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New approach to the optimal planning of maintenance and repairs of equipment for hydropower facilities

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Abstract. The effectiveness of maintenance and repairs of hydropower equipment largely determines the environmental safety and reliability of the operation of modern hydroelectric power plants. The article proposes a new approach to planning the maintenance and repairs of hydraulic equipment. The task is to determine the sequence of control actions of the system of maintenance and repairs of hydropower equipment, which, at a minimum cost, will ensure the maintenance of a given level of technical condition of the fleet of this equipment at a hydroelectric power plant for a specified period. It is taken into account that the equipment is at different stages of operation. The article considers the formulations of scheduling optimization problems for various industries. A mathematical formulation of the optimization problem for planning a multi-stage maintenance and repair process for hydropower facilities is formulated.

1 Introduction

To date, one of the priority areas for increasing the competitiveness, environmental safety and adaptability of hydropower enterprises to the conditions of modernization of the main hydro-generating equipment is the revision of the principles of planning maintenance and repairs (hereinafter referred to as MRO - Maintenance, Repair and Overhaul). In general, the MRO planning problem can be formulated as follows. In changing operating conditions and the external environment of the enterprise, it is necessary to determine the sequence of control actions of the maintenance and repair system, which, at a minimum cost, will ensure the maintenance of a given level of technical condition of the equipment park at different stages of operation for a specified period.

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An analysis of studies in the field of maintenance and repair planning [1-4] showed that, despite the general trend of transition to predictive maintenance systems, the enterprises of the hydropower industry use the Time-Based Maintenance (TBM) system, which is characterized by a long planning period (more than 5 years) and strict standardization of regulatory documentation of the time of repairs and their sequence.

On the one hand, the use of such a system is justified by the critical level of equipment failures and the inclusion of each hydroelectric power plant in the overall energy management system. On the other hand, such a system is focused on normative management and maintenance planning, which does not always correspond to the actual need for repairs. This leads to high operating costs, for example, for enterprises with a long-life cycle, the share of maintenance and repair costs is more than 70% of the total costs. As a rule, the multi-criteria evaluation of operation is not taken into account and this is not effective for the modernization period. In this case, both new equipment and equipment that is outside the standard service life are involved in the production process at the same time.

Thus, in order to ensure the company's strategic goals and maintain the system of long-term maintenance and repair planning, it seems expedient for HPPs to switch to the Reliability-centered maintenance (RCM) system. The RCM system combines both elements of a preventive concept, which ensures the planning of repair work, and a predictive one, that is, it takes into account many operating factors.

The task that an enterprise needs to solve when moving to a new MRO organization system is the formation of a new method for determining the optimal sequence of MRO tasks. Note that this problem has already been identified as a key one in the maintenance of other industries such as aviation [5].

2 Materials and methods

In general terms, determining the sequence of maintenance and repair tasks in the hydropower industry can be reduced to the task of scheduling. In fact, within the framework of planning the technical impact on equipment, the tasks typical for scheduling are solved, namely:

– time task, which allows to coordinate the implementation of technical impact modes in time both for one piece of equipment and for a group of equipment of the same type; as a result of solving the time problem, the schedule is determined, i.e., start and end dates of each mode of technical impact;
– the resource task involves linking the timing of a particular mode of technical impact and ensuring timely supply and distribution of common resources in compliance with the specified conditions for their use;
– the solution of the cost problem consists in determining the volume of the total operating costs of the enterprise at each interval of the planning period.

Scheduling is a decision-making process related to the allocation of resources for tasks in certain periods of time, and its purpose is to optimize one or more tasks. Resources and tasks in an organization can take many forms. Resources can be machines in a workshop, runways at an airport, crews at a construction site, processing units in a computing environment, and so on. Tasks can be operations in a manufacturing process, takeoffs and landings at an airport, phases of a construction project, execution of computer programs, and so on. Goals can also take many different forms. One goal may be to minimize the completion time of the last task, and the other may be to minimize the number of tasks completed after their estimated deadlines [6].

Thus, the task of scheduling should be considered as an optimization problem, that is, finding the optimal combination of work, resources, etc., ensuring the fulfillment of requirements and conditions, and also aimed at achieving the goal of the enterprise. From a

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mathematical point of view, the problems under study are among the NP-hard problems of discrete optimization. The following examples illustrate the formulation of the scheduling optimization problem in a number of real environments.

In [7], a mathematical formulation of the task of planning works with limited resources for industrial enterprises is formulated, where the main goal is to minimize the time for performing maintenance and repair work. The task can be described as follows:

$$\min \max_{i \in V} x_i + p_i \, ;$$

$$x_i + p_i \le x_j, \forall (ij) \in E;$$

$$\sum_{i \in V(t)} r_{ik} \le R_k, \ \forall k \in R, \ t \in Z_+^1, \ x_i \in Z_+^1.$$

Note that in this formulation it is necessary to fulfill a set of tasks and the priority requirements between some tasks. The scheduling problem involves determining the start time of each task in order to minimize the total time to complete the project.

The following notation was used to formulate the problem: V is the set of all tasks; E is a set of precedence constraints; p_i is task processing time, $i \in V$; R is resource set, R_k – are available type resources, $k \in R$, and r_{ik} are resources of type k required for the task i.

The variable is the start time for each task, where x_i - task start time, $i \in V$. Other scheduling optimization problems with limited resources aimed at minimizing the execution time of work have similar properties.

For enterprises with several technological processes, the problem of profit maximization when planning maintenance and repair is formulated in [8] and has the following form:

$$\begin{cases} \sum_{n=1}^{G} \pi_n(Y_n) \to \max; \\ Y_n \ge Y_n^*, \ n = \overline{1, G} \ ; \\ \sum_{n=1}^{G} W_n(Y_n) \le b \ . \end{cases}$$

where $\pi_n(Y_n)$ is function of profit from the produced n-th product name; Y_n is output of the n-th product name; Y_n^* is the minimum required output of the n-th product name; G is number of product names (number of technological processes); $W_n(Y_n)$ are is the minimum average cost of equipment repair for one period for the n-th process; b is average budget for equipment repairs for one period.

Profit maximization will be achieved by maximizing sales of the most profitable product items, the demand for which exceeds the minimum required. Therefore, there is a need for such a throughput of technological processes that produce the most profitable goods that correspond to real demand. Given the tight budget for maintenance and repair, the minimum required throughput of each process must be achieved with minimal maintenance costs.

In particular, the determination of the scope of repair work at minimal cost for the aviation industry is considered in [9]. The task statement is as follows. It is necessary to determine the composition and timing of the maintenance procedures, in which the selected criterion will take the minimum value, i.e., determine all x_{kn} for which

$$S \to min;$$

$$R = \max{(R_n)} \to min,$$

where x_{kn} is boolean variable, the value of which is determined by the occurrence of the *k*-th job in the *n*-th MRO procedure, if *k*-th work is included in the *n*-th procedure, then $x_{kn} = 1$, otherwise $x_{kn} = 0$; S is the total logistical cost of producing the MRO; R_n is the complexity of the *n*-th MRO procedure.

Despite the fact that the described formulations of the planning optimization tasks are focused on the maintenance and repair of various industries, they do not consider such important aspects for the hydropower industry as assessing the state of the equipment at the end of the planning period, depending on combinations of standard maintenance and repair procedures carried out on the equipment, as well as the complexity of planning MRO for the entire equipment fleet. Thus, it seems appropriate to formulate a mathematical statement of the optimization problem of planning maintenance and repair for hydropower facilities.

3 Results

Based on the materials and methods discussed above, we formulate the problem of optimizing maintenance and repair for hydropower enterprises, in particular, for hydroelectric power plants (HPPs). A typical HPP (Figure 1) has a list of equipment (repair facilities) characterized by a long period of operation. According to [10], repair objects at HPPs can be:

- equipment (hydro turbine, hydro generator, transformer, pump, electric motor, diesel engine, valve, device, etc.);
- installations (hydroturbine, hydrogenerator, transformer, etc.).

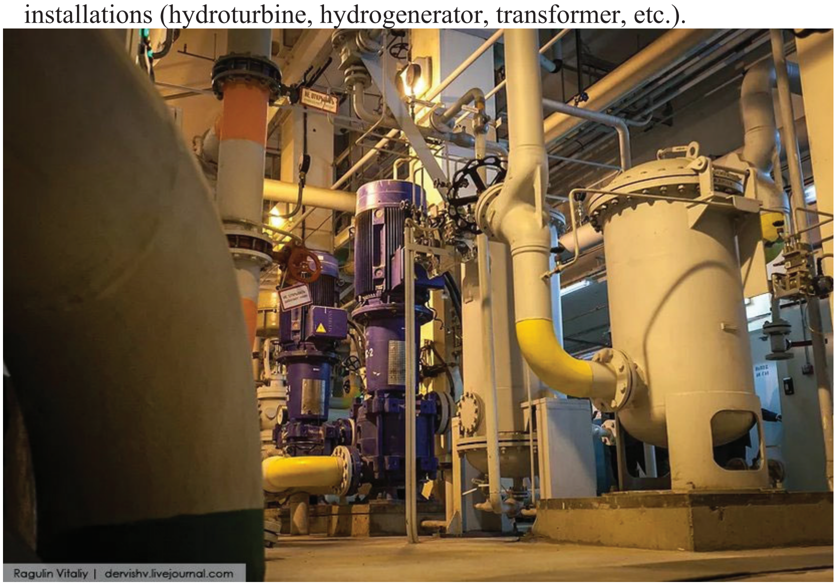

Fig. 1. Installations and equipment (repair facilities) of a typical HPP (source: https://principraboty.ru/gidroelektrostancii-princip-raboty/?ysclid=lfjfb63zqw994964586).

The specifics of the operation of a hydroelectric power plant provides that during scheduled repairs, the equipment being repaired stops generating electricity, therefore, it is advisable to consider the hydroelectric unit as an enlarged piece of equipment as an object of maintenance and repair. Such enlargement is also confirmed by the current system of long-term maintenance and repair planning, within the framework of which the schedule for bringing the hydroelectric unit into repair is approved.

The hydropower unit is understood as equipment consisting of a hydraulic turbine and an electric hydroelectric generator (Figure 2), which ensures the performance of the main function of the HPP related to the generation of electricity.

There is a scheduling interval. For a long-term maintenance plan, this interval is 5 years, and it is divided into additional time intervals. Within the framework of the problem being solved, the additional time interval is equal to one year. In one time interval, one maintenance and repair procedure takes place at each of the repair facilities. MRO procedures include:

- maintenance,
- current repair,
- overhaul.

The implementation of each of the procedures involves the consumption of operating resources, which include financial resources, material and technical, labor, etc. At the same

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time, each maintenance and repair procedure ensures the restoration of the equipment condition.

Fig. 2. Horizontal hydro generator (source: https://principraboty.ru/gidroelektrostancii-princip-raboty/?ysclid=lfjfb63zqw994964586).

As part of the problem statement, we need to determine the sequence of maintenance and repair procedures over the entire planning interval for each of the equipment and form the most beneficial general plan of maintenance and repair procedures in relation to the operating resources and the condition of the equipment. The task involves taking into account several generalizations and extensions of the scheduling problem [11], allowing you to take into account the conditions common in practice.

3.1 Restrictions on the type of MRO procedures

In variants of the scheduling problem, the assumption about the sequence of work on the equipment is common. In the proposed variant of the task, there is no specific order in which procedures are performed on the equipment, but there is a dependence between the procedures performed on different equipment in one time interval. The number of current or major repairs on all equipment should not exceed a given value, determined by the norms for the duration of major and current repairs per year. The table shows the standard duration of scheduled repairs established in the INVEL organization standard STO 70238424.27.140.031-2010 (Hydroelectric power plants. Repair and maintenance of equipment, buildings and structures. Organization of production processes. Norms and requirements) and also briefly presented in work [10].

Table 1. Standards for the duration of scheduled repairs.

Hydro turbine type	**Duration of repair, calendar days**	
	in the year of the overhaul	**in the year of the current repair**
Rotary vane with impeller diameter from 3.6 to 4.5 m.	33	8
Rotary vane with impeller diameter from 5 to 7.5 m.	38	9
Rotary vane with impeller diameter from 8.0 to 5 m.	43	8
Rotary vane with impeller diameter 7.0 m.	47	14

Capsular hydraulic units with a turbine wheel diameter of up to 6.0 m.	37	9
Capsule hydraulic units with a turbine wheel diameter of more than 6.0 m.	43	9

3.2 Restrictions on the condition of the equipment

Usually, if the application task is related to the repair of equipment, the state of the equipment should not fall below a certain predetermined value, defined by regulatory documentation. Therefore, restrictions on the state of equipment are basic for most variants of maintenance and repair planning tasks and are taken into account in the proposed task as restrictions for each time interval.

3.3 Conditions of time restrictions and rationing of MRO procedures

In the classical formulation of the problem, a necessary condition for the search is to determine the earliest start and completion of work or to minimize the time of the entire process of equipment maintenance. Under the conditions of long-term planning of maintenance and repair, when the entire planning period, intermediate intervals are determined and the time of maintenance and repair procedures is normalized, this condition can be neglected, taking into account only the fact that the maintenance and repair procedure enters the time interval. Time conditions can be taken into account when optimizing the annual maintenance plan.

The accumulated statistical data on the cost of resources for maintenance, repair and overhaul make it possible to use the assumptions about the normalization of resource consumption.

3.4 Mathematical formulation of the problem of optimizing maintenance and repair planning

It is proposed to formulate a new task of optimizing maintenance and repair planning, the mathematical model of which, unlike the existing ones, will make it possible to find a sequence of maintenance and repair procedures that provides both the required level of equipment condition and the minimum consumption of operating resources.

There is a finite set $I = \{i_i\}$, $i = \overline{1, m}$ of elements of the production system. Only one procedure is associated with an element of the production system at a certain time t_i.

Denote $\{P_1, P_2, P_3\}$ - partitioning of the set P into subsets, respectively: P_1 - maintenance procedure; P_2 - current repair procedure; P_3 - overhaul procedure.

The prospective MRO plan is a sequence of MRO procedures performed during the planning period $T = \{t_n\}$, $n = \overline{1, m}$, specified by a set of time periods (quarter, year) - t_n.

Let us introduce the following notation.

1. $J = \{j_p\}$ is the totality of resources for the operation of elements of the production system: financial resources; material and technical resources; labor resources. The resource corresponding to $j \in J$ will be taken as the j-th resource.
2. $K = \{k_j\}$ is a set of criteria for estimating the resources of operation. The criterion corresponding to $k \in K$ will be taken as the k-th criterion.
3. x_{0i}^{k} is the current state (or initial resource) of the i-th element of the production system, estimated by criterion k.
4. Z_i^k is the normative level of depreciation of the state of the i-th equipment, estimated by the k-th criterion, for one time period.

5. For each procedure $p \in P$, the consumption rates of the j-th resource estimated by the k-th criterion (N_{ip}^{k}), as well as the recovery rates of the i-th equipment state, estimated by the k-th criterion (M_{xip}^{k}) are specified.
6. $x_{it}^{'}$ - lower restrictions on the state level of the i-th equipment in period t.
7. $x_{it}^{''}$ - upper limits on the state level of the i-th equipment in period t.
8. $x_{i}^{кр}$- critical level of the equipment condition, signaling that the equipment is not ready for the next planning period.
9. K_{p2}, K_{p3} – the allowable number of current repairs and overhauls carried out in one time period.

The calendar long-term maintenance plan is considered to be optimal when the amount of costs from performing maintenance and repair procedures tends to a minimum:

$$\sum_{i=1}^{m} \sum_{p=1}^{3} N_{jp}^{k} \to min.$$

The description of the patterns that determine the sequence of maintenance and repair procedures for the entire list of equipment is indicated in the form of the following three restrictions.

1. The total resource of the equipment fleet at the end of the planning period must exceed the critical one, otherwise the next planning period will be characterized by a high repair load. This condition can be considered a criterion for the end of the planning process and formally it looks like this:

$$\sum_{i=1}^{m} (x_{0i}^{k} + \sum_{p=1}^{3} M_{xip}^{k} - \sum_{T} Z_{i}^{k}) \geq \sum_{i=1}^{m} x_{i}^{кр}.$$

2. The state of the equipment in each time period (t_n) must be greater than the normative state of the equipment, while not being redundant:

$$x_{it}^{\prime} \leq x_{0i}^{k} + M_{xip}^{k} - Z_{i}^{k} \leq x_{it}^{''}.$$

3. The time interval cannot include the number of repairs exceeding the allowable number of current and major repairs. This limitation is due to the duration of the repair and the rate of generation of the power plant per year:

$$\sum_{i=1}^{m} P_{2i}(t) \leq K_{p2} \quad \sum_{i=1}^{m} P_{3i}(t) \leq K_{p3}.$$

Due to the nature of the statement, the MRO planning problem is characterized by high dimensionality, complexity and a large number of parameters, the values of which constantly change over time and depend on a large number of factors.

For complex planning tasks, when the number of possible schemes for planning maintenance and repair procedures becomes very large, the effectiveness of accurate calculation methods drops significantly. An analysis of the methods presented in a number of works [12-16] showed that the complexity of using both the exhaustive search method and the dynamic programming method is associated with an exponential increase in the duration of calculations depending on the dimension of the problem. In addition, in scheduling problems, the system of constraints changes at each planning step, which makes it difficult to use the branch and bound method. Therefore, to solve it, approximate methods are most often used, based on the concept of not an optimal, but an acceptable solution. Approximate algorithms are built on the basis of some plausible ideas (heuristics).

4 Conclusion

Thus, the proposed optimization problem of planning maintenance and repair for hydropower facilities, taking into account the integrated planning of the entire equipment fleet, is formalized using a mathematical apparatus. As a result of the analysis, the algorithmic feasibility of the approach of multi-criteria assessment of the operation of hydropower equipment was obtained for the possibility of effective planning of repair work at enterprises.

The considered optimization problem is widely used not only in the hydropower industry, but also in those applied areas where there is a need for long-term planning of equipment repair, characterized by a long period of operation and high cost of the equipment life cycle. Characteristic examples of the industries to which the described task is oriented are: industries of the fuel and energy complex, mechanical engineering, and metallurgy.

The use of genetic and bioinspired algorithms in solving the task at hand makes it possible to develop information and software support for automated control systems of hydropower enterprises.

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