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SYNTHESIS OF THE STRUCTURE OF FUNCTIONAL SYSTEMS OF CONVERSION CLASS WITH A PORTIONAL SUPPLY OF INITIAL PRODUCTS

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Основні зусилля, пов'язані зі створенням і розвитком підприємства, спрямовані на підвищення ефективності використання ресурсів в процесі його функціонування. Таке завдання може бути успішно вирішена тільки в тому випадку, якщо домогтися максимальної ефективності на кожному етапі перетворювального процесу технологічного класу. У свою чергу, вирішення цієї задачі, на кожному окремому етапі, пов'язане зі створенням обґрунтованої структури об'єкта, відносно функціонального перетворення вхідних продуктів у вихідні продукти системної операції. Такий об'єкт, функціонування якого здійснюється максимальною ефективністю використання ресурсів, заочно визначили поняттям «функціональна система».

На прикладі технологічного процесу нагріву рідини в роботі вирішена задача синтезу функціональної системи перетворювального класу з порціонної подачею продуктів спрямованого впливу. В ході синтезу, на першому етапі, вирішувалося завдання забезпечення можливості інтерактивної взаємодії системних об'єктів в процесі формування готового продукту з заданими споживчими якостями.

На другому етапі синтезу розроблялася архітектура модуля ідентифікації системних операцій і визначення граничних значень області ефективних управлінь.

На третьому етапі створювався модуль, що пов'язує рівень запасів готової продукції системи з її продуктивністю.

Використання запропонованого підходу дозволило створити функціональну структуру що має максимальну кількість ступенів свободи управління. У свою чергу, таке рішення дозволило забезпечити формування оптимальної траєкторії управління у функції споживчого попиту на готову продукцію.

Запропоноване рішення дозволяє використовувати синтезовану архітектуру для класу функціональних систем перетворювального класу з порціонної подачею вхідних продуктів

Ключові слова: синтез системи, структура об'єкта, кібернетична модель, ефективності функціонування, модель операції

1. Introduction

The main task of any enterprise consists in maximizing its manufacturing capabilities through effective use of available resources [1] in the process of production of consumer products with required qualitative indicators [2].

Naturally, this can be achieved only if all resource-intensive technological processes of the enterprise will proceed in a mode of maximum efficiency [3].

In turn, this means that some structural units of an enterprise must function interactively but without losing the degree of freedom necessary for selecting the most efficient [4], optimal [5] control.

At the level of intuitive perception, such a structural unit was defined by the notion of "system" [6], as some integrity [7].

Due to realizing practical importance of establishing principles of such system functioning [8], the process of this establishment and attempts to synthesize their structure have arisen [9, 10].

The fact that there is no universally adopted definition of a functional system and principles of its synthesis have not been developed so far indicates complexity of this problem solution.

Therefore, the issue of synthesizing structure of a functional system is an important scientific and practical problem.

2. Literature review and problem statement

Attractiveness of ideas of cybernetics as the science of systems and system interactions lies in the possibility of creating general models of functional objects [11]. In the case of realization of such an approach, replacement of a process mechanism with another process mechanism will not lead to changes in the functional system structure.

On the other hand, cybernetic structure of the functional system must ensure fulfillment of all necessary technological and control functions [12]. A resulting product with required quantitative and qualitative parameters should be obtained at the output of such a structure with maximum resource usage efficiency. In turn, this means that the system being synthesized must have maximum possible number of degrees of freedom.

At the same time, processes of resource-intensive systems need to be optimized first of all [13]. However, technological objects of such systems do not undergo a procedure of optimization at the design stage but only that of cost minimization. Process mechanisms of product conversion in such structures are in a close interconnection. Such production strings have relations and parameters necessary for production of products with required qualitative [14] and qualitative indicators [15]. However, the degrees of control freedom are lost [16].

This is explained by the fact that local extremes of the systems included in such synthesized structure can coincide only by chance and maximum efficiency of resource usage in such production is unattainable in principle [17].

Efficiency of such production structures is improved not by optimizing control processes but by creating and introduction of new technologies [18]. In cases where limited control capabilities are still being realized, mechanisms of not optimal but extreme control are embedded [19].

In some cases, the topic of structural optimization degenerates into a task of technological consistency of production mechanisms [20] and does not provide for solving the optimization problem [21].

Researchers try to solve optimization problems by creating new data processing technologies [22], for example, by integration of neural nets into the system structure [23]. However, the neural net must undergo a training procedure in order to distinguish one effective solution from another, more or less effective solution.

Studies show that the level of demand for products has a decisive impact on efficiency of the production structure functioning [24]. If demand exceeds supply, the production system should operate at maximum efficiency. If demand is significantly below the level achievable in the mode of maximum efficiency, transition to a mode of maximum value added is necessary [25]. To stand demand instability, buffering systems are created, however, principles of their functioning are considered in no connection with the processes of production systems [26] and are not related to the technologies of business analysis [27].

Thus, the problem on synthesizing the functional systems that ensure production of quality products with the required quantitative parameters at maximum efficiency and at varying demand level has not been resolved so far.

3. The aim and objectives of the study

The study objective was to synthesize a cybernetic structure of a functional system with a portioned supply of process products.

This should enable development of a unified architecture for controlled systems of a conversion class with portioned supply of process products.

To achieve the study objective, the following tasks were solved:

– to substantiate the need to use system structures in production tasks;

– to synthesize a system object that ensures production of the end products with required qualitative and quantitative parameters;

– to synthesize a structure of identification of the range of effective controls;

– to create a structure of matching the mechanism of conversion class and the buffering mechanism.

4. Synthesis of a structure of a functional system of conversion class with a portioned supply of process products

4. 1. Substantiation of the need to use a systems approach in problems of synthesis of production structures

Production problems for any enterprise are solved in the course of performing necessary production operations (PO). Effectiveness of these production operations depends on control quality and presence of restrictions of various kinds imposed on the control process.

In order to evaluate PO effectiveness, it is necessary to build its target model, i.e. such a model that a certain judgment can be made concerning effectiveness of the formed operations proceeding from its study results.

For example, a cybernetic single-product model of the process mechanism can be represented as shown in Fig. 1.

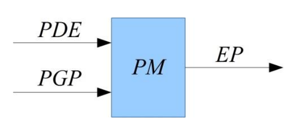

Fig. 1. The single-product model of the process mechanism

Here, inlet of the process mechanism (PM) receives a single product of directional effect (PDE) and a power generating product (PGP). End product (EP) is formed at the PM exit.

Since the level of PM wear changes as intensity of the PGP supply changes, the PO model must take into account state of the PM itself as one of the initial products of the operation. It is conditionally can be assumed that PDE, PGP and PM itself as a technical product (TP) are supplied to the PS inlet. An end product and a somewhat depreciated technical product are obtained at its exit upon completion of the operation (Fig. 2) [28].

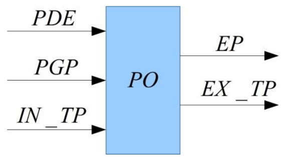

Fig. 2. Cybernetic model of the process step

Difference between the state of equipment at the inlet to and exit from the operation is determined by the concept of "wear". Therefore, it can be assumed that PDE, PGP and the equipment life in a form of its wear are necessary for executing the PO (Fig. 3) [29].

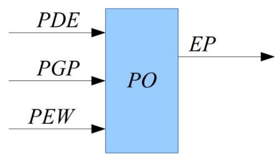

Fig. 3. Simplified cybernetic model of the process operation: PEW: process equipment wear

The quantitative parameters characterizing movement of the operation products can be represented as recording signals, $rq_D(t)$, $rq_P(t)$, $rq_W(t)$ $pq(t)$. Here, $rq_D(t)$ is the PDE motion recording signal, $rq_P(t)$ is the PGP motion recording signal, $rq_W(t)$ is the signal of equipment wear recording, $pq(t)$ is the signal of the operation end product motion recording.

In order to compare operation parameters obtained at different levels of productivity, it is necessary to represent the recording signals in the form of their integral values. Then

$$RQ_D=\int_{t_S}^{t_F} rq_D(t)\mathrm{d}t;\quad RQ_P=\int_{t_S}^{t_F} rq_P(t)\mathrm{d}t;$$

$$RQ_W=\int_{t_S}^{t_F} rq_W(t)\mathrm{d}t;\quad PQ=\int_{t_S}^{t_F} pq(t)\mathrm{d}t,$$

where RQ_D is the amount of PDE supply; RQ_P is the volume of PGP supply; RQ_W is the level of equipment wear; PQ is the volume of the end product of PO; t_S is the moment of PO start; t_F is the moment of PO completion.

Studies have established [30] that an increase in productivity usually results in a decrease in the amount of energy consumption and an increase in the level of the TM wear (Fig. 4).

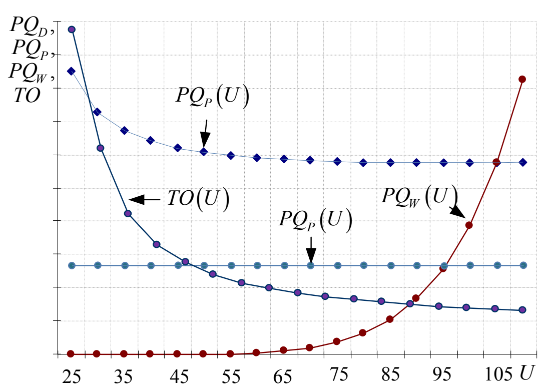

Fig. 4. Dependence of parameters of a process operation on control: control (U); power consumption (PQ_P); a product of direct effect (PQ_D); wear (PQ_W); time of the process operation (PO)

A monotonically increasing function of wear change depending on control is characteristic for the case when the process physics does not change [31]. Otherwise, the wear function may have local extrema [32].

In order to form a judgment about efficiency of the operational process, losses associated with energy consumption and wear must be reduced to comparable cost values. In this case, volumes of initial and end products of the operation can be compared with each other.

Then

$$RE=RQ_D\cdot RS_D+RQ_P\cdot RS_P+RQ_W\cdot RS_W;$$

$$PE=PQ\cdot PS,$$

where RE is the cost estimate of the initial operation products; PE is cost estimate of the end operation products; RS_D is the cost estimate of a PDE unit; RS_P is the cost estimate of a PGP unit; RS_W is the cost estimate of a unit of equipment wear; PS is the cost estimate of a unit of the end product (Fig. 5).

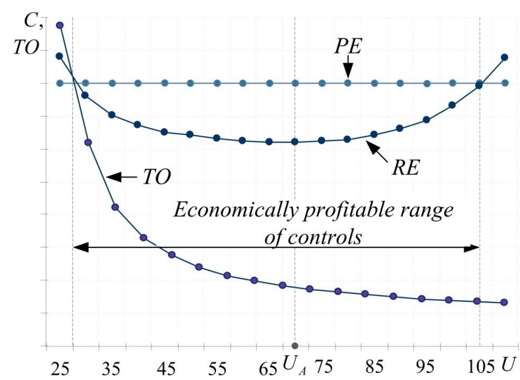

Fig. 5. Change of operation time (PO) and comparable parameters for input (RE) and output (PE) depending on control (U)

Thus, a properly designed process mechanism that performs a single technological function can function throughout entire economically profitable range of controls. In this range, cost estimate of the output products of the operation (PE) is greater than the cost estimate of the initial products of the operation (RE), that is, ($PE>RE$).

It is obvious that the most favorable mode of the process equipment operation is within this range. In particular, the U_A mode is available (Fig. 5) to which the minimum cost or maximum value added corresponds.

The situation changes if the production string is represented by several directly related process mechanisms of the same class.

Fig. 6 shows a model consisting of two consecutive single-product process mechanisms (Fig. 6).

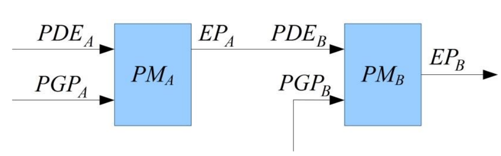

Fig. 6. The model of the production line in the form of two interconnected process mechanisms

Here, the end product of the TM_A is the initial product of the TM_B.

In such a situation, when output of the previous conversion PM is directly connected to the input of the subsequent PM, it is necessary to control supply of the power generating products PGP_A and PGP_B in such a way that productivity of the mechanisms PM_A and PM_B is coordinated.

Each PM has its own characteristics of initial and end products the extremes of which do not coincide in the general case (Fig. 7).

Since a change in productivity of one mechanism leads to the need for a corresponding change in productivity of another mechanism, the above characteristic of consumption of input products of the production process PM_A and PM_B must be considered as a single whole (Fig. 8).

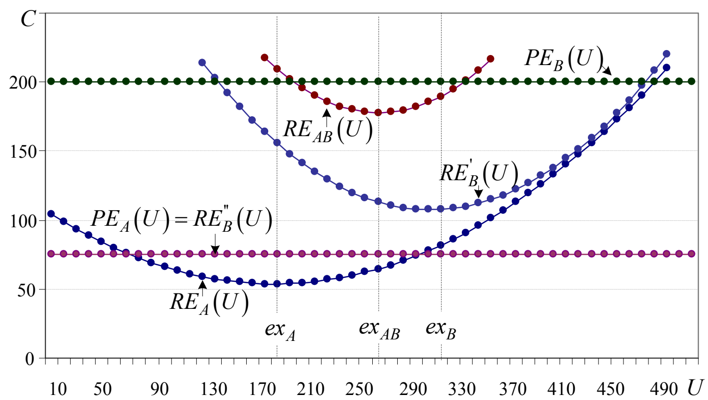

Fig. 7. Dependence of individual and joint characteristics of change of comparable products of operations on control

As can be seen (Fig. 7), the minimum cost of the generalized PO_{AB} operation does not coincide with the minimum cost of both the PO_A operation and the PO_B operation.

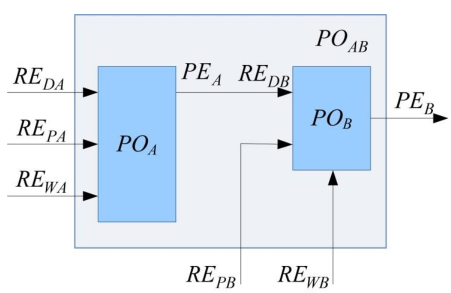

Fig. 8. Structure for building a generalized model of the process operation

If one realizes the possibility of independent functioning of the PM_A and PM_B mechanisms, then in the minimum cost mode (ex_A and ex_B modes) one could get value added $DE_A=PE_A-RE_A$=21.24 mon. units and $DE_B=$ $=PE_B-(RE'_{DB}+RE'_{PB})$= 22.08 mon. units for the PM_B process.

The total value added ($DE_{(A+B)}$) will amount $DE_{(A+B)}=$ $=DE_A+DE_B$=38.72 mon. units.

In the mode of coordinated productivity of PM_A and PM_B, value added PM_{AB} will amount $DE_{AB}=PE_B-(RE_A+$ $+RE'_{PB})$=22.08 mon. units.

That is, the loss in value added for connected mechanisms is 57 % for the case in Fig. 7.

Thus, the possibility of maximizing the obtained positive effect is higher if the PMs of conversion class are not directly interconnected but are part of independently functioning systems. This is possible if systems of conversion class interact with buffering systems (Fig. 9) [33].

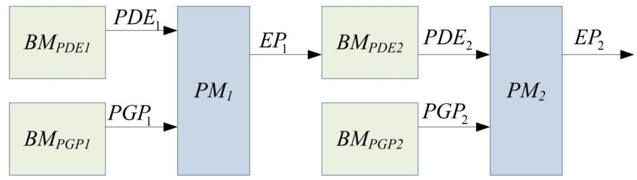

Fig. 9. Structure of a production line with additional buffering mechanisms

In this case, the mode of operation of the PM_1 in the presence of its own controls does not depend on the mode of operation of the PM_2.

End product should be formed at the exit of the functional system with both required qualitative and quantitative parameters. Therefore, composition of the synthesized complete system should include both PM transformations and PM buffering.

4. 2. Synthesis of a complete functional system structure

The process of synthesis of a functional system consists in a successive building-up of the object functional capability until all functions necessary for implementing system operations are fulfilled.

At the first stage of synthesis, system structure was formed which enables formation of an end product with required qualitative and quantitative parameters in the process of interaction with similar system structures.

The synthesis process is based on the use of simple functional mechanisms in the developed architecture. In such a case, an operable structure will reflect internal structure of the functional system.

A process of heating a liquid and its buffering was considered as a main technological process.

The synthesized structure that realizes the process of interaction between the PM of heating a liquid and its buffering is shown in Fig. 10.

The main technological part of the functional system consists of a heating mechanism (HM), a buffering mechanism (BM), and service mechanisms for delivery of main (SM_1) and end (SM_2) products.

In turn, the heating mechanism consists of a heater buffering mechanism (HBM), a heater (H), and a temperature sensor (D_2).

To ensure the system operation, the following signals are injected to its inputs: a signal for setting low level of reserves (u_{ZL}); a signal for setting high level of reserves (u_{ZH}); signal for setting volume of cold liquid supply (u_{ZD}); a signal of intensity of the power generating product supply (u_{ZP}); temperature of the liquid heating (u_T).

The synthesized structure works as follows.

In the initial state, low-level signals are set at outputs of the mechanisms of comparison MC_2 and MC_3. Accordingly, a low level signal is set at the input and output of memory location ML and, therefore, at the inputs of the coordination mechanism CM_3 and the NOT element.

A signal of high level is set at the output of the NOT element.

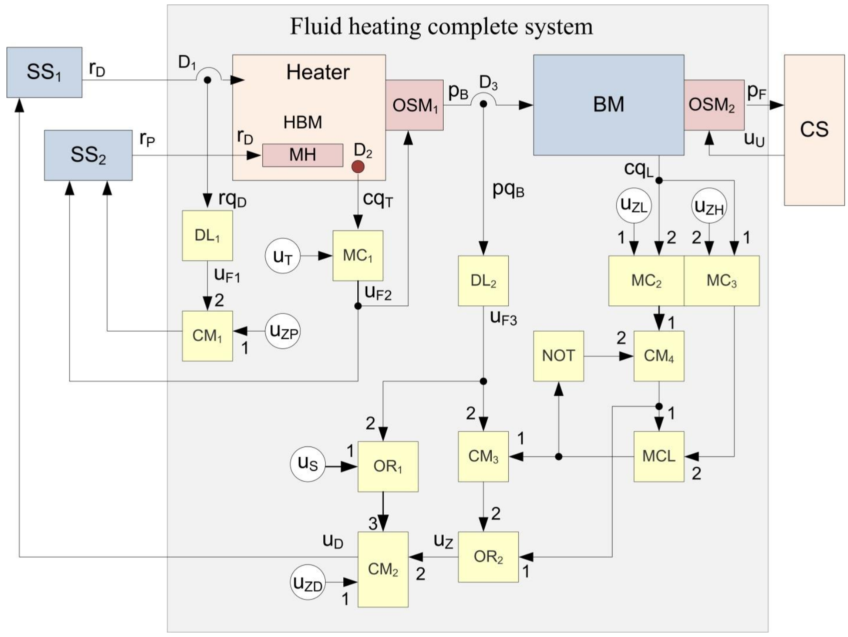

Fig. 10. The model of a complete system providing an end product in a mode of interaction with counterpart systems: SS1— supply system of the product with a targeted effect; SS2 — Energy product supply system; CS — consumption system; MC — mechanism of comparison; DL — differentiating link; CM — coordination mechanism; MCL — memory cell; OSM — sutput service mechanism; HBM — heater buffering mechanism; HM — heating mechanism; BM — buffering mechanism

To begin automatic operation, a single high-level pulse signal is sent to the first input of the OR_1 element. From the OR_1 output, this signal comes to the input 3 of the coordination mechanism CM_2.

The coordination mechanisms CM_1–CM_4 memorize parameters of the signals coming to their inputs. If a signal of a non-zero level is set at one information input of the CM and high-level signals are set on the other inputs of transmit permission, the information signal is transmitted to the CM output and the transmit permission signals are zeroed.

A signal proportional to the current level of the heated liquid comes from the output of the D_2 sensor of the buffering mechanism to the second input of the comparison mechanism MC_2 and the first input of the comparison mechanism MC_3.

If the current level of reserves of the BM is less than the low level, a single high-level pulse signal is formed at the output of the MC_2.

Since a high level signal is set at the NOT element output (at the second input of CM_4). Therefore, a high-level pulse signal is transmitted from the output of MC2 through the coordination mechanism CM_4 to the first recording input of the ML memory cell and to the first input of the OR element. The ML output (inputs of CM_3 and the NOT element), high level signals are set.

A high-level pulse signal arrives from the output of the OR element to the second input of the coordination mechanism CM_2.

Since the high-level signal is set at the third input of the CM_2, the u_{ZD} task signal enters from the CM_2 output to the input of the cold liquid supply system.

Cold liquid r_D in a volume u_{ZD} enters the heater buffering mechanism. A signal proportional to the intensity of liquid flow, $rq_D(t)$, is fed from the output of D_1sensor to the input of the differentiating link DL_1.

At the time of stopping the liquid flow, a pulse signal of a single high level is generated at the DL_1 output and sent to the second input of permission of CM_1.

Since the first information input of CM_1 receives a signal of power generating product supply intensity u_{ZP}, a pulse signal of value u_{ZP} arrives at the input of the power generating product supply system at the moment of arrival of the permission signal.

From this point in time, the power generating product r_P begins to arrive to the input of the heating mechanism HM of the heater and the liquid starts to heat up.

Sensor D_2 transmits current value of the heating temperature to the input of the comparison mechanism MC_1 where it is compared with the reference signal u_T.

As soon as these signals get equal in value, a single pulse signal is generated at the MC_1 output. This signal is fed to the input of the mechanism of cutting supply of the power generating product of the PGPSS and to the input of the service mechanism for delivery of the main product SM_1.

The SM_1 service mechanism of delivery transfers the heated liquid to the buffering mechanism BM.

Sensor D_3 records flow of the transferred heated liquid and transmits it to the input of the differentiating link DL_2 as a record signal $pq_B(t)$.

On the one hand, the output signal of DL_2 passes through the OR element and activates input 3 of CM_2, and on the other hand, activates input 2 of CM_3.

Since the input 1 of the CM_3 is already active, a pulse signal from the CM_3 output is fed through the OR element and CM_2 to the input of the cold liquid supply system and the process is repeated.

As soon as the liquid level in the buffering mechanism reaches the upper level u_{ZH}, a high-level signal is generated at the output of the comparison mechanism MC_3 which zeroes the ML cell. As a result, low level of the output signal of the ML blocks passage of signals through the CM_3.

On the other hand, a high level is established at the second permitting input of CM_4.

As replenishment of BM reserves stops, the level of heated liquid decreases and at a certain point in time reaches a lower level.

At the output of the MC_2, a high-level pulse signal is generated and the process begins anew.

Fig. 11 shows timing diagrams of functioning of the synthesized structure in the EFFLI modeling environment [30].

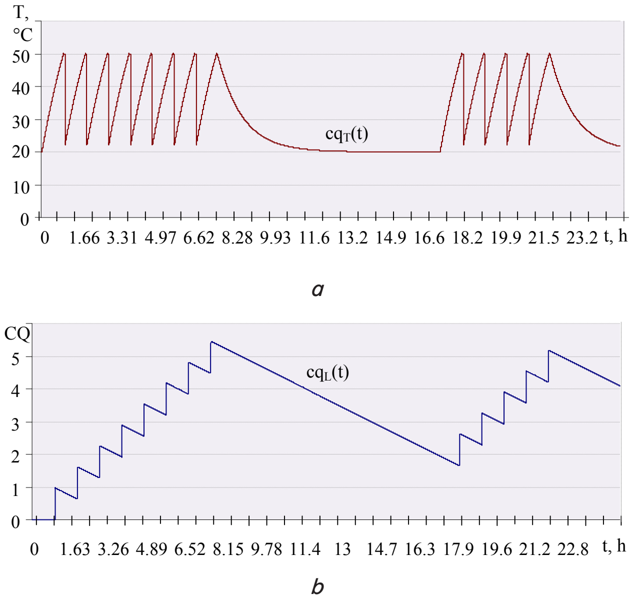

Fig. 11. Timing diagrams of the synthesized system: heating diagram (*a*); reserve change diagram (*b*)

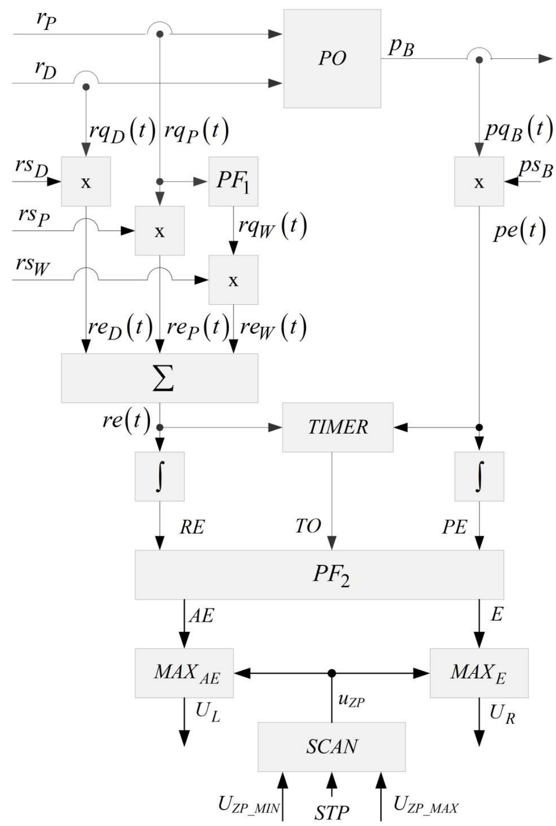

Fig. 12. The module of identification of the range of admissible controls

4. 3. Synthesis of a structure of identification of the range of effective controls

Structure of the module for identification of the range of effective controls was developed at the next stage of synthesis (Fig. 12).

To this end, wear of the heating mechanism was determined as a function of the energy flow [34]. For this purpose, a functional transducer FP_1 was introduced into the structure. A wear signal of recording wear flow, $rq_W(t)$, is generated at its output.

Cost estimate of input (*RE*) and output (*PE*) operation products is determined from expressions

$$RE = \int_{t_S}^{t_F} \left(\sum \left[rq_D(t) \cdot rs_D + rq_P(t) \cdot rs_P + rq_W(t) \cdot rs_W \right] \right) \mathrm{d}t;$$

$$PE = \int_{t_S}^{t_F} \left(\sum \left[pq_B(t) \cdot ps_B \right] \right) \mathrm{d}t.$$

Time of operation PO is determined with the help of a timer.

The signals *RE*, *PE* and *PO* come to the input of the functional converter FP_2. In the framework of FP_2, value added, AO, and efficiency of resource usage, E, are determined using the structures realizing computational operations from expressions $AE=PE-RE$ и $E=(PE-RE)^2/(RE \cdot PE \cdot TO^2)$.

The SCAN module provides enumeration of admissible controls. For this purpose, its inputs are supplied with a minimum control value $U_{ZP\neg MIN}$, maximum control value $U_{ZP\neg MAX}$ and a control change step.

A control value and a corresponding value added AE are fed to the MAX_{AE} module input. Control U_L to which maximum value added corresponds is extracted at the output.

On the other side, control value and corresponding value of efficiency, E, arrive to the input of the MAX_E module. At the output, U_R control is formed to which maximum value of resource usage efficiency corresponds (Fig. 13) [35].

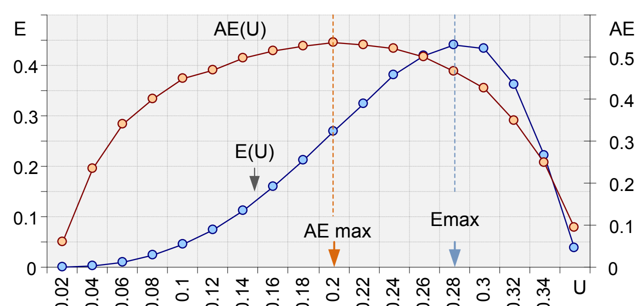

Fig. 13. Determining the range of effective controls

The estimation indicator which passed the verification procedure for the possibility of its use as an efficiency formula was used as an indicator of efficiency [36–40].

4. 4. Development of a structure of matching the conversion class mechanism and the buffering mechanism

At the final stage of synthesis, a module was developed for matching the level of demand with the control of the conversion process (Fig. 14).

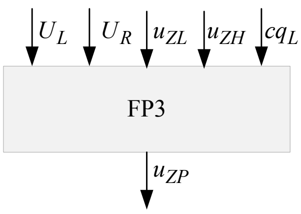

Fig. 14. The model of matching control of the conversion process with the level of demand

The module input receives boundary values of the U_L and U_R controls, minimum (u_{ZL}), maximum (u_{ZH}) and current (cq_L) resource levels of the buffering mechanism.

At the output of the module, a signal is generated to control intensity of the power generating product supply in accordance with the expression in [41]

$$u_{ZP} = \frac{U_R(u_{ZH} - u_{ZL}) + (U_L - U_R)(cq_L - u_{ZL})}{u_{ZH} - u_{ZL}}.$$

Fig. 15 shows diagrams of control change depending on the resource level in the buffering mechanism.

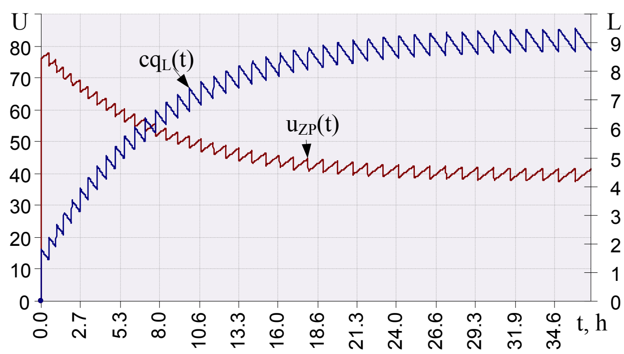

Fig. 15. Diagrams of control change (u_{ZP}) depending on the level of resources (cq_L) in the buffering mechanism

It can be seen that control reduces productivity of the conversion part of the system with an increase in the reserves level.

In turn, a decrease in reserves levels leads results in an increase in productivity of the conversion mechanism.

Thus, the synthesized system provides the possibility of obtaining end products with required qualitative parameters at the output of the buffering mechanism in the process of interaction with the external systems.

Within the system, transformation operations are identified using indicators such as value added and resource usage efficiency.

Control of the conversion process is changed in such a way that when the buffering mechanism reaches its lowest level of resources, the conversion process operates in the mode of maximum productivity and efficiency. This accelerates exit from the zone of possible commodity deficiency.

As reserves levels increase, productivity of the conversion processes drops to the limit of maximum value added (minimum cost).

Replacement of the process mechanism with any other one-product process mechanism with portioned PDE supply does not change structure of the synthesized system.

Working model of the synthesized system is considered in [42].

Since the model was implemented in Visual Basic for Applications environment, macros use should be allowed.

The system is started by pressing the Start button in the Display page. By changing the level of demand in D3 cell of the mGstA page from 0.001 to 0.002, one can observe an automatic change in control depending on a change in the source level in the mAdpA_R page upon completion of the work.

5. Discussion of results obtained in synthesis of structure of a complete functional system

Internal structure of a complete functional system was synthesized in this study. Interaction of the intrasystem conversion processes with the buffering process and the system environment was enabled in the course of fulfillment of this system process function. Due to this interaction, it is possible to obtain necessary degrees of control freedom.

On the example of the heating process, studies were carried out for a class of systems with a portioned supply of the input process products. Thus, the class of systems with continuous supply of products of directional effect was not considered. For the same reason, stability related issues have not been studied since stability issues do not arise in the systems of this class.

Parameters of the heating system were determined in such a way that the region of admissible controls covered the entire range of profitable controls. In turn, parameters of the buffering system were chosen so that there was no shortage of end products in conditions of maximum demand.

In conditions of modernization of existing technological systems, this possibility cannot always be realized. Thus, the extremum of minimum costs and/or maximum efficiency may appear outside the scope of available controls. Actual parameters of the buffering mechanism may also introduce correction.

Thus, the proposed approach can be fully used in the case when the design parameters of the entire technological part are selected for a certain level of demand (certain productivity). In this case, minimum costs and maximum efficiency should fall within the scope of admissible controls.

The question of choice of equipment parameters was not considered in the study.

It should also be noted that the proposed approach to synthesis of autonomously controlled single-function systems will be justified where technological processes are energy-intensive or, in general, resource-intensive. Otherwise, an attempt to perform each technological function using a separate functional system will lead to a significant increase in the size of equipment and its excessive cost rise.

9. Conclusions

1. It has been established that the direct functional relation between process mechanisms narrows the range of effective controls and, accordingly, reduces efficiency of resource usage.

2. Architecture of a complete system responsible for qualitative and quantitative parameters of the end products in the process of interaction with the systems providing resources and consuming end products was synthesized.

3. A module for identifying the range of effective controls has been synthesized. Its use makes it possible to define the left and right boundaries of the range of admissible controls. The left boundary of the range of permissible controls corresponds to the maximum value added and the right one to the maximum value of resource usage efficiency.

4. A structure of complete functional system with a portioned supply of process products was synthesized. Control of the conversion process of such a system is a function of the resource level in the buffering mechanism. The rate of change of control in the system depends on the change of the level of demand for end products.

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