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APPLICATION OF GRAPHS AND NETWORK MODELS FOR DESIGNING PROCESSES FOR CONTROL OF THE STRESS-STRAIN STATE OF A ROCK MASS

Andrii Khorolskyi, Andrii Kosenko and Ihor Chobotko
Branch for Physics of Mining Processes of the M.S. Poliakov Institute of Geotechnical Mechanics,
the National Academy of Sciences of Ukraine, Dnipro, Ukraine
E-Mail: andreykh918@gmail.com

ABSTRACT

To develop a new approach to the design of multiparameter processes for control of the stress-strain state of a rock mass based on the use of a decomposition approach and optimization algorithms. To solve the problem, a complex method was applied, which consists of formalizing alternative technological solutions for managing the stress-strain state of a rock mass by converting it into network models. Further application of optimization algorithms on network models and graphs allows you to choose the most optimal technology for the construction or operation of mine workings. A methodological approach to the design of processes for managing the stress-strain state of a rock mass has been developed. To this end, a decompositional approach was used as a decision-making tool, which made it possible to take into account the variety of parameters that affect the efficiency of the construction or operation of mine workings. After selecting decision-making tools, a criterion was proposed for evaluating the effectiveness of the construction or operation of mine workings, which takes into account the probabilistic reliability and costs of construction or operation. To design multi-parameter processes for managing the stress-strain state, technological cycles for the construction and operation fixing of mine workings were studied using alternative technologies and materials, which made it possible to identify common stages and proceed to the formalization of the problem of finding the optimal technology. The formalization procedure involved the presentation of alternative technologies and solutions through a network model. Further application of optimization algorithms made it possible to determine the most optimal type of support from the standpoint of minimizing the optimization parameter. An algorithmic procedure for the process of designing multi-parameter processes for controlling the stress-strain state of a rock mass based on the use of a decomposition approach has been developed and presented, which made it possible to take into account the diversity in nature and the degree of influence of parameters, as well as to determine the most optimal methods for constructing or operating mine workings. The criteria for the effectiveness of the process of construction or operation of mine workings are determined, which made it possible to proceed to the generalization of the technological stages of construction and operation of mine workings, regardless of the type of support. Based on the use of optimization algorithms on networks and graphs, a decision support system was created that allows automating the design process, as well as determining the most optimal technology for the construction and operation of mine workings, depending on a given optimization parameter and efficiently, a particular case has been considered determining an optimum production method for a coal producer.

Keywords: rock mass, design, parameter, technology, exploitation, mine working, goaf, software.

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INTRODUCTION

Management of the stress-strain state (SSS) of a rock mass is a complex and multi-parameter process. This process provides for the coordination in time and space of technological operations for the delivery, unloading, auxiliary work, and direct fixing of the goaf. At the same time, the necessary conditions are high-reliability fixing of the goaf, the minimum amount of materials required for fixing the goaf, improvement of the organizational structure of the process, as well as accelerating the pace of fixing or construction of mine workings. The presence of these requirements entails the search for new types and technologies for managing the SSS of a rock mass [1, 2], the use of the latest materials [3, 4], measures for the search and reproduction of internal reserves in the organizational structure [5], the creation of new mixtures [6, 7] and the corresponding technique [8]. At the same time, insufficient attention is paid to design processes that allow evaluation of the effectiveness of the implementation of the above measures, technologies, materials, etc. This is due to the following key points:

- During the design process, special attention is paid to the criterion of optimality. It is this criterion that significantly influences the choice of SSS control technology for a rock mass. However, it is more expedient to consider the design process from several mutually exclusive sides. Thus, the first task is formed, which is to develop a universal tool for research, evaluation, and choice of the method fixing of the goaf.

- The effectiveness of the process is influenced by several factors, different in nature and degree of impact at different stages of the construction or operation of mine workings. If linear programming methods are used to optimize one parameter, then this is the search for n=1 solutions - a linear surface. To optimize two parameters, then it is n=2 solutions - a voluminous task. And if there

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are more than two such parameters, then this is 2n - the space (n is the number of parameters), which cannot be optimized by arithmetic calculations. Even the use of modern computer technology does not allow taking into account all the parameters (due to the lack of computing resources). At the same time, the reliability of the solution obtained will be minimal, because the parameters are different in nature and degree of impact at different stages. Therefore, the second task is formed, which is to create an approach that will take into account the diversity of parameters;

- Feedback between technology and mining and geological conditions. Indeed, on the one hand, mining and geological conditions determine the technology for constructing mine workings, but on the other hand, the technology for constructing mine workings allows minimizing the negative manifestations of unfavorable mining and geological conditions (filtration, watering, fracturing, etc.). Thus, the problem of managing the SSS of a rock mass refers to the technological aspects of the physics of mining processes [9, 10]. Therefore, based on the ideas about the patterns of formation of the efficiency of the field exploitation process [11] and the methodological foundations for designing mining processes [12], it is possible to implement the technology for designing multi-parameter SSS control processes

Therefore, the creation of new approaches to the design of SSS control processes for a rock mass based on the use of the decomposition method is an urgent scientific task. To solve this problem, in the presented work, decision-making methods and an optimization procedure are given, and a decision support system (DSS) is described. All this made it possible to create a new approach to the design of the processes of construction and operation of mine workings. Based on the above approach, it is possible to evaluate the effectiveness of using alternative types of support, and the given DSS allows you to automate the design process. The study is intended to solve the problems.

MATERIALS AND METHODS

The development of a new approach for designing the processes of fixing the mine working involves several definitions, without clarification of which it is impossible to proceed to the presentation of the research methodology.

Method is the technique, action, or method used in the course of performing any work or doing something. Therefore, the method of fixing a mine working is aimed at maintaining the goaf and is implemented by a sequence of certain stages.

Stage is the separate moment, a period in any activity, in its nature and consequences different from the previous and subsequent periods of this activity. Thus, regardless of the method of fixing the mine, it is necessary to establish the general stages that affect the parameters of the technological scheme.

The parameter is the value that characterizes the main essential features of processes or objects. It follows that the parameter itself can be optimized to improve efficiency.

Efficiency is the relationship between the result achieved and the resources used. The definition itself implies a search for a balance between the funds spent and the final efficiency. In the case of fixing, this is expediency.

Expediency is the correspondence of a phenomenon or process to a certain state, the material or ideal model of which acts as a goal, a form of manifestation of cause-and-effect relationships

The adopted definitions allowed us to form the following procedure, which consists of establishing a criterion for the effectiveness of fixing, identifying common stages at the stage of support erection, regardless of its type, building a model, and proposing a decision support system.

When fastening, they use an expediency indicator that takes into account the probable reliability and probable efficiency [13]

$$\mathrm{k_D = V + k_{ef}},$$

where

k_D – coefficient of expediency of type of support;
V – probable reliability of the support;
k_{ef} – probable efficiency of the support.

At the same time, if the probable reliability of the support is determined only by experience, based on observations of the number of rock falls and collapses. Then the probable efficiency is characterized by the ratio between the cost of fixing the running meter of a mine working by the proposed type of support to the cost of fixing the running meter - another or reference. It should also be noted that at the design stage, the value of V always tends to be 1 [14, 15]. Therefore, it is necessary to pay more attention to the indicator of probable efficiency. The latter takes into account the construction technology of mine workings, allows you to optimize the operation parameters, and can be determined by the formula

$$\mathrm{k_{ef}} = \frac{\mathrm{Q_{min}}}{\mathrm{Q_{et}}} \to 1,$$

where

k_{ef} - probable efficiency of the support;
$Q_{\min}$ - the cost of fastening the running meter of a mine working;
Q_{et} - the cost of fixing a running meter of a mine working with a reference or other type of support.

The cost of fixing consists of capital C_k and operating costs C_o. In turn, the operating costs C_o consist of the cost of depreciation charges C_d, ventilation C_v repair, and restoration work C_r, that is $C_o = C_d + C_v + C_r$. The methodology for determining the capital and operational characteristics is given in [16].

From the above expressions, it is possible to form the basic requirements for fixing mine workings:

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maximum service life, maintaining a constant cross-section over time, and the maximum degree of mechanization of labor with minimal construction and maintenance costs.

Therefore, at the stage of designing the fixing of a mine working, it is necessary to take into account both organizational issues related to technology and determining the reliability of the fixing of a mine working, and economic ones that directly affect the overall efficiency of the process. Therefore, we proposed to use the decomposition approach to solve this problem [17]. The essence of the decomposition approach is to single out the goal of the lower levels in the hierarchy from the goal of the upper level. Thus, after that, each of the determined factors is decomposed into smaller factors. That is, there is a transition from more to less, and the achievement of the final goal occurs due to the analysis and optimization of parameters at the initial stages. There is a transition from solving a general n-dimensional problem to a particular, lower-ranking (one-dimensional) problem in the hierarchy, which allows for saving computing resources [18].

The use of graphs and network models allows us to solve this problem. To optimize the process of construction of mine workings, as an optimization parameter, you can take the cost of fixing a running meter. The main condition for solving this problem is the interconnection of all stages with each other.

RESULTS

Each top corresponds to a separate decision (alternative) that can be made, and the distance between the tops (edge) has its own length, which corresponds to the value of the optimized parameter (cost, labor, time, etc.). At the same time, links between tops are mutually exclusive. That is, if the spritzbetonausbau or roof bolting, then there is no possibility of its reuse, and there are also no costs for dismantling. The same thing can be considered in the reverse order of the model, if it is impossible to dismantle the support from the mine working, then the roof bolting is not used.

The model is structured by stages (levels). That is, alternative fastening options, possible transport options, possible technologies for erecting false timbering, etc. can correspond to the tops. To find the optimal strategy, all stages must be analyzed. That is, it is necessary to find the shortest route from the top 1 to the top 17. A set of tops corresponding to stages and distances between tops that correspond to the value of the optimization parameter form a network model.

To optimize the network model, it is necessary to perform preparatory work - to exclude parameters that cannot be optimized from further calculation. The mathematical meaning of the proposed methodology is as follows: a set of intermediate operations in the technology of support construction, to which the peaks correspond, ensure the maintenance of a mine working, at the same time forming the relative cost of its construction.

For optimization, it is proposed to use the algorithm of Dijkstra [19] and Floyd-Warshall [20].

The algorithm is implemented in the following sequence [19]:

Step 1: Before starting the algorithm, all tops and arcs are not filled in. Each top is assigned a value *d(x)*, which corresponds to the shortest route from s (start) to x (end). Wherein

$$d(s) = 0, d(x) = \infty, \qquad \text{для } \forall\, x \neq s$$

At the same time, we should color the tops and take *y*=*s*; where *y* – is the last painted top. It should be noted that not only the tops are colored, but also the arcs (edges) connecting these tops.

Step 2: For each unfilled vertex x, determine the length *d(x)*

$$d(x) = \min\{d(x), d(y) + a(y, x)\}$$

At the same time, if *d(x)*=∞, then there is no route; if *d(x)*≠∞ then *y*=*x* it is necessary to paint over the top.

Step 3: If *y*=*t* it is necessary to complete the procedure. The shortest route from top *s* to top *t* is found. That is, this is the only route from the initial to the final top of the colored arcs.

The colored tops in a directed graph form a tree rooted at top *s* to any top *x*. According to the problem of finding the optimal technological process for the construction of the mine working, the structure of the process with the lowest value of construction costs will be proposed.

To streamline the structure of the construction process, the Floyd-Warshall algorithm is used [20]. It is usually referred to as "Floyd's algorithm" for simplicity. The algorithm compares all paths between pairs of tops. As a result of the algorithm execution, a matrix will be built that contains data on the shortest routes between pairs of tops, but there is no information about the routes.

The essence of the algorithm: let the tops of the graph $G = (V, E), |V| = n$ be numbered from 1 to n. Then we introduce the notation for the shortest route from i to j in the form d_{ij}^{k}, which, in addition to tops i and j passes only through tops $1 \dots k$. Thus d_{ij}^{0} is the length of the edge (arc) between tops i and j, otherwise $d_{ij}^{0} = \infty$.

There are only 2 possible options that the length of the edge $d_{ij}^{k}, k \in (1, \dots, n)$:

a) $d_{ij}^{k} = d_{ij}^{k-1}$ – that is, there is a shortest route between tops i and j does not pass through top k;
b) $d_{ij}^{k} = d_{ik}^{k-1} + d_{kj}^{k-1}$ – that is, there is a shortest route between tops i and j that passes through top k when from first passes from i до k, and then from k to j.

Then it becomes clear that to find the shortest route, it is necessary to find the minimum value among the two values: $d_{ij}^{k} = d_{ij}^{k-1}$ та $d_{ij}^{k} = d_{ik}^{k-1} + d_{kj}^{k-1}$.

Floyd's algorithm can be written as a single recursive formula

$d_{ij}^{k} = \min(d_{ij}^{k-1}, d_{ik}^{k-1} + d_{kj}^{k-1})$

Taking into account the impact of each stage on the overall efficiency of the process and making a single right decision at each stage of the technological process allows you to make the best decision. We will consider the optimal fastening with the lowest cost and minimal risks of water tides in the mine. The developed approach makes it possible to take into account hydrogeological parameters. This is done in the following way - knowing the degree of watering of the massif and their hydrogeological characteristics, it is possible to provide measures to increase the stability of workings.

Floyd's algorithm sequentially determines all values d_{ij}^{k}, $\forall i, j$ for k from 1 to N. The value d_{ij}^{k} is the shortest path between all pairs of tops i and j.

Applying Floyd's algorithm, we obtain the matrix D_1. Unlike matrix D_0, matrix D_1 will present data on the value of costs for the construction of mine workings at a certain stage (first).

The algorithm will be completed when the matrix D_n is built – the ordinal index of the matrix corresponds to the number of tops in the network model. That is, an ordered structure of the technological process of construction of mine workings with the lowest value of construction costs will be obtained.

At the same time, depending on the stage of support construction, the parameters to be taken into account will be different.

Taking into account the impact of each stage on the overall efficiency of the process and making a single right decision at each stage of the technological process allows you to make the best decision. We will consider the optimal support with the lowest cost and minimal risks of water tides in the mine. The developed approach makes it possible to take into account hydrogeological parameters. This is done in the following way - knowing the degree of watering of the rock mass and their hydrogeological characteristics, it is possible to provide measures to increase the stability of mine working.

Regardless of the support material (yielding support, spritzbetonausbau, roof bolting, etc.), the existence of common stages has been established, consisting of the allocation of several local problems, we will dwell on them separately (Table-1).

Table-1. Stages of performing the task of constructing mine workings.

Stage	Stage name	Problem;	The essence of solving the problem
I	loading operations of supports on the daylight	technology needs to be organized to reduce travel costs	it is necessary to balance the flows of incoming and outgoing resources, as well as to solve the problem of placing suppliers of materials and consumers in space
II	delivery of support to mine workings, taking into account storage costs	it is necessary to organize the technology in such a way as to reduce storage costs and eliminate temporary downtime	it is necessary to balance in space the relationship between the surface complex of the enterprise, warehouses, underground mine workings, faces
III	first working (drilling boreholes, etc.)	it is necessary to organize the technology in such a way as to reduce the cost of first work and reduce time costs	it is necessary to choose drilling, installation, etc. equipment with a minimum unit cost, as well as to reduce the amount of rock mass resulting from the first working
IV	construction of temporary supports	it is necessary to design the technology so that material savings are achieved, as well as the time spent on the installation and dismantling of auxiliary support is reduced	it is necessary to justify the method of erecting an auxiliary support with a minimum material consumption, minimum downtime, and a minimum amount of rock mass issued.
V	construction of permanent supports	it is necessary to design the technology so that material savings are achieved, as well as the time spent on mounting and dismantling permanent support is reduced	it is necessary to justify the method of erecting a permanent support with a minimum material consumption, minimum downtime, a minimum amount of rock mass issued
VI	stoping and transportation of rock mass as a result of work mining operations	it is necessary to design the technology in such a way as to reduce temporary downtime associated with the removal of rock mass from the face and minimize the cost	it is necessary to organize the work of loading and hauling equipment, and means of transportation, to balance the flows of rock mass in time
VII	withdraw the supports	it is necessary to organize the technology so that the time costs are minimal	it is necessary to justify the dismantling technology so that time and human resources are minimal

As can be seen from Table-1, all stages are universal and do not depend on the type of support, however, each of the considered stages can also be divided into stages and optimized.

Thus, the problem of choosing the method of fixing mine workings is solved in the following sequence:

– First, it is necessary to choose an efficiency criterion in the course of choosing a method, for example, the cost of fixing the running meter of the mine working;

– secondly, it is necessary to single out the stages in the technology of support construction;

– thirdly, for each solution, at the stage, determine the value of the optimization parameter (in our case, the cost of fixing the running meter of the mine working);

– fourthly, to present a set of alternative solutions using a network model, where the tops correspond to alternatives, and the distances between them are the value of the optimization parameter;

– fifthly, find the shortest distance from the initial to the final top, which will correspond to the optimal solution.

In all of the above problems, the essence of the solution is to minimize the parameters. To do this, it is necessary to represent the entire cycle of fixing mine workings in the form of a network model, where certain alternatives and technologies will correspond to the tops, and the value of the optimization parameter will correspond to the distances between these tops.

Let's depict in Figure-1 the network model of the mine working construction process.

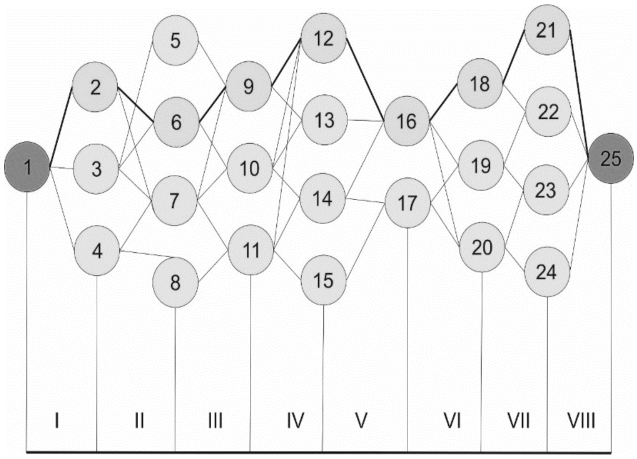

Figure-1. A network model for optimizing the parameters of the construction of mine workings.

As noted earlier, technology options are taken as tops, and the value of the optimization parameter is taken as the distance between tops. We give in Table-2 an explanation for the network model shown in Figure-1.

Table-2. Network formalization of the problem of construction of mine workings.

Stage designation in figure-1	Stage name	Start top	Final top (top in intermediate stages)	Interpretation
I	loading operations of supports on the daylight	1	2-4	1 - top for the reference point; 2-4 transport technology options
II	доставка кріплення у виробках з урахуванням складських витрат	2	5-8	2 – optimal technology after the first stage; 5-8 transport technologies
III	first working (drilling boreholes, etc.)	6	9-11	6 – optimal technology after two stages; 9-11 drilling technology
IV	erection of a false timbering	9	12-15	9 – optimal technology after three stages; 12-15 technology options for erecting auxiliary support
V	erection of a final support	12	16-17	12 – optimal technology after four stages; 16 - technologies of fixing
VI	winning and transportation of rock mass as a result of work	16	18-20	16 – optimal technology after five stages; 18-20 transport technologies
VII	extraction of support	18	21-24	18 - optimal technology after six stages; 21-24 dismantling technologies
VIII	completion	24	25	21 – optimal technology after seven stages; 25 – completion

Then the task of finding the optimal solution is to find the shortest route from top 1 (beginning) to the final top (in our case 25). For clarity, we depicted the shortest route as a thickened line, and the tops at which optimal solutions are achieved at intermediate stages were highlighted in a different color (pink). A necessary

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condition is that the distance between the tops (edges of the network model) corresponds to real production relationships. That is, if there is a relationship between points (tops) 2 and 6, as well as 2 and 7, then the distance between these tops corresponds to the value of the optimization parameter. And if there is no relationship between the tops (for example, between 2 and 8, 2 and 5), then the value of the parameter is taken equal to infinity.

Finding the shortest distance from the start to the end top will correspond to the optimal solution.

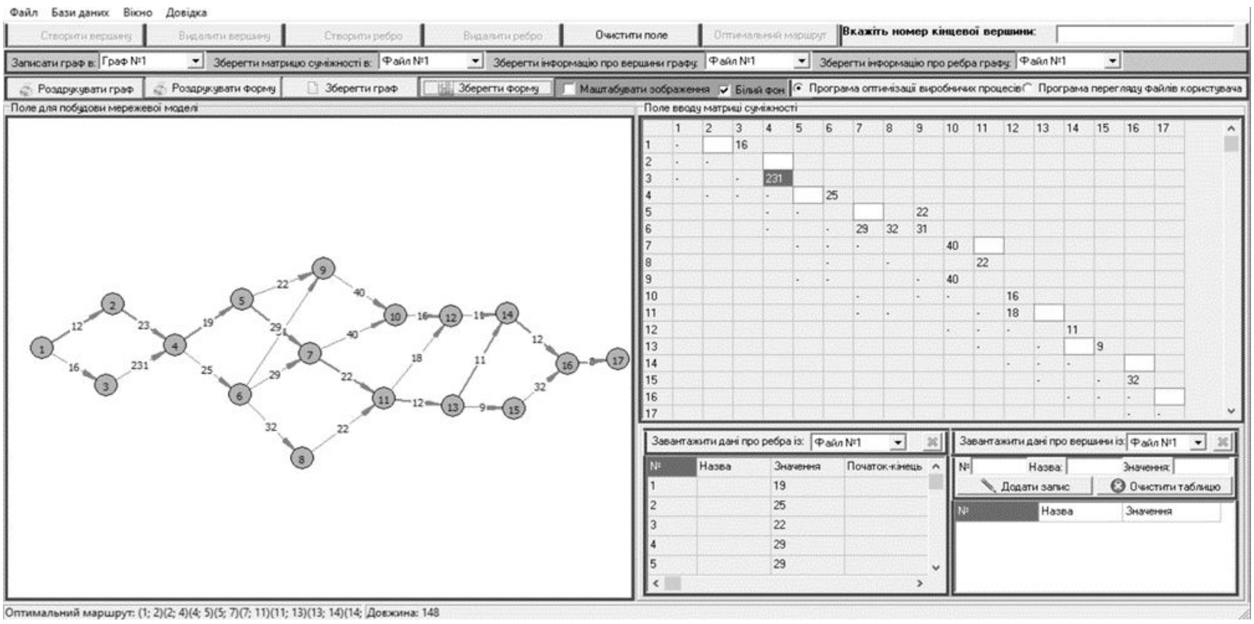

Figure-2. Software package for optimizing operation parameters.

The use of the developed DSS [22] (Figure-2) makes it possible to implement the design process. As an object of study, the mine is named after "Heroes of Space" PJSC DTEK "Pavlograd coal". It was necessary to provide measures to minimize the negative impact of hydrogeological factors. Various technology options were analyzed and it was proposed to use roof bolting with the use of a reinforced roof-rock structure [23].

The economic effect from the application of the adopted decisions can be calculated for several cases: obtained through the reuse of the drift; by reducing GOR downtime and shortening the time for preparatory operations, which will allow to increase in production volumes and sell more products; thanks to material savings.

For the above cases, the economic effect was calculated. The economic effect of applying the adopted technological solutions, as well as saving materials, will be from UAH 9 to 12 million (depending on the calculation method) per one drift. In addition, the proposed solutions make it possible to obtain an additional economic effect: the reuse of the drift [24, 25]; due to the reduction of GOR downtime and reduction of time for preparatory operations [26], which will allow an increase production volumes and sell more products; thanks to material savings.

It is also worth noting that the reserve for increasing the efficiency of managing the state of the rock mass is the optimization of the parameters of the construction of mine workings. This is realized based on the choice of technology with the lowest cost, labor intensity, and time costs.

Thus, this paper proposes an integrated approach to solving the problem of designing multi-parameter processes for controlling the SSS of a rock mass.

CONCLUSIONS

In the course of the study, a new approach to the design of processes for managing the SSS of a rock mass was created. To find the optimal solution, a model was developed that provides for the representation of the life cycle of the support in the form of a network model that takes into account alternative options. Each top corresponds to a separate decision (alternative) that can be made, and the distance between the tops (edge) has its length, which corresponds to the value of the parameter that needs to be optimized (cost, labor, time, etc.). It was found that each stage has its control parameter that can be optimized, while other parameters are at a lower hierarchical level it is a decomposition approach. Taking into account the impact of each stage on the overall efficiency of the process and making a single right decision at each stage of the technological process allows you to make the best decision. The proposed decision support system will make it possible to introduce the results into production.

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