be neglected; FE is a function of the results of the movement of an additional number of value estimates of input technological products in cases where the distributed nature of the fe_i function can be neglected; $v_d=v_1+1$ – the time between the end of one control trajectory and the calculation of the potential effect; v_1 – the time to determine the potential effect of the operation at the time of changing the control trajectory; v_0 – end time of the current control trajectory; re_i is the result of the movement of the input products of the conversion class system at the i-th moment; fe_i is the result of the movement of an additional number of cost estimates of input technological products at the i-th point in time; pe_i is the result of the movement of the output products of the conversion class system at the i-th moment; pe_i^* – valuation of output technology products at the i-th point in time when using fe_i; u_0 – the time of the beginning of determining the main evaluation indicators of the continuous process; u – the time to complete determining the main indicators of the continuous process; w_0 – time to start a continuous process; w is the current time of the process.

Thus, cybernetic assessment of the effectiveness of the use of reserves makes it possible to formalize and fully automate the processes of optimization and adaptation of functional systems of the enterprise, which have a large resource intensity.

Based on the described principles of optimization of continuous processes and the proposed formulas for evaluating efficiency, it is possible to proceed to the development of an optimal resource-intensive dynamic system with a continuous supply of raw materials.

5. Results of studying resource-intensive dynamic systems with a continuous supply of raw materials

5. 1. Building an interface model of a resource-intensive dynamic system with a continuous supply of raw materials

To achieve the set goal, the first step is to build an interface model of a resource-intensive dynamic optimal system with a continuous supply of raw materials (Fig. 2), which involves a chain of such series-connected systems. The first step of optimization is the use of dual buffering systems between each process system of the converter class. The second step in optimizing the system according to the criterion of the minimum resources used is the introduction of an adaptation mechanism that automatically selects the mode of operation of the system.

The interface model consists of two main parts: the technological part and the coordinating or controlling part. In the technological part, the sConvA1 system performs the main converter function. The targeted product (TP) to be transformed is supplied by the sSrcA1 system. The source of the energy product is sSrcP1, with the help of which the conversion process is performed. The converted product – the target product – enters the dual product buffering system sSepA1 product, from which it then enters the next stage of conversion and processing.

The port sections of the mechanism and systems have the following designations:

– $\mathrm{sSrcA1}_{\mathrm{PD}}$ – output of the source of raw material supply;
– $\mathrm{sSrcA1}_{\mathrm{ZD}}$ – input of the supply source;
– $\mathrm{sSrcP1}_{\mathrm{PP}}$ – output source of energy product supply;
– $\mathrm{sSrcP1}_{\mathrm{ZPS}}$ – input source of energy product supply;
– $\mathrm{sConvA1}_{\mathrm{RD}}$ – input;
– $\mathrm{sConvA1}_{\mathrm{UD}}$ – output;
– $\mathrm{sConvA1}_{\mathrm{UD}}$ – input;
– $\mathrm{sConvA1}_{\mathrm{UPS}}$ – output;
– $\mathrm{sConvA1}_{\mathrm{ZP}}$ – setting the intensity of the energy product supply;
– $\mathrm{sConvA1}_{\mathrm{Z}}$ – task signal for the production of a quality product;
– $\mathrm{sConvA1}_{\mathrm{PD}}$ – output product;
– $\mathrm{sSepA1}_{\mathrm{RD}}$ – input for supplying a quality product;
– $\mathrm{sSepA1}_{\mathrm{U}}$ – issuance of control for replenishment of the dual system;
– $\mathrm{sSepA1}_{\mathrm{ZHL}}$ – setting the top level of stocks;
– $\mathrm{sSepA1}_{\mathrm{UCL}}$ – issuance of the current value of the reserve level of the dual system;
– $\mathrm{sSepA1}_{\mathrm{ZLL}}$ – setting the lower level of stocks;
– $\mathrm{sSepA1}_{\mathrm{PA}}$ – output for issuing the finished product;
– $\mathrm{mAdpA1}_{\mathrm{ZCL}}$ – section for issuing the current value of the reserve level;
– $\mathrm{mAdpA1}_{\mathrm{ULL}}$ – lower level of reserves;
– $\mathrm{mAdpA1}_{\mathrm{UHL}}$ – upper level of reserves;
– $\mathrm{mAdpA1}_{\mathrm{UP}}$ – energy product supply control;
– $\mathrm{mAdpA1}_{\mathrm{UL}}$ – left control boundary;
– $\mathrm{mAdpA1}_{\mathrm{UR}}$ – right control boundary;
– FP is a quality product of constant consumption.

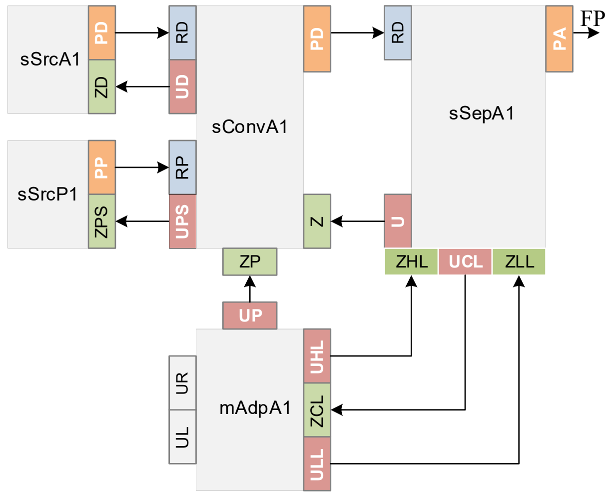

Fig. 2. Interface model of an optimal dynamic system with a continuous supply of raw materials, where sSrcA1 is the source of supply of raw materials; sSrcP1 – source of energy product supply; sConvA1 – technological system; sSepA1 – dual buffering system of the processed high-quality raw material; mAdpA1 – upper and lower level adaptation mechanism of the buffering system

The process is controlled using the mAdpA1 adaptation mechanism. The proposed mechanism involves the analysis of the current workload of production systems, the intensity of their work, and the calculation of the effectiveness of the control trajectory according to one of the formulas (1) to (3).

To determine the efficiency of dynamic systems with a continuous supply of a technological product, it is necessary to determine the moment of completion of the operation. For the type of systems under consideration, this may be the moment of changing the control trajectory. At this point, the time interval for data analysis is outlined. Such actions are performed in order to obtain indicators that make it possible to assess the effectiveness of the system in the prevailing external and internal production conditions and determine the subsequent trajectory.

The function of forming a new quasi-optimal control trajectory is calculated and transmitted by the adaptation mechanism of the upper and lower level of the buffering system (mAdpA1). The signal from the mAdpA1$_{UP}$ section to the sConvA1$_{ZP}$ section is generated as follows:

$$U=\frac{U_R(HL-LL)+(U_L-U_R)(h-LL)}{HL-LL}, \quad (4)$$

where U_R is the value of the right control boundary; U_L is the value of the left control boundary; HL – the value of the specified upper level of stocks; LL – the value of the specified lower level of stocks; h is the value of the current level of the dual buffering system.

Thus, a model for managing a continuous production process is proposed, which, with the help of an adaptation mechanism, makes it possible to calculate the current efficiency of the converter process and, at the next step, change the control trajectory towards the optimum of resource use. Formulas for calculating efficiency and a formula for calculating the function of forming a quasi-optimal control trajectory are shown.

5. 2. Verification of the interface model of a resource-intensive dynamic optimal system with a continuous supply of raw materials

To experimentally test the possibility of work and change the control trajectories towards reducing the use of resources, the EFFLI software designer was used [13]. The developed constructor was written using macros in Microsoft Excel, which made it possible to automate the modeling of the process. As an example of a dynamic system with a continuous supply of raw materials, a liquid heating system was taken.

The proposed structure of the system has passed repeated checks at different starting values of the parameters and confirmed its operability. Some of the options for the operation of the system are described below.

For a detailed analysis of the work of the proposed optimal dynamic system with a continuous supply of raw materials, time diagrams were constructed.

To prevent a clutter of the interface model, not all port sections were shown in Fig. 2. However, the work of some of them must be represented on time diagrams to understand the logic of the control process and the reaction of systems to them.

Fig. 3 shows the plotted charts of information flows during the operation of the technological subsystem sConvA1. The time diagram (Fig. 3, *a*) of the dependence of the current level of the target product in the technological system on time (sConvA(CL)) shows the dynamics of tank replenishment from the source of raw materials. If a chain of interconnected systems of the converter class is considered, it can be either a system with a portion supply of the target product or a previous buffering system that adaptively selects the level of stocks depending on the operation of the subsequent system.

The period with the conversion of 4 servings of raw materials is considered. Note that the second portion contains a smaller amount of the product since the processing time of this portion is not 250 units of time but 240. This was due to a change in the trajectory of the adaptation mechanism management in order to reduce the cost of inventory of the technological operation.

The following diagram (Fig. 3, *b*) shows the dynamics of temperature change of each portion of raw materials in the reservoir of the technological subsystem (sConvA(TMP)). The first portion was heated to a temperature of 51 °C, the second – up to 50 °C, the third and fourth – up to 52 °C. Note that the values of the control parameters changed in a given range and their combinations made it possible to maintain the value of a quality product at the output in a set limit. In addition, the model takes into consideration the fact that after the first pumping of the target product, the tank cooled not to the original temperature but a little less. In our case, it was 1 °C.

A single signal (Fig. 3, *c*) from the output of the sConvA(PAF) port section appeared during the completion of one iteration of the process, that is, after the target product was completely pumped out of the tank into the dual buffering system. The first single signal (Fig. 3, *d*) from the output of the sConvA(RED) port section appeared after the set temperature in the tank was reached. The second single signal appears at the next clock cycle, which indicated the restoration of the supply of the energy product to maintain the temperature of the quality product.

In Fig. 4, plots of information signals of control of the technological subsystem sConvA1 are built. A single signal (Fig. 4, *a*) from the sConvA(RDF) port section appears when the target product reaches the required amount in the tank. A single signal (Fig. 4, *b*) from the sConvA(UPF) port section appears when the conversion process is complete and the target product is issued to the dual buffering system. The transmission of a single signal (Fig. 4, *c*) from the sSepA(U) port section to the sConvA(Z) port section appears when it is necessary to increase the level of inventory in the buffering system.

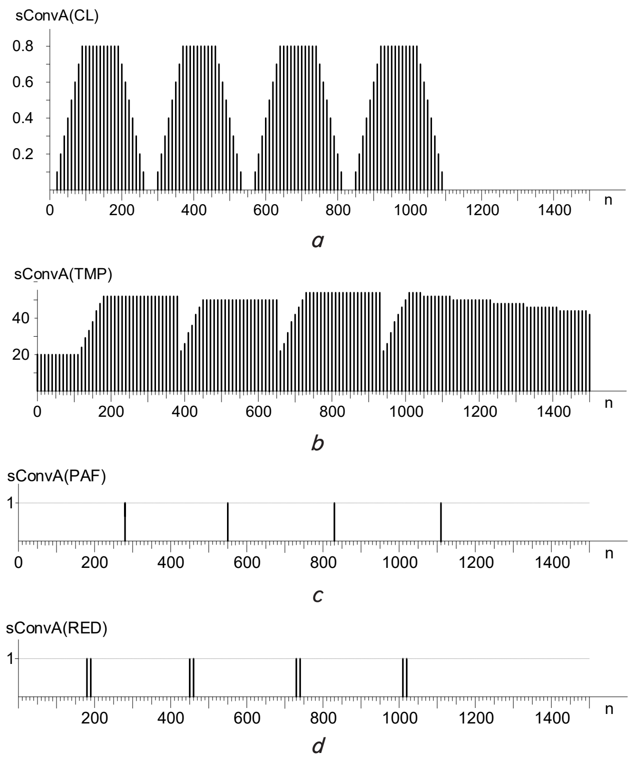

Fig. 3. Time diagrams of the operation of the technological subsystem sConvA1: *a* – dynamics of tank replenishment from the source of raw materials; *b* – dynamics of temperature change of each portion of raw materials in the tank of the technological subsystem; *c* – the appearance of single signals for the completion of the iteration of the technological process; *d* – the appearance of single signals of termination and the beginning of the supply of energy product

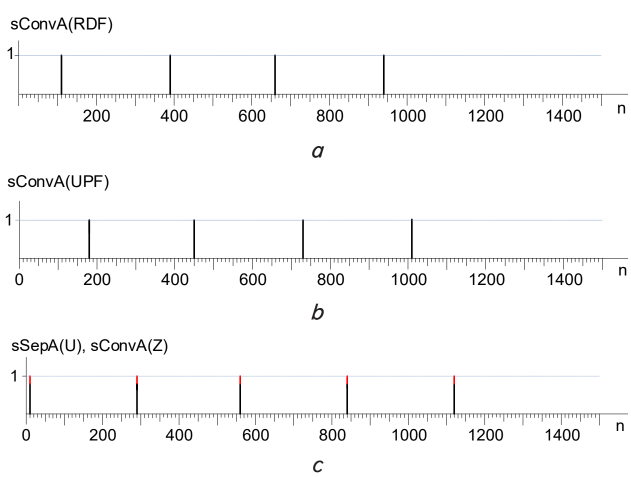

Fig. 4. Time diagrams of the sConvA1 management subsystem: *a* – a single signal from the sConvA(RDF) port section; *b* – a single signal from the sConvA(UPF) port section; *c* – transmission of a single signal from the sSepA(U) port section to the sConvA(Z) port section

Fig. 5 shows diagrams of the interaction between the adaptation mechanism and the systems of a resource-intensive dynamic optimal system with a continuous supply of raw materials.

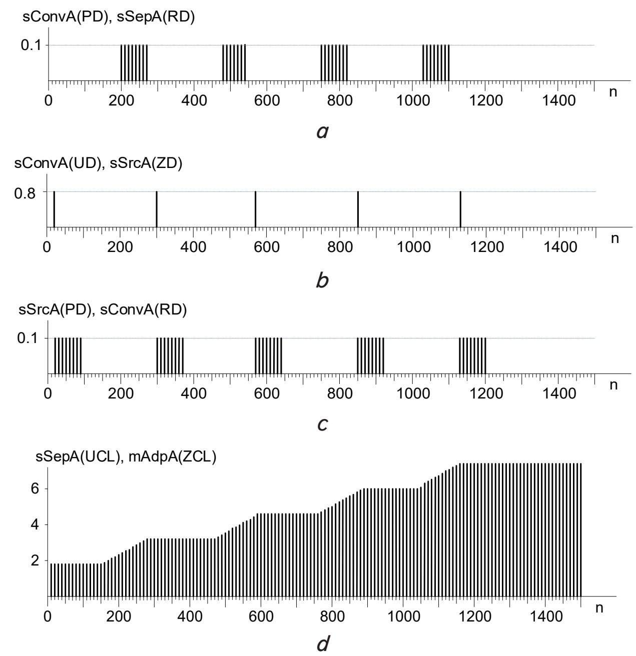

Fig. 5. Time diagrams of the interaction between the adaptation mechanism and systems of a resource-intensive dynamic optimal system with a continuous supply of raw materials: *a* – transfer of information flow from the sConvA(PD) port section to the sSepA(RD) port section; *b* – the appearance of a single signal from the sConvA(UD) port section to the sSrsA(ZD) port section; *c* – transfer of information flow from the sSepA(PD) port section to the sConvA(RD) port section; *d* – transmission of a signal about the current value of the inventory level

The first time diagram (Fig. 5, *a*) shows the transfer of information flow from the sConvA(PD) port section to the sSepA(RD) port section when the target product is pumped into the dual buffering system. A single signal (Fig. 5, *b*) from the sConvA(UD) port section to the sSrsA(ZD) port section indicates a TP recharge request. In the next clock cycle, the transmission of TP from the source of raw materials to the reservoir of the technological subsystem begins (Fig. 5, *c*).

Different modes of operation of the chain of systems of the converter class are considered. If the links of this chain work with different intensities, this is the most difficult option to manage. To solve these problems, the use of dual buffering systems with dynamically changing upper and lower levels of inventory storage is envisaged.

This allows the control subsystems to operate almost independently of each other. To do this, a signal about the current value of the reserve level is transmitted from the sSepA(UCL) port section to the mAdpA(ZCL) port section throughout the life of the resource-intensive dynamic optimal system (Fig. 5, *d*). This is necessary for the analysis of the current situation and the subsequent formation of particular control.

The intensity of the output of the target product from the buffering system to the next system of the converter class (Fig. 6) is also controlled. This process can be traced back to the sSepA(PA) port section (Fig. 6, *a*). In this case, there is a constant consumption with an intensity of 0.0015 units. According to the information from the mAdpA(ULL) port section to the sSepA(ZLL) port section, the adaptation mechanism sets the required lower reserve level (Fig. 6, *b*), and, from the mAdpA(UHL) port section to the sSepA(ZHL) port section, the upper reserve level (Fig. 6, *c*).

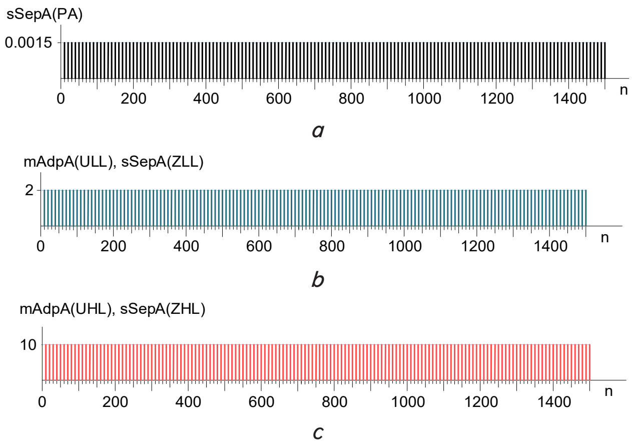

Fig. 6. Time diagrams of the interaction between the adaptation mechanism and a dual buffering system: *a* – the intensity of the target product supply from the buffering system; *b* – transfer of information from the mAdpA(ULL) port section to the sSepA(ZLL) port section; *c* – transfer of information from the mAdpA(UHL) port section to the sSepA(ZHL) port section

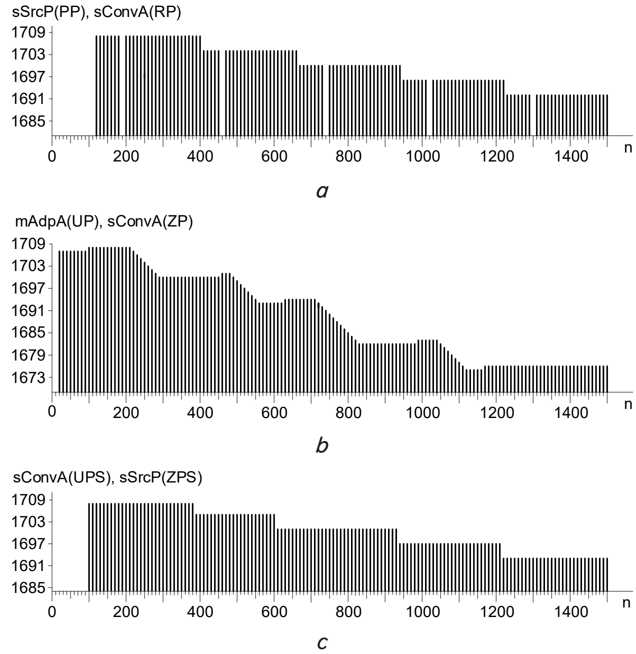

Fig. 7. Time diagrams for controlling the intensity of supply of an energy product: *a* – change in the intensity of supply of an energy product from the source to the technological subsystem; *b* – information flow of setting the intensity of supply from the adaptation mechanism to the technological subsystem; *c* – request for supply from the process subsystem to the power supply

As a result of the operation of the system with four portions of raw materials, the intensity of the energy product supply decreased from 1708.2 units to 1691.5 units. Optimization of the conversion process in Fig. 6 is shown by three time diagrams. Let us analyze each of them in more detail.

In the first diagram (Fig. 7, *a*), at 120 time points, the process of heating the first portion of TP began. It was carried out at a heating intensity of 1708.2 units. At time point 180, the heating process stops due to the achievement of a given quality of the target product, after which the target product is pumped out and the next portion is pumped in. From time point 400, the next converter process begins, which is performed with a lower intensity of 1703.5 units, which is 4.7 units less than the previous one.

This is possible by converting a smaller portion of the raw product to a lower level of quality within acceptable limits, analyzing the intensity of consumption by the next TP converter system and the current level of stocks in the buffering system. At time point 670, there is again a decrease in the intensity of the supply of energy product for conversion. The third portion of raw materials is heated longer, to the highest quality of the target product. This is due to an increase in the number of TP in the buffering system due to the lower intensity of its consumption by the subsequent system. Thus, the probability of overflow of buffering systems, stopping the process, and subsequent start in the overall production chain is reduced and, most importantly, there is a decrease in resource consumption, which leads to an overall reduction in production costs.

Thus, during the description of the research results, the proposed model was verified and the possibility of reaching the optimum of using the resources of the production line was demonstrated.

6. Discussion of research results related to the optimization of resource-intensive dynamical systems by the criterion of minimum reserves

We report the devised resource-intensive optimal dynamic system with a continuous supply of raw materials, which automatically changes the control trajectory in order to reduce the resources used.

Similar to [1], it is possible to note the prospects of continuous processes in contrast to discrete or discrete-continuous, which make it possible to reduce costs, increase productivity, and improve quality control of products. Taking into consideration the Paris Climate Agreement, described in [3], a new, more energy-efficient approach to the implementation of continuous dynamic processes is proposed. A given approach contains both structural changes in the construction of the system and management actions aimed at optimizing the process according to the criterion of the minimum use of reserves.

Reviewing the scientific literature on the implementation and management of continuous processes, the following conclusions can be drawn.

In contrast to [2], where a model of the current process is built, the devised model includes structural innovations that make it possible to increase the degree of freedom for the control system. An interface model of the system (Fig. 2) has been built, in which the continuity of the process is provided by buffering systems, and the optimality of operation is provided by adaptation mechanisms.

In contrast to [4], where it is supposed to optimize the process in a manual mode after automated control of current parameters, the proposed structure performs both automated control and change of control trajectories. Automation at all stages of work could allow for rapid and expedient changes when both internal and external conditions change.

In works [5, 8], only structural changes to the system have been proposed. In our study, both structural innovations and proposals in the optimization of management are carried out. Automation of the control process is provided by an adaptation mechanism that changes the control trajectory based on a calculation of the effectiveness of the current production situation. The efficiency calculation is performed in accordance with (1) to (3), and the calculation of the function of forming a new quasi-optimal control trajectory is performed using (4).

In contrast to [6, 7], where optimization is carried out according to the criterion of maximum performance, the result obtained in our study tends to the minimum inventory used, which is more relevant as noted in [3]. In addition, in [6], new approaches to process management have been proposed. However, the process is seen as a closed system that does not take into consideration the interconnections and the possibility of several such sequential systems. The proposed system takes into consideration this interaction through buffering systems and information exchange with control systems.

Verification of the proposed model was carried out by the EFFLI software designer [13]; its results are represented in time diagrams.

Due to the purposeful search for permissible controls in the model of a resource-intensive optimal dynamic system with a continuous supply of raw materials, a constant reduction in the consumption of the energy product and stabilization of the intensity of the target product being processed was carried out. Over 4 iterations of control actions, energy consumption decreased by 0.8 % (Fig. 7).

However, an advanced resource-intensive dynamic system with a continuous supply of raw materials has a limitation such as a possibility of using intermediate buffering only to processes that can allow such technological innovations. The disadvantage is the presence of significant economic costs at the stage of implementation of the current optimization approach.

Thus, by changing the intensity of consumption and the amount of resources processed simultaneously, a reduction in overall costs has been achieved within the framework of the devised dynamic optimal system with a continuous supply of raw materials.

7. Conclusions

1. A resource-intensive dynamic system with a continuous supply of raw materials has been improved, which differs from the existing ones by the presence of an adaptation mechanism operating under an automatic mode of selection of the control trajectory. The proposed innovations make it possible to maintain the quality of the product with a decrease in resource consumption by 0.8 %.

2. A simulation of the developed resource-intensive dynamic optimal system with a continuous supply of raw materials has been carried out. The results of the research showed a decrease in the consumption of energy resources due to a change in control trajectories by 0.8 %. In addition, the possibility of operation of a chain of systems with different intensities of consumption of the raw material product and the possibility of their independent management have been shown. This approach minimizes the likelihood of stopping the production line and restarting it, which also contributes to avoiding additional financial costs.

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