

A method for evaluating and upgrading systems with parallel structures with forced redundancy

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Highlights

- A system model with continuous delivery (24 hours a day) and forced oversupply is described.
- A method has been developed to assess the technical condition of the system.
- Indicators for assessing the status have been proposed.
- Exemplification for a complex underground primary mine drainage system

Abstract

The objects of the study are parallel-structure machine systems with redundancy associated with safety assurance of continuous material flow. The problem concerns systems in which the supply of materials takes place continuously (24 hours a day), and the system of operated machines must ensure the receipt and movement of the material at a strictly defined time and in the desired quantity. It is a system where the presence of a failure poses a threat to human life and environmental degradation. This paper presents a method for system condition assessment and upgrading for maintaining proper operation under conditions of continuous operation. A database of information about the current parameters of the system components (measurements, monitoring) is necessary for condition assessment. The method also uses lean techniques (including TPM). System evaluation and selection criteria for a suitable structure in terms of further operation were proposed. Exemplification was performed for an underground mine drainage system. As a part of the identification, selected parameters of the system components were measured, and their characteristics (motors, pumps, pipelines) were developed. The results of the analysis and the values of the adopted criteria were compared to the indicators for new pump sets. A two-option system upgrade was proposed, in addition to machine operating schedules, maintenance periods, and overhaul cycles.

Keywords

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evaluation and retrofit method, parallel structure, redundancy, safety, process energy consumption.

1. Introduction

Maintaining a continuous flow of materials is one of the most important tasks in numerous operating systems. The problem is particularly relevant for systems with continuous operation, which additionally need to be resistant to hazardous environmental effects (safety function [23]). Security risk reduction through a security information transmission model was considered by Lei [17]. These systems should be resistant to abnormal disturbances (disasters) [5]. For a broad treatment of the safety assessment issue, see [16]. In case of tasks where failure of a work item results in mission failure, Levitin proposed models based on Poisson processes [18]. Redundancy of operational components is often used in the structures of such systems. A method for evaluating the security level of $k z n$ systems was proposed by Młynarski [27], while a formulation using a Markov process for multi-state $k z n$ systems was presented by Ruiz-Castro in his paper [29]. Balancing the probability of mission success and the risk of system failure by allocating redundancy has been described by Levitin in his publication [19]. Determining the optimal structure for these systems is the subject of numerous studies. A novel method for assess-

ing the reliability of multi-state systems based on structure learning algorithm was described by Li [21]. An optimal operation and maintenance schedule for $m z n$ systems with reusable components was presented by Levitin in [20]. The use of Semi-Markov processes to assess readiness and reliability was demonstrated in the paper [31]. A reliability model for parallel systems under simultaneous failures was presented by Zhang [34]. In some areas, there are additional safety restrictions imposed by relevant directives and regulations. This is the case, for example, in aviation [10], or in offshore oil platform systems. Furthermore, the mining industry imposes additional restrictions on mine drainage (both in underground and open-pit mining). The problem with disposing of water of natural origin, flowing from the rock mass, is particularly important. The factors affecting the amount of inflowing water and the hazards resulting from them were described in many papers, such as by Bukowski [2] and others [7], [15], [24]. The effect of random factors on mine water inflow was analysed by Miladinović [26] and Quazizad [28]. For the safety of people and the operation of the deposits, the waters are pumped out using an appropriate system [3], [12], [33] and modern techniques [9], [13], [22]. These systems are very expensive to maintain and operate.

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Having considered the foregoing, issues related to cost reduction are the focus of many papers, including those by Du Plessis [6], Gunson [9] and Afum [1], as well as Huang [14]. Over the last years, the issues of prevention and predictability were the focus of numerous researchers. A comprehensive approach to the issue was demonstrated in a paper by Werbińska [32]. Multi-criteria optimization for systems maintenance was proposed by Syan [30]. On the other hand, Han [11] proposed predictive strategies for multi-state systems, and Fauriat [8] proposed aperiodic control optimization based on information value. An example analysis of repair effectiveness using TPM techniques was presented in [4]. Most of the papers described herein deal with theoretical considerations related to typical reliability and operational problems. In the literature, there are no solutions related to forced redundancy. Cases of improper operation of such systems, known to the authors, were the genesis for the development of a method to evaluate and upgrade these systems.

2. General system model

An SPM material flow system is a certain ordered collection of E elements and R relationships between them (Figure 1):

$$\text{SPM} = \langle (\mathbf{E}, \mathbf{R}) \rangle = \langle \{ \mathbf{X}, \mathbf{Y}, \mathbf{T} \}, \mathbf{R} \rangle,$$

$$\mathbf{T}: \mathbf{X} \Rightarrow \mathbf{Y}$$

where:

$\mathbf{X} = \{X_1, X_2, \dots, X_i, \dots, X_M\}$; for $i = 1, \dots, M$ – a set of external quantities describing the input elements (machines, material, among others),

$\mathbf{Y} = \{Y_1, Y_2, \dots, Y_j, \dots, Y_N\}$; for $j = 1, \dots, N$ – a set of external quantities describing elements of the output (e.g., performance evaluation indicators, process performance),

$\mathbf{T} = \{T_1, T_2, \dots, T_k, \dots, T_S\}$; for $k = 1, \dots, S$ – a set of quantities describing the transformation of the input vector processing into an output process,

$\mathbf{R} = \mathbf{R}_X \times \mathbf{R}_Y \times \mathbf{R}_T$ – material, information couplings between elements (X, Y, T) of the SPM system.

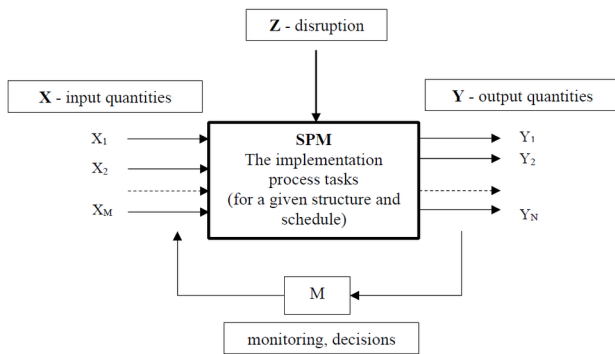


Fig. 1. SPM material flow system model

In the most general terms, two cases can be considered:

- developing new systems,
- modernization (retrofitting) of systems that have been in operation for many years.

In the studied system, the quantities that determine its specificity are (Figure 2):

- continuous supply of material (24 hours a day, all year round),
- the need to receive and move the material at the precise time and in the quantity requested,
- maintaining very high reliability of operation - system failure poses a threat to human life and can result in environmental degradation, hence the need to apply law-imposed safety conditions through a specific redundancy in the system structure.

Because of that, the quantities describing the outputs from the system should include information about the cost of process execution,

the efficiency achieved, the efficiency of operation, as well as the availability and utilization rate of the redundant system components.

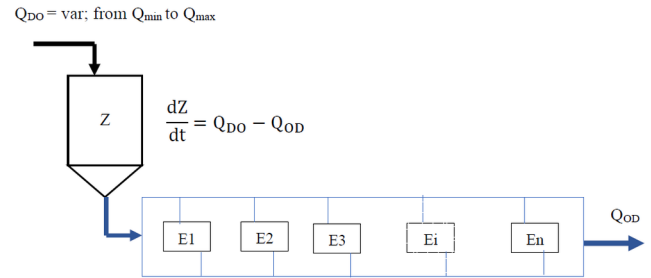


Fig. 2. Model of the continuous delivery and forced oversupply system

An example of redundancy forcing is shown in Figure 3.

For the case of 2-element operation ($n = 2$), the minimum number of system elements is $i = 2n + 1 = 5$.

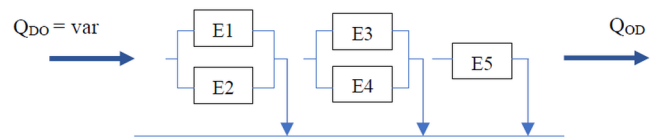


Fig. 3. A system model for the two-element operation case

In case of a three-element structure ($n = 3$), the minimum number of system elements is $i = 2n + 1 = 7$.

Observed cases of improper operation of these systems became the genesis for the development of a method to assess their technical condition. The assessment result is a variant solution – continue operating the system or upgrade it.

3. The method of assessing the condition and upgrading the system

The proposed method is multi-stage (consisting of seven stages). A simplified block diagram of the method is shown in Figure 4.

The main components of each stage are described below.

Stage I – Process identification – Actions: 1-2-3-4-5-6

1. Selecting a process for analysis.
2. Establishing security constraints for system operation (directives, industry regulations).
3. Drawing up an accurate process diagram (process structure, including forced redundancy of components).
4. Identifying the basic quantities that describe the process.
5. Determining the parameters (characteristics) describing the assumed quantities (making measurements, necessary calculations).
6. Collection of process data (database, including historical).

Stage II – Identifying machine functioning – actions: 7-8-9-10

1. Describing losses and waste in the process (e.g., 7 muda, 6 big losses).
2. Identifying machine downtime and damage.
3. Drawing up a Pareto diagram – causes of downtime. Selecting causes for improvement.
4. Setting targets – MTTR and MTBF limits.
5. Determination of OEE effectiveness measure.

Stage III – Establishing criteria for evaluating system condition and performance – actions: 12-13

1. Defining criteria for evaluating the system.
2. Determining the values of evaluation indicators (measurements, calculations).

Stage IV – Analysing system effectiveness – actions: 14 – 16

1. Analysing the compliance of the identified redundant structure with process requirements and enforced constraints.
2. Analysing the timing of system operations.
3. Analysing the system performance evaluation metrics obtained.

Stage V – Evaluating the system and selecting a strategy for further action – actions 17-18

1. If the assessment complies with the adopted criteria – further operation in accordance with the implemented schedule.
2. If the assessment is non-compliant – a proposal to upgrade the system.

Stage VI – Implementing changes – actions: 20-21

1. Making changes to improve system performance evaluation metrics.
2. Developing a schedule for machine operation, maintenance, and overhaul.
3. Developing a schedule (implementation map) for system upgrades.

Stage VII - Analysing the effects and improving - actions: 22-23

1. Analysing effects after making changes.
2. Persistent implementation of kaizen principles!

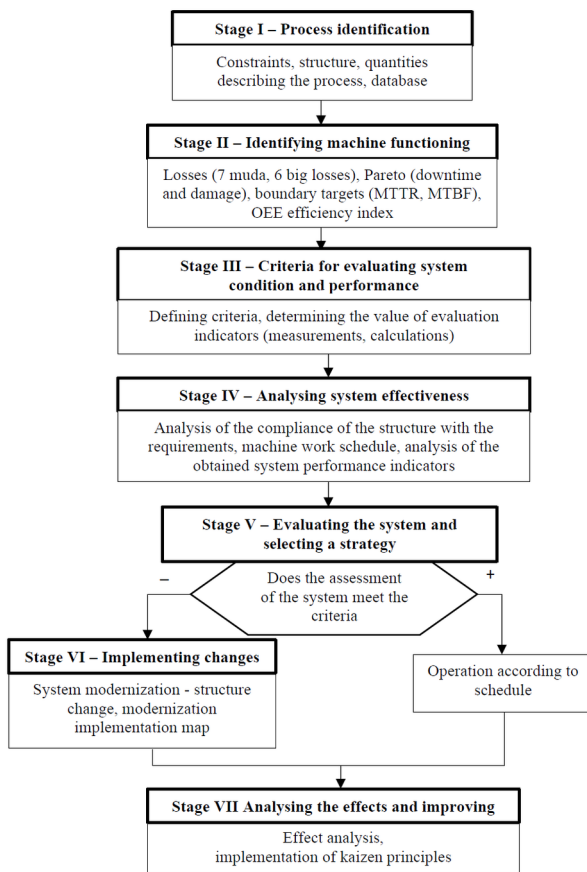


Fig. 4. Block diagram of the system state assessment method

4. Exemplification – the main drainage system

4.1. System identification

The main water drainage system analysed (Figure 5), is located in an underground mine at the 500 m level. Ten pumping units (P1 to P10) consisting of OW250/8 pumps and SCUd134u motors are installed in the main drainage pumping station. Each pumping unit is connected to two pressure pipelings with diameters of 500 mm,

through which water is pumped to the surface at the height of $H = 500$ meters. Based on the hydrological conditions and the size of the underground excavations, the projected water supply is $0.28 \text{ m}^3/\text{sec}$ ($16.83 \text{ m}^3/\text{min}$), which means that the daily water supply is equal to 24235 m^3 . The capacity of the water roads in which water is collected is 20196 m^3 . The requirements for the main drainage equipment are governed by the *Regulations of the Minister of Energy of 2016* and stipulate that the discharge of the daily inflow of water must be realized in a time not exceeding 20 hours, and the minimum number of pumps is determined by the relation: $i = 2n + 1$ (n – the calculated number of pumps).

A schematic of the main drainage system under study is shown in Figure 5.

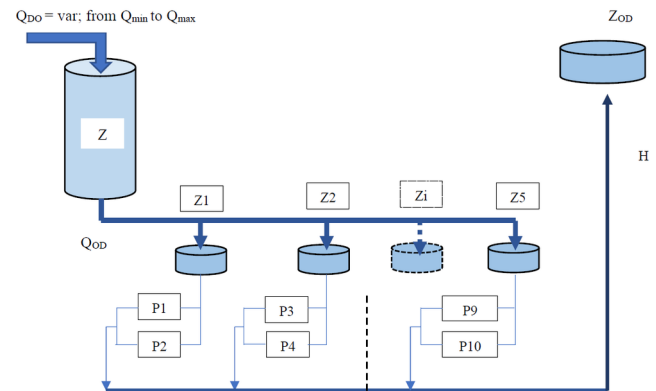


Fig. 5. Diagram of the main drainage system

With the forecasted mine water inflow, the required total pumping capacity, meeting the limitations of the mining regulations, is $Q = 20,20 \text{ m}^3/\text{min}$ (pumping for 20 hours), while the pumping head $H_u = 530 \text{ m}$. The eight-stage OW250/8 pumps installed in the pumping station have a rated capacity of $Q = 8.33 \text{ m}^3/\text{min}$ ($500 \text{ m}^3/\text{h}$) and a head $H_u = 560 \text{ m}$. The requirements specified by mining regulations are met with two pumps working continuously and the third pump working half the time. Having considered that, the number of pumps required (assuming a total number of pumps $n=3$) is seven – according to the rules: $i = 2n + 1$. There are ten pumping units in the pumping station, i.e., the main drainage system analysed is definitely overdimensioned.

The basic principles of monitoring the technical condition of pumping units were described by Nowicki [21, 22], and other diagnostic tests related to the test object (drainage system) were presented in papers [25] and [35].

A complete analysis of the main drainage system operation included:

1. Measurement of operating parameters
 - analysis of water composition and quality,
 - determination of pump characteristics,
 - characteristics of flow pipelines (manifolds),
 - the suction height of the pumping system.
2. Assessing the technical condition of pump units
 - testing the thickness of the discharge manifold walls,
 - measuring the power consumed by the pump,
 - vibro-acoustic diagnostics of pump units.
3. Qualitative and quantitative assessment and classification of failures and damages for a 5-year period.

To calculate the parameters of the flow characteristics of the pumps, known relationships were used to determine the values:

- useful lifting height H_u ,
- c velocities of water in the suction and discharge ports,
- P_u power output transferred to the pumped water flow,
- η_{zp} efficiency of the pump unit (related to the power of electric motors),

- P_m power on the pump shaft,
- η_p pump efficiency.

In order to evaluate the condition of the pumps, sections of the catalogue characteristics in terms of measured changes in pump performance are plotted on the figures. Figures 6 and 7 show examples of the characteristics of pump #1 (P1).

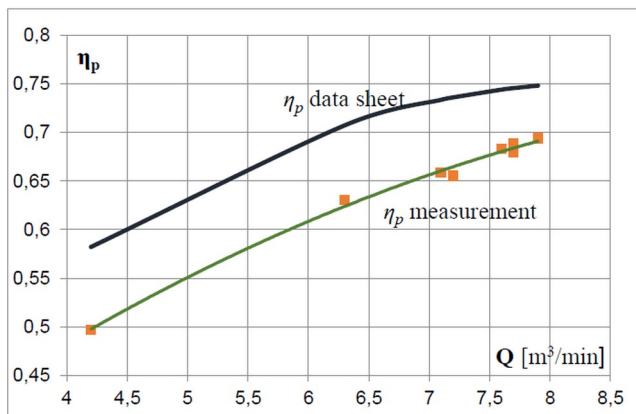


Fig. 6. P1 pump utility power characteristic

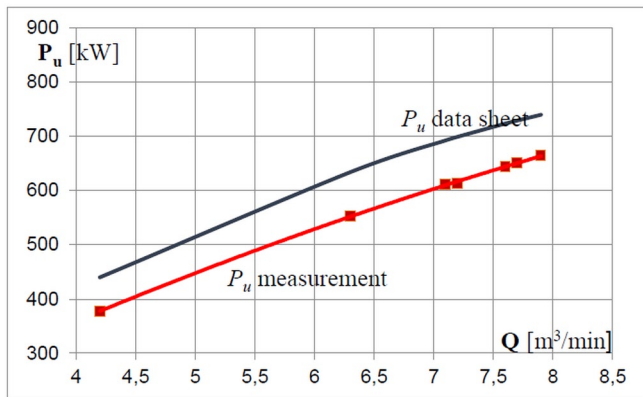


Fig. 7. Efficiency characteristics of pump P1

The efficiency of pump no. 1 is lower than catalogue efficiency from about 8% at 8 m³/min to 14% at 4.5 m³/min. The nature of pump operation means that the useful head characteristics are minimally affected by throttling. The decisive factor is the geometric head $H_g = 489$. The pressure increase in the pump depending on the flow resistance is relatively small, amounting to a few percent (approx. 5% on average) with respect to the geometric head.

Table 1. Comparison of operating parameters of pump units at maximum efficiency

		P 1	P 2	P 3	P 4	P 5	P 6	P 7	P 8	P 9	P 10	average
Volumetric stream Q	m ³ /min	7,9	8,1	9,2	8,1	8,5	8,4	8,0	9,2	7,6	8,2	8,3
Effective head H_u	m	514,7	523,6	535,1	508,8	516,4	513,9	498,2	514,0	503,3	498,2	512,6
Electrical power P_{el}	kW	1030	1214	1200	1195	1263	1275	1266	1399	1137	1314	1229
Pump efficiency η_p	--	0,694	0,614	0,721	0,615	0,613	0,595	0,553	0,594	0,591	0,547	0,614
Relative pump efficiency η_p/η_{pk}	--	0,93	0,82	0,97	0,82	0,81	0,79	0,74	0,80	0,79	0,73	0,82
Energy consumption q_p	kWh/m ³	2,173	2,498	2,174	2,459	2,476	2,530	2,638	2,534	2,493	2,671	2,465
Total pump operating time $\Delta\tau$	h	3336	12032	757	21000	24000	29017	24015	6015	23473	32041	17569
Pump operating time $\Delta\tau_R$	h	238	3142	1667	1470	1857	646	299	2883	1936	3837	1634

Pi – pump units, i = 1 ÷ 10.

Similar characteristics were developed for all other pumps (P2 through P10). Additionally, characteristics were developed for each pump unit:

- flow Q in relation to the discharge height H ,
- power output P as a function of stream flow rate Q .

4.2. Analysis of the study results

Efficiency, energy consumption, and unit pumping costs were determined for all of the main drainage pumping units studied. The results obtained are placed in Table 1.

The value of the quotient of the efficiency ratio η_p and the catalogue efficiency η_{pk} of the pump at a fixed water flow was taken as a quality measure of the pump condition. A smaller quotient value indicates a worse condition of the operating pump. For the pumps tested, the value of the η_p/η_{pk} quotient takes values in a wide range. For pumps 1 and 3, it has a value above 0.90, while for pump 10, it is only 0.73. The condition of pumps for which this quotient takes values below 0.80 should be considered unsatisfactory. The average value for all pumps in the pumping station is $\eta_p/\eta_{pk} = 0.82$ (relatively low, close to unsatisfactory).

Table 1 also shows the coefficients determining the pumps energy consumption q_p . The q_p coefficient determines the amount of electricity in kWh needed to pump out 1 m³ of water. This is one of the most important indicators of system evaluation, as it directly affects operating costs. For the pumping units of the studied pumping station, the energy consumption of the water pumping-out process takes the values $q_p = 2.173 \div 2.671$ kWh/m³, whereas the mean value is $q_p = 2.465$ kWh/m³. The value of costs should be related to the current price per unit of delivered electricity. The energy consumption of water pumping is shown in Figure 8, with the red line indicating the average value for the main drainage pumping stations.

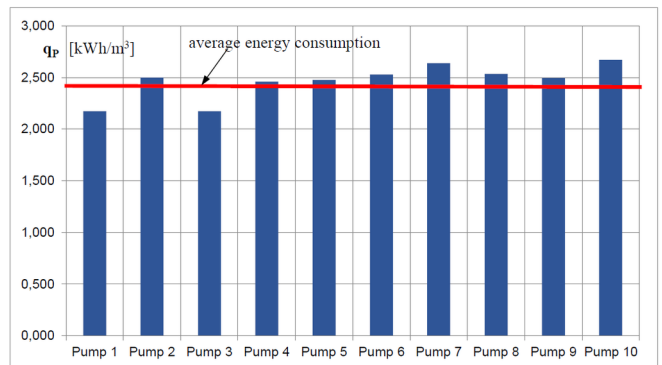


Fig. 8. Energy consumption of the pumping-out process

Figure 9 shows the efficiency of the pumps as a function of operating time – it can be observed that operating time above 5,000 hours

results in a clear drop in efficiency. The dependence of energy consumption on operating time is illustrated in Figure 10. The course of the energy consumption curve is obviously the opposite of the efficiency characteristics.

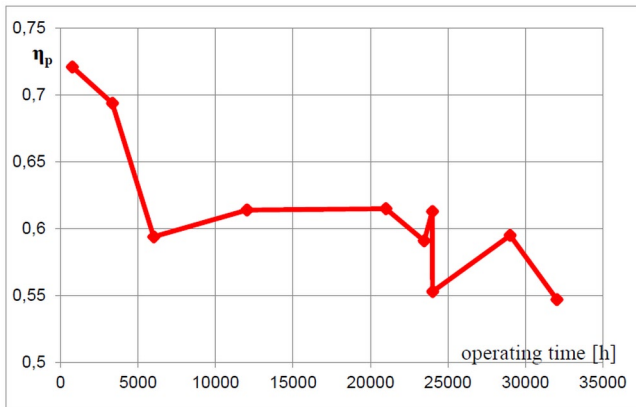


Fig. 9. Dependence of average pump efficiency on time

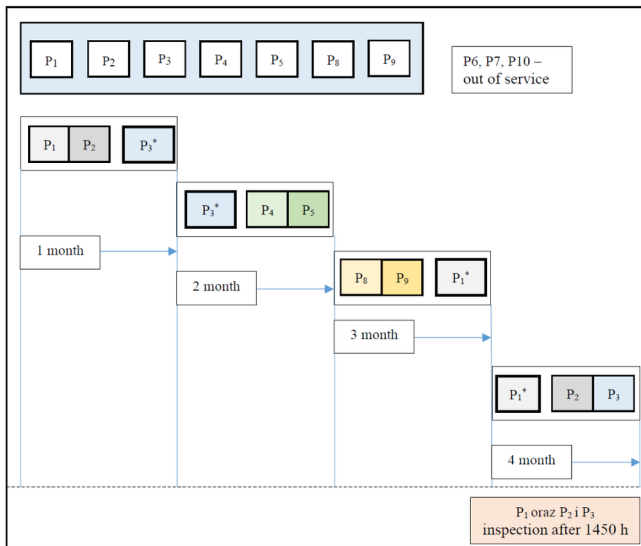


Fig. 10. Time dependence on the mean energy consumption

Above 5000 hours, there is a deterioration of pump technical condition due to operational wear, which results in an increase in demand for electricity to pump out 1m^3 of water – from about 2.17 to 2.67 kWh/m³.

4.3. Suggested changes

The conducted study and the analysis of the obtained results allow to clearly state that the assessment of the drainage system technical condition is unsatisfactory. According to the proposed evaluation method (stages V and VI – Figure 4), a system upgrade is required. The most significant elements of the proposed upgrade are:

- taking out of service units showing high wear (P6, P7, P10),
- double-variant operational improvement (for existing and new units),
- developing a model schedule for units (Figure 11),
- developing an implementation map for system upgrades (several years, high purchase and investment costs).

OPTION 1 – for existing units (motor + pump)

Proposed model unit operation schedule (3 + 3 + 1).

Decommissioning of units: P6, P7, P10, monthly unit cycles.

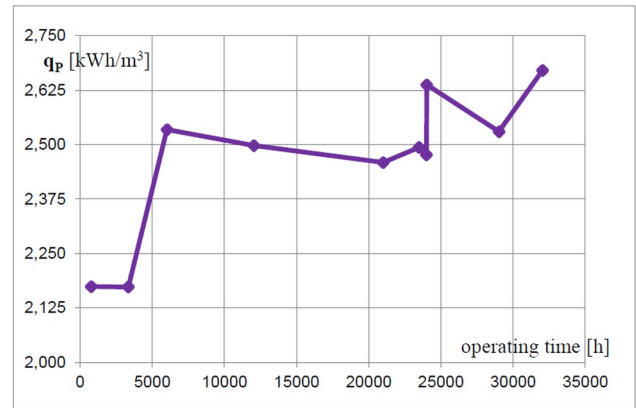


Fig. 11. Work schedule for pumping units – variant (3+3+1)

OPTION 2 – for new units (purchase)

Structure: 5 pumping units; arrangement (2 + 2 + 1).

unit selection (motor + pump): to be determined – the best.

Selection criteria: performance, efficiency, electrical power, price.

5. Summary

In systems executing tasks associated with continuous supply of the material (24 hours a day) and with limitations imposed on the reception and movement of these materials, there is a necessity to apply redundancy of the system elements. In case of a task in which the failure of the system poses a threat to human life and leads to environmental degradation, there are additional rules applied to determine the necessary redundancy (dependence on the industry, industry branch). The encountered cases of improper operation of these systems were the basis for the development of an original method of condition assessment and retrofitting to improve system evaluation indices. The proposed method is multi-stage (consisting of seven stages) and requires numerous identification tests, measurements, and calculations. However, it does result in correct operation of the system and a clear reduction in costs.

The application of the developed method is presented on the example of the main drainage pumping station located at 500 m level of an underground mine. The system consists of ten pumping units (P1 to P10). Continuous pumping activity requires the operation of 2.5 pumping units with a total capacity of 20.20 m³/min. This results in a requirement for 7 pumping units (as per $i = 3+3+1$). The analysed system is thus clearly overdimensioned. The measurement results and the characteristics and quality indicators determined from them demonstrate unsatisfactory or poor condition of most pumps. This is mainly a consequence of long pump operation times with no overhauls (with 6 pumps working for over 20,000 hours). Analyses show that the operation runs properly up to 5,000 operating hours, with a clear drop in efficiency above this number. Most pumps are about 20% less efficient than the catalogue efficiency of new pumps. Pumping efficiencies as low as those obviously translate into increased energy consumption and unit cost of pumping the water out (with energy consumption increasing from 2.173 to 2.671 kWh/m³). It can be concluded that the energy consumption and the cost of the pump-out process increases at the same rate as the efficiency decreases, which is about 20%. System upgrades are required due to the high energy consumption and operating cost ratios. Modernization should include the gradual installation of new pumps, with significantly better technical and economic indicator values. The authors proposed a new solution for this system, in which one can optionally choose a version with five (2+2+1) new units (more expensive solution) or with seven (3+3+1) pump units. A schedule for implementing changes to the system was also proposed as a part of the modernization.

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