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IDENTIFICATION OF TARGET SYSTEM OPERATIONS. THE PRACTICE OF DETERMINING THE OPTIMAL CONTROL

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Розробка критерію ефективності використання ресурсів дозволяє ідентифікувати об'єкт дослідження і визначити найефективнішу цільову операцію. У роботі пошук оптимуму здійснюється на конкретному прикладі – технологічної операції порційного нагріву рідини. Наведено методику визначення величини зносу механізму для нагріву рідини. Показано, як змінюється положення оптимуму управління при зміні вартісної оцінки одного з вхідних продуктів

Ключові слова: оптимальне управління, сигнатура мети, цільова операція, ефективність, ефективність використання ресурсів

Разработка критерия эффективности использования ресурсов позволяет идентифицировать объект исследования и определить самую эффективную целевую операцию. В работе поиск оптимума осуществляется на конкретном примере – технологической операции порционного нагрева жидкости. Приведена методика определения величины износа механизма для нагрева жидкости. Показано, как изменяется положение оптимума управления при изменении стоимостной оценки одного из входных продуктов

Ключевые слова: оптимальное управление, сигнатура цели, целевая операция, эффективность, эффективность использования ресурсов

1. Introduction

Improvement of the competitiveness of an enterprise largely depends upon the efficiency of its current performance. The maximum capacity can be achieved only if the operation objectives of all the plant systems are coordinated and the processes in these systems are based on the common criterion of optimization.

The designed model of an extended target operation [1] allowed working out the common criterion for the resource efficiency [2]. However, the technology of its practical application involves a number of issues that require detailed explanations. The problems include design of the architecture of a controlled system [3] and estimation of the cost of technology products, particularly the depreciation of the working mechanism that performs the basic function in the system under research.

The object of study is the process of heating a portion of liquid. The choice is due to the inertia of the object (which is important for the required precise measurements), a sufficient number of the degrees of freedom necessary for optimal control, the dependence of product quality upon the time of operation, and an available analytical determining of the wear-out rate for the heating mechanism.

2. Analysis of the scientific references and formulation of the problem

The overall trend of the system engineering is viewing the controlled systems as objects, the technological processes in which are subject to optimization [4].

The practical use of the principles of optimal control is hampered by ambiguity that results from the substitution of notions, when the search for the extrema is defined as the optimum search.

At the same time there exist five main variants. Selection of control is based on the following factors: (1) the search for the extrema of a technical parameter [5], (2) the economic indices (of profit, cost, and efficiency), (3) a synthetic index that combines economic and technical parameters of a multi-criteria optimization [6], and (4) minimization of the time of operation [7] or maximization of the efficiency [8].

It is generally known that the better of two controls is that which is more effective. That is, the optimal, by definition, is a control that provides the highest efficiency of the process within the constraints.

It is also common knowledge that a technological operation is secured by conversion products, energy products, and technical products (equipment). The output of a manufacturing operation is a formed consumer (output) product. The operating machinery wears out, which leads to the consumption of the technical product as a wear.

Quantifying the volume of each input and output product of the operation and further expert evaluation of the products and the time of the operation allow proceeding to a model that is defined as the model of a target operation (Fig. 1).

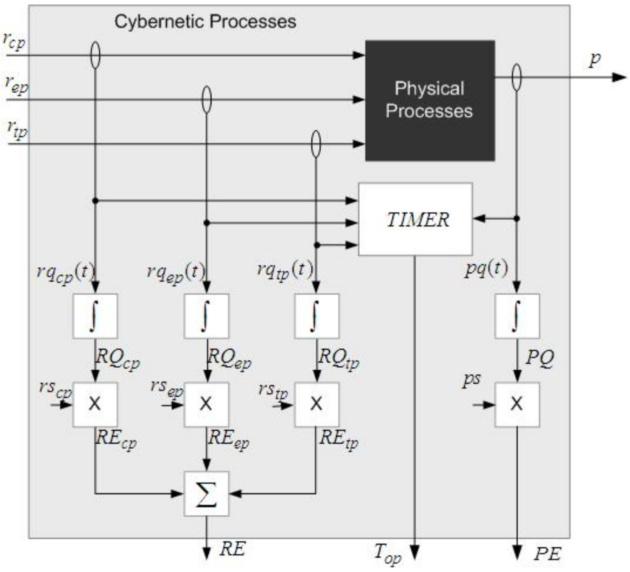

Fig. 1. Formation of the basic indices of a simple target operation

Here, r_{rp}, r_{ep}, and r_{tp} are input (raw, energy, and technical (wear)) products, p designates output products, $rq_{rp}(t)$, $rq_{ep}(t)$, and $rq_{tp}(t)$ are registration signals for a quantitative parameter of input (raw, energy, and technical) products, $pq(t)$ is a registration signal for a quantitative parameter of the output product, rs_{rp}, rs_{ep}, and rs_{tp} designate the valuation of units of (raw, energy, and technical) products, ps is the valuation of a unit of the output product, RQ_{rp}, RQ_{ep}, and RQ_{tp} designate the consumed volumes of input (raw, energy, and technical) products, PQ is the volume of the output product, RE_{rp}, RE_{ep}, and RE_{tp} designate the cost of input (raw, energy, and technical) products, PE is the cost of the output product, RE is the total cost of the input products, and T_{op} is the time of the operation.

A target operation can be displayed as a vector (Fig. 2).

In economic systems, expert assessment is replaced by the valuation.

Consider the assessment of the operational efficiency if only one parameter of a target operation varies. Fig. 3 presents two target operations with equally valuated input and output products but different operation time.

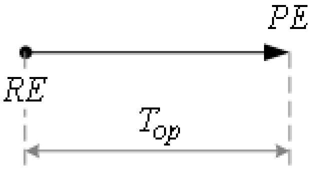

Fig. 2. A vector image of a target operation

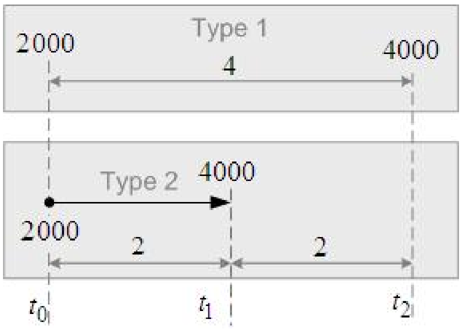

Fig. 3. Target operations of various duration

Since the added value of the operations is the same, the second operation is more efficient because the time $T_{op} = 4$ is sufficient to carry out two second-type operations and get an added value of 4000 monetary units, whereas the first operation allows an added value of 2000 monetary units.

Fig. 4 shows target operations with different valuations of the input products.

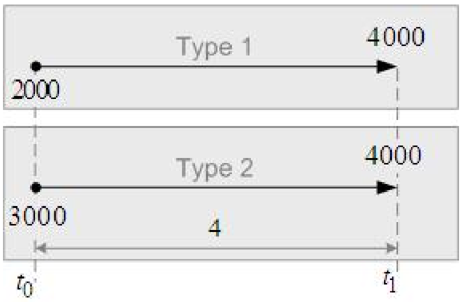

Fig. 4. Target operations with different valuations of the input products

In this case, the first-type operation is more efficient, because its implementation requires input products with a lower expert assessment.

The third variant (Fig. 5) shows a situation when comparable operations differ in the valuation of the output products.

It is obvious that the second-type operation is more efficient than the first one.

Thus, it is evident that the efficiency of an operation depends on all the three parameters.

As can be seen from the variant (Fig. 3), in general, the economic parameters such as cost (RE) [9], profit or added value (PE − RE), as well as profitability $\left[(\mathrm{PE}-\mathrm{RE})/\mathrm{RE}\right]$ do not comprehensively assess the efficiency of the operation under research, since these expressions at least do not engage all the basic parameters of a target operation.

The same is true for attempts to assess the efficiency on the basis of either time parameter or performance.

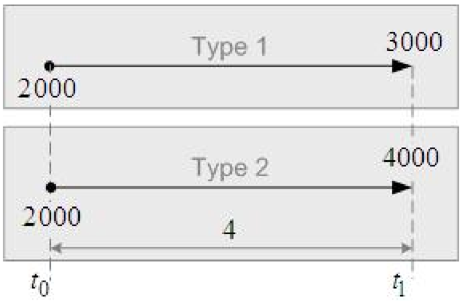

Fig. 5. Target operations with different valuations of output products

The previous study [2] presents a devised index of the resource efficiency, which is supported by the basic indices of a target operation.

This study, being logical continuation of the former, presents the practical use of the devised criterion for the optimal control that would provide the most efficient target operation.

The problem is that the existing classic methods do not meet the peculiarities of the technological operations whose output quality depends on the operation time.

In addition, comprehensive optimization can be achieved only if the process under research deals with a single technological operation, and the choice of an adequate criterion for optimization does not automatically result in reliable findings without a full consideration of all the relevant factors.

3. The purpose and objectives of the study

The study aims at revealing the dependence of the factors that affect optimization of a liquid heating system, in which the liquid is supplied in portions, on the system control.

The goal can be achieved via solution of the following tasks:

(1) measuring the dependence of the heating mechanism wear on the operation management;

(2) quantifying the integral parameters of the input and the output products in the system of batch liquid heating at comparable cost values;

(3) determining the target operation efficiency on the basis of the target signature and the operation control;

(4) assessing the response of the criterion to a change in the output valuation;

(5) interpreting the findings.

4. Studying the technological operation of a liquid portion heating as an example of determining the basic parameters for a simple targeted operation

Any operation is implemented only if the valuation/expert assessment of its output products exceeds the valuation/expert assessment of its input products. These cybernetic parameters would be determined due to the designed model of a target operation. The output product of a target operation is the added value of the operation under research.

Valuation of the input products, the output products and the operation time of a target operation form the target signature.

The process of electric liquid heating serves an example that discloses the structure of a target operation model. The choice is predetermined by the fact that the heating process is well known and relatively simple to implement. In addition, an important factor is that the value of the electric heater depreciation can be described by means of an analytical expression [10].

The object of study is the process of batch liquid heating, which is predetermined by the fact that a batch heating system has the maximum number of degrees of freedom (in comparison to continuous heating where any change in the rate of a liquid flow is rigidly connected with a specific rate of the energy supply). Parametric optimization in such “connected” systems is impossible.

In the heating operation, cold liquid is a raw product, consumed electricity is an energy product, and an electric heater wear is a technical input product. On the other hand, the heated liquid is the output product.

The research started with assembling a plastic container with a working capacity of 3 liters. 4-cm thick foam was placed between the double walls of the container and its lid to reduce the heat loss. An incandescent bulb with a power of 200 W was used as an electric heater. The socket of the bulb had been isolated in a special way to allow its dive to the bottom of the container. The initial temperature of heating was 20 °C, while the final heating temperature comprised 60 °C.

The power of the electric heater (control) varied from operation to operation in the range of 40 W to 340 W due to changing the rate of the supplied voltage U, in increments of 20 W. As a result, we have obtained the heating time for each type of control (T_{op}) (Fig. 6).

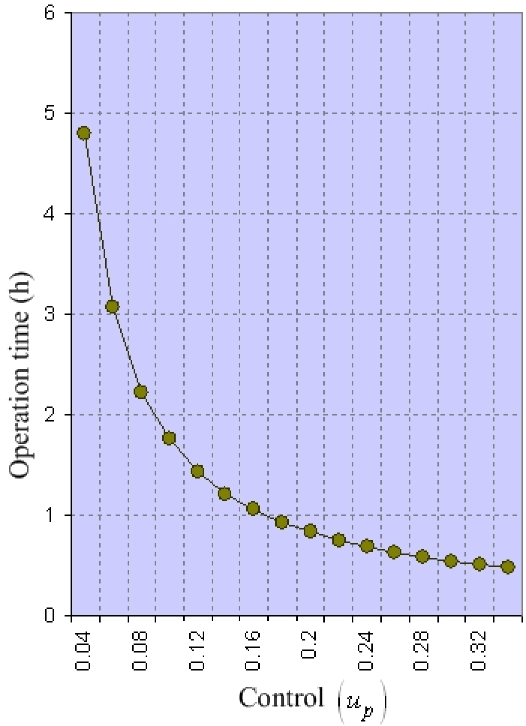

Fig. 6. Change in the operation time according to the heating control

In the course of the experiments, we obtained the following data (Table 1) and design parameters (Table 2) for each heating operation.

Table 1

The operation parameters, their units of measurement and symbols

N	Parameters of the operation	Units of measurement	Symbols
1	The volume of liquid to be heated	m^3	RQ_{cw}
2	Supplied power	kW	rq_{kW}
3	Set voltage	U	U
4	Time of the operation	h	T_{op}
5	The heater capacity at nominal operation	h	T_n
6	The index of the varying average life of an incandescent lamp	–	α
7	The cost of a cubic meter of water	USD	rs_{cw}
8	The cost of a kilowatt hour of electricity	USD	rs_{kWh}
9	The cost of an electric heater	USD	rs_{wt}

Table 2

The experiments' findings and the calculated parameters

N	kW	U	m^3	T_{op}	T_n	α	rs_{kWh}	rs_{cw}	rs_{wt}
1	0.04	98.4	0.003	4.8	1000	14	0.07	0.00015	0.3
2	0.06	120.5	0.003	3.06	1000	14	0.07	0.00015	0.3
3	0.08	139	0.003	2.22	1000	14	0.07	0.00015	0.3
4	0.1	155.6	0.003	1.75	1000	14	0.07	0.00015	0.3
5	0.12	170	0.003	1.43	1000	14	0.07	0.00015	0.3
6	0.14	184	0.003	1.21	1000	14	0.07	0.00015	0.3
7	0.16	196.8	0.003	1.05	1000	14	0.07	0.00015	0.3
8	0.18	208.7	0.003	0.925	1000	14	0.07	0.00015	0.3
9	0.2	220	0.003	0.83	1000	14	0.07	0.00015	0.3
10	0.22	230.7	0.003	0.75	1000	14	0.07	0.00015	0.3
11	0.24	241	0.003	0.685	1000	14	0.07	0.00015	0.3
12	0.26	250.8	0.003	0.63	1000	14	0.07	0.00015	0.3
13	0.28	260	0.003	0.58	1000	14	0.07	0.00015	0.3
14	0.3	269	0.003	0.54	1000	14	0.07	0.00015	0.3
15	0.32	278.3	0.003	0.5	1000	14	0.07	0.00015	0.3
16	0.34	286.8	0.003	0.47	1000	14	0.07	0.00015	0.3

Methods of determining the parameters RE and PE of a simple target operation for heating cold water are illustrated by the example with a power supply of 0.26 kW. The calculations were made with an accuracy of up to 5 significant digits. The cost indices were given in the US dollar equivalents.

(1) The amount of power consumed during the heating operation RQ_{kWh} is calculated as follows:

$$RQ_{kWh} = rq_{kW} \cdot T_{op} = 0.26 \times 0.63 = 0.1638, \text{kWh}.$$

(2) The cost of electricity consumed during the operation is calculated as follows:

$$RE_{kWh} = RQ_{kW} \cdot rs_{kWh} = 0.1638 \times 0.07 = 0.01147, \text{USD}.$$

The value of the electric heater depreciation during the technological operation is determined by means of the expression $T = T_n k_u^{-\alpha}$ [11], where T designates the life of the electric heater, T_n is the number of the operation hours at the rated voltage, k_u is the ratio of the actual voltage to the nominal voltage, α is the index of the varying average life of an electric heater (for incandescent bulbs $\alpha = 14$).

(3) The life of the heater at the voltage supply of 250.8 U (0.26 kWh) is determined as follows:

$$T = T_n k_u^{-\alpha} = 1000 \cdot \left(\frac{250.8}{220}\right)^{-14} = 159.70999, \text{h}.$$

(4) The value of the electric heater depreciation during the operation is calculated as follows:

$$RQ_{cw} = T_{op} / T = 0.63 / 159.70999 = 0.00394.$$

(5) The cost of the consumed technical resource of the electric heater is calculated by means of the following expression:

$$RE_{wt} = RQ_{wt} \times rs_{wt} = 0.00394 \times 0.3 = 0.00118, \text{USD}.$$

(6) The cost of the cold water used in the heating operation is determined by means of the following expression:

$$RE_{cw} = RQ_{cw} \times rs_{cw} = 0.003 \times 0.05 = 0.00015, \text{USD}.$$

(7) The total valuation of the input products is determined as follows:

$$RE = RE_{cw} + RE_{kWh} + RE_{wt} = 0.01415, \text{USD}.$$

(8) The cost of the heated water is obtained from the following expression:

$$PE = PE_{hw} = PQ_{hw} \times ps_{hw} = 0.003 \times 7 = 0.018, \text{USD}.$$

The difference (AE), $AE = PE - RE$ determines the value of the desired product of the target operation, while the chain (RE, PE, T_{op}) denotes the target signature (characteristic).

The calculated valuations of the heating operations' products vary according to the control (kW). They are shown in Table 3.

Fig. 7 shows the charts of varying basic parameters that depend on the management (kW).

Table 3

Valuations of the heating operations' products according to the heating control (kW)

N	kW	T_{op}	RE_{kWh}	RE_{cw}	RE_{wt}	RE	PE
1	0.04	4.8	0.01344	0.0015	0	0.01494	0.018
2	0.06	3.06	0.01285	0.0015	0	0.01435	0.018
3	0.08	2.22	0.01243	0.0015	0	0.01393	0.018
4	0.1	1.75	0.01225	0.0015	0	0.01375	0.018
5	0.12	1.43	0.01201	0.0015	0.00001	0.01352	0.018
6	0.14	1.21	0.01186	0.0015	0.00003	0.01339	0.018
7	0.16	1.05	0.0118	0.0015	0.00007	0.01333	0.018
8	0.18	0.925	0.01165	0.0015	0.00013	0.01329	0.018
9	0.2	0.83	0.01162	0.0015	0.00025	0.01337	0.018
10	0.22	0.75	0.01155	0.0015	0.00044	0.01349	0.018
11	0.24	0.685	0.01151	0.0015	0.00074	0.01374	0.018
12	0.26	0.63	0.01147	0.0015	0.00118	0.01415	0.018
13	0.28	0.58	0.01137	0.0015	0.0018	0.01467	0.018
14	0.3	0.54	0.01134	0.0015	0.0027	0.01554	0.018
15	0.32	0.5	0.0112	0.0015	0.00403	0.01673	0.018
16	0.34	0.47	0.01119	0.0015	0.00577	0.01846	0.018

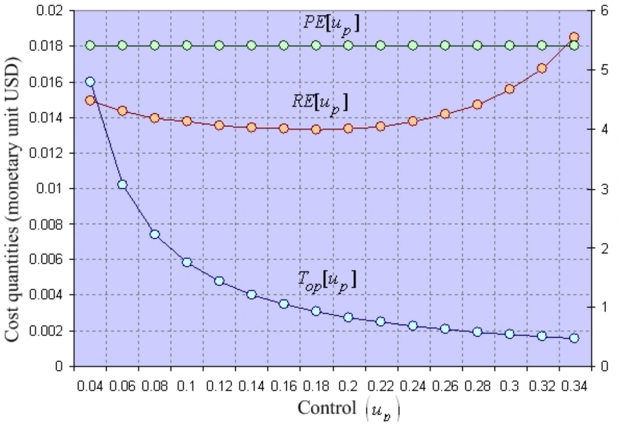

Fig. 7. Basic indices for the heating operation according to the heating control

As can be seen from Table 3, the value of depreciation has a significant impact on the variation of the control-dependent cost of the input products (Fig. 2). Accounting for depreciation in this case is a prerequisite for a reliable calculation of the total operation cost.

The study of the obtained dependences leads to some important conclusions. For example, it is clear that control $U_{kW} = 0.18$ corresponds to the minimum valuation of the input products in the heating operation. Transition to control $U_{kW} = 0.24$ increases the valuation of the input products by 0.3 % and reduces the operation time by 35 %. It is obvious that operation with control $U_{kW} = 0.24$ is more effective than the one with control $U_{kW} = 0.18$.

Answer to the question: "Which management of a number of available types is the most effective one?" requires quantifying the efficiency of the technological operations.

5. The criterion for the resource efficiency

The requirements to the optimization criterion allow answering the question of why such factors as cost (RE), added value (cost and profit), profitability $((PE-RE)/RE)$, or the operation time (T_{op}) cannot be taken as criteria for optimization. All these indices only partially take into account the parameters that are necessary for a target technological operation.

The index of the resource efficiency [2] is free from such disadvantages.

Simple target operations use the following expression to determine the criterion of the resource efficiency:

$$E = \frac{(PE-RE)^2 T_1^2}{PE \cdot RE \cdot T_{op}^2}, \quad PE > RE,$$

where E is the efficiency index.

The values of efficiency for each target signature of the heating operation are shown in Table 4.

Table 4

The resulting table with the calculated efficiency criterion for test operations

N	kW	T_{op}	RE	PE	E
1	0.04	4.8	0.01494	0.018	0.00994
2	0.06	3.06	0.01435	0.018	0.02886
3	0.08	2.22	0.01393	0.018	0.06149
4	0.1	1.75	0.01375	0.018	0.10384
5	0.12	1.43	0.01352	0.018	0.16537
6	0.14	1.21	0.013389	0.018	0.2394
7	0.16	1.05	0.01333	0.018	0.3231
8	0.18	0.925	0.01329	0.018	0.42056
9	0.2	0.83	0.01337	0.018	0.51131
10	0.22	0.75	0.01349	0.018	0.60695
11	0.24	0.685	0.01374	0.018	0.67952
12	0.26	0.63	0.01415	0.018	0.71994
13	0.28	0.58	0.01467	0.018	0.73453
14	0.3	0.54	0.01554	0.018	0.65716
15	0.32	0.5	0.01673	0.018	0.52644
16	0.34	0.47	0.01846	0.018	0.31372

The graphs (Fig. 8) show that the optimal control significantly deviates to the left relative to the minimum cost (Fig. 7).

In general, the efficiency extremum shift is affected by changes in the valuation of any of the input products.

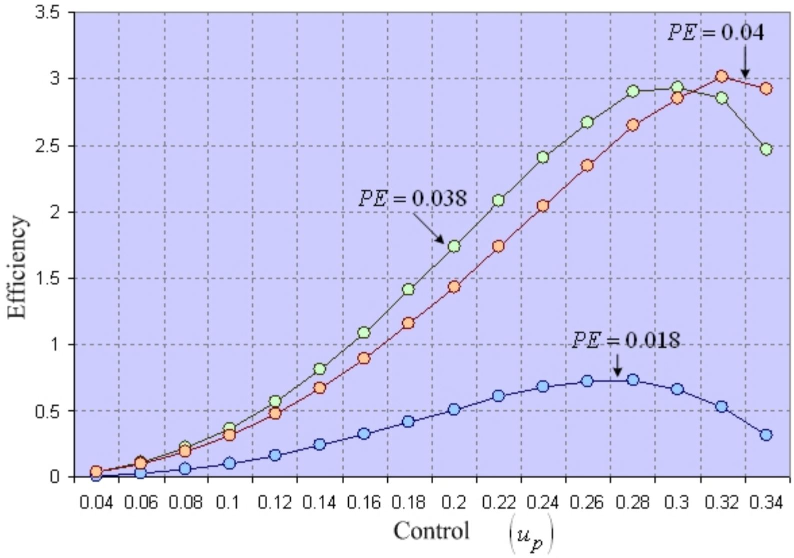

Fig. 8. Illustration of the efficiency extremum shift relative to the value of the heated liquid cost

6. Discussion of the research findings

The study uses an example of the target operations of batch liquid heating with an electric heater to solve the problem of determining the value of the criterion for the resource efficiency, devised in [2].

The study demonstrates the common for all target operations methods of determining the target signature – the ternary $\left(\mathrm{RE}, \mathrm{PE}, \mathrm{T}_{\mathrm{op}}\right)$. The obtained values of the target signature form the basis for determining the value of the efficiency criterion with the use of an expression for identifying simple target operations.

As can be seen from the findings (Fig. 2), each control has its own target signature $\left(\mathrm{RE}, \mathrm{PE}, \mathrm{T}_{\mathrm{op}}\right)$. Obvious and important is the fact that the time of the heating operation cannot remain a stable value while the control changes. This means that the operation efficiency cannot be assessed with the classic methods, such as dynamic programming and the Pontryagin maximum principle.

Formally, this is due to the fact that the initial and the final moments of time must be determined for the minimized or the maximized functional. In fact, it is impossible to assess the efficiency at a given time, since the intermediate products are not of comparable quality to that of the output products.

This does not happen, for example, in the operations of moving cargoes, which probably predetermines the choice of problems associated with the trajectories of movement as the objects of study. These problems illustrate the classic methods of determining the extrema of the selected criterion.

The analyzed integral-shaped functional does not have any fixed end of integration and is always determined within the interval from the beginning t_0 to the actual end of the studied operation t_a:

$$\mathrm{E} = \frac{\int_{t_a}^{t_d}\left(\int_{t_a}^{\tau}\left[\int_{t_0}^{v} \mathrm{pe}(s)ds + \int_{t_0}^{v} \mathrm{re}(s)ds\right]dv\right)d\tau}{\int_{t_0}^{t_a}\left[\int_{v_0}^{v}\left|\int_{v_0}^{v} \mathrm{re}(\nu)d\nu\right|dv - \int_{v_0}^{v}\left(\int_{v_0}^{v} \mathrm{pe}(\nu)d\nu\right)dv\right]dv}, \quad v \in [0,\ t_a],$$

where $\mathrm{re}(t)$ is the total registration signal for the input i (reduced to comparable cost values) products of the studied system

$$\mathrm{re}(t) = \sum_{i=1}^{I} \mathrm{rs}_i \int_0^t \mathrm{rq}_i(t)dt,$$

$\mathrm{rq}_i(t)$ is a registration signal showing the quantitative parameter of the i input product of the studied system, rs_i is valuation of the input product of the target operation, $\mathrm{pe}(t)$ is the total registration signal for reduced to comparable cost values j output products of the studied system

$$\mathrm{pe}(t) = \sum_{j=1}^{J} \mathrm{ps}_j \int_0^t \mathrm{pq}_j(t)dt,$$

$\mathrm{pq}_j(t)$ is a registration signal showing the quantitative parameter of the j output product of the studied system, and ps_j is valuation of a unit of j output product of the target operation.

As can be seen (Fig. 8), the criterion of the resource efficiency has its extrema that are sensitive to changes in the quantity and cost parameters of the system operation. Higher valuation of the output product, other conditions being equal, results in higher efficiency of the operation.

Naturally, the technical criteria do not pass the simple check for the adequacy of response.

Studies show that a necessary condition for determining the authenticity of the optimality criterion is the account of depreciation of the technological equipment in situations where its impact on the assessment of the efficiency is significant. That is, the question of whether to consider or ignore the equipment depreciation when searching for the optimum must be justified in each case.

The shift of the efficiency maximum to the right relative to the minimum cost and maximum profit can be justified on the basis of the charts interpretation (Fig. 7).

Transition from control 0.18 to control 0.2 leads to the increase of cost by 0.6 % and the decrease of operation time by 11.4 %. That is, the rate of profitability growth by far exceeds the increase in cost.

This method of determining the efficiency criterion can be used to optimize technological processes with a batch supply of raw materials.

The above examples of the target operations are classified as coordinated operations, i. e. operations where the output product is fully presented to the consumer. The class target operations with a mismatch at the output is interesting for further studies. This situation can occur if the consumer does not need the entire output.

7. Conclusion

1. Determining the efficiency of the studied operation generally requires processing the whole trajectory of the moving object, since the time of the entire cycle of a technological process is not known beforehand and the quality of the product in motion is changeable.

2. Implementation of any technological operation is accompanied by a depreciation of the working mechanisms of the system under study. It is shown that the wear can have a significant impact on the determining of the optimum. Thus, the problem related to depreciation of a working mechanism in optimization must be justified.

3. The purpose of a technological operation is to provide a consumer product, in this case – heated liquid, and the desired product – the added value. The added value of each operation has its parameters – the target signature. On the other hand, to determine the target signature it is necessary to quantify the integral parameters of the input and the output products in the system of batch liquid heating in comparable cost values, the calculation of which is shown in the paper.

4. The maximum efficiency in these studies is shifted to the right relative to the minimum costs and maximum added value (profit in open systems). This is due to the fact that the growth rate of costs, in the vicinity of the minimum costs, is much lower than the decline in the rate of operation (productivity increase). Ultimately, if the cyclic operations are handled more efficiently, this leads to an increase in the integral added value.

5. Increase in the value of the output product leads to increased efficiency and a shift towards a more optimal performance.

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