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THE DEVELOPMENT OF THE THEORY OF OPERATION OF MINE MACHINE SYSTEMS OF NON-CONTINUOUS ENGINEERING STRUCTURES - BASIC RESULTS OF INVESTIGATIONS

Summary. This paper provides: basic results of the investigations into the calculation and analysis of dynamic multiproduct, multichannel, cyclic machine systems which are a formal model of transport-and-winning systems operating in mining, and also regeneration systems; nomogram for calculation of these systems; a principle of combining single systems into multiple systems, which are a formal model of winning-and-transport systems with regeneration, in this case specificity of systems used in mining was taken into account; basic results of the investigations concerning the developed simulation method and simulator of operation of winning-and-transport systems with regeneration.

1. INTRODUCTION

In both open-cast and underground mining, the physico-mechanical properties of rocks and the geological structure of deposits require the application of non-continuous engineering processes to winning and haulage. In effect, winning-and-transport machine systems of non-continuous engineering structures are in operation both in open-cast and underground mines. Figs. 1 and 2 represent pictorial and calculation diagrams of these systems. The specific feature of the systems identified in Figs. 1 and 2 is the fact that both winning systems (U) and transport systems (T) are cyclical systems; and - furthermore, - they are interdependent (in the sense of operation effects). This dependence results formally from the fact that one stage is common, eg in the case of transport system, it is "loading of winning", and in the case of winning system, it is "remowing of winning from working face". These phases are formally identical. The effective application of winning-and-transport systems depends significantly on a correct choice of machines an devices which are constituents of these systems. For this reason, there was a need, stemming from engineering practice, to develop a theory of cyclic multiple systems and to adapt it for practical applications to the design of new systems as well as to testing and improving systems which are already in operation. In [1] is given a way of solving single cyclic systems; another approach to this problem being presented in [2], and - subsequently - in [2, 3] are pre-

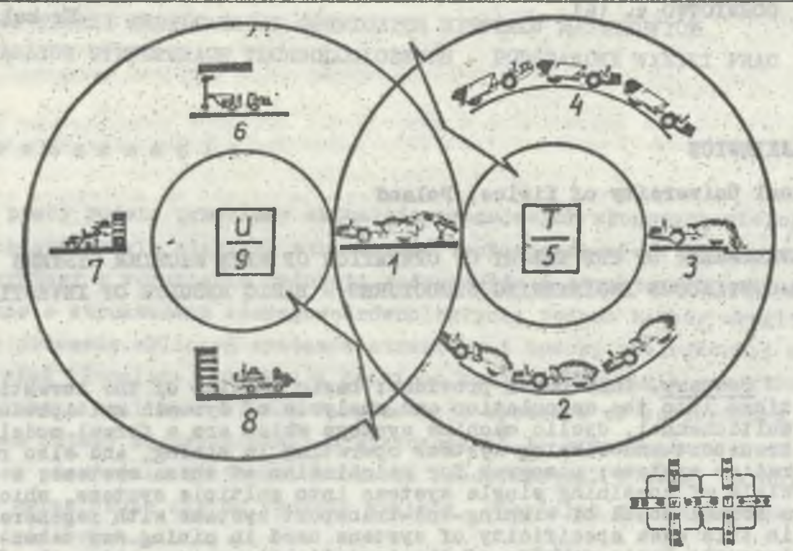

Fig. 1. Diagrams of machine winning-and-transport system in underground mining

a) pictorial diagram, b) calculation diagram

Rys. 1. Schematy systemu maszynowego urabiająco-transportowego stosowanego w górnictwie podziemnym

a) poglądowy, b) obliczeniowy

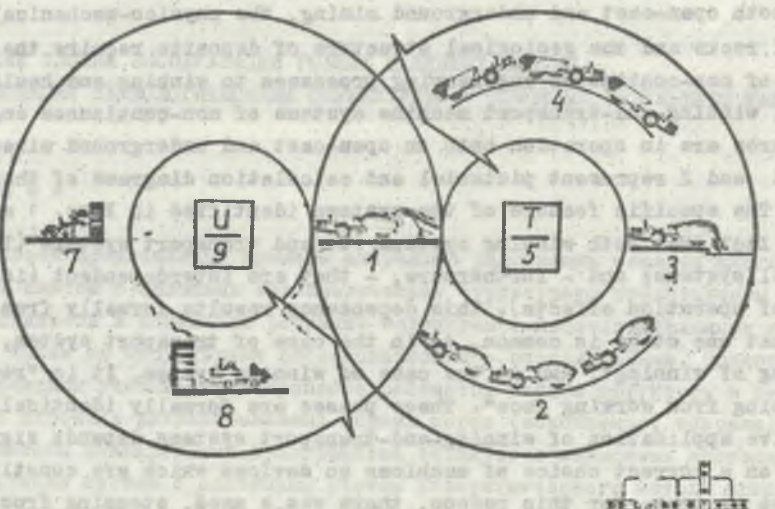

Fig. 2. Diagrams of machine winning-and-transport opencast mining:

a) pictorial diagram, b) calculation diagram

Rys. 2. Schematy systemu maszynowego urabiająco-transportowego stosowane w górnictwie odkrywkowym

a) poglądowy, b) obliczeniowy

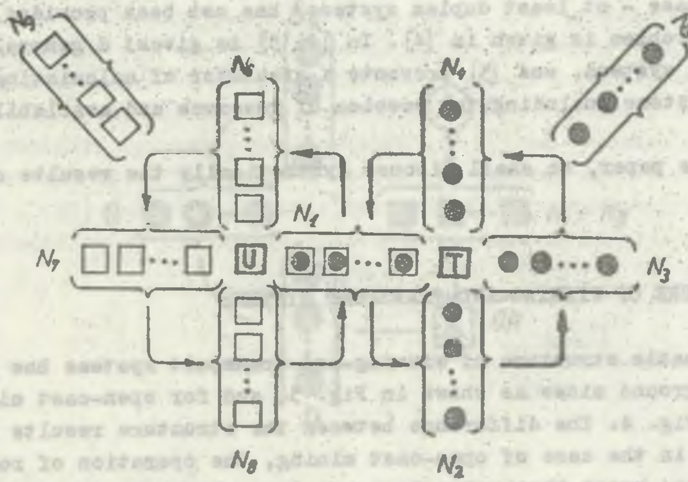

Fig. 3. Diagram of the structure of flat winning-and-transport system in an underground mine

Rys. 3. Schemat struktury oddziałowego systemu urabiająco-transportowego kopalni podziemnej

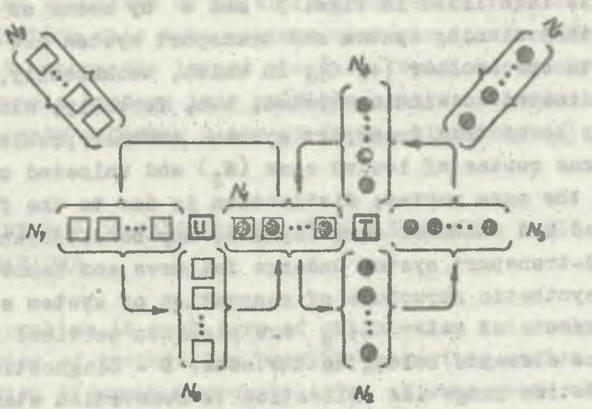

Fig. 4. Diagram of the structure of winning-and-transport system in an opencast mine

Rys. 4. Schemat struktury systemu urabiająco-transportowego kopalni odkrywkowej sented applications of the developed methods to the calculation of systems operating in mining. In both cases, a method of solving multiple systems (in our case - at least duplex systems) has not been provided. Solution to this problem is given in [4]. In [2, 5] is given: a general solution of cyclic systems, and [5] presents a simulator of calculating multiple cyclic systems including the problem of reserves and availability of systems.

In this paper, we shall discuss synthetically the results obtained so far.

2. STRUCTURE OF WINNING-AND-TRANSPORT SYSTEMS

A schamatic structure of winning-and-transport systems has the form for underground mines as shown in Fig. 3, and for open-cast mining as shown in Fig. 4. The difference between the structure results from the fact that in the case of open-cast mining, the operation of roof bolting is not made; hence the system does not accomplish the operation of "roof bolting"; therefore, a set of elements $N_6 = \emptyset$. In winning -and-transport systems, serviced elements (devices) include working faces (set N_9) and wheel cars (set N_5), respectively. Service elements (devices) include cars (set N_6), gadding cars (set N_7), shot gangs, and accompanying devices (set N_8), loaders (set N_1), travelling routes of loaded cars (set N_2), unloaders (set N_3), routes of inloaded cars (set N_4). Operations accomplished by sets of service devices are referred to as service stages. Sequence of stages is identified in Figs. 3 and 4 by means of arrows. It should be noted that winning system and transport system are hierarchically subordinated to one another [4, 6]; in which, technically, transport system is subordinated to winning system, but, formally, winning system is hierarchically lower than transport system. Another problem to be accounted for concerns routes of loaded cars (N_2) and unloaded cars (N_4). These are as a rule the same routes; distinction is due to the fact that service rates of loaded and unloaded cars (speeds) may be different. Elements of winning-and-transport system undergo failures and hence renovation is necessary. A synthetic structure of renovation of system elements is shown in Fig. 5. Elements of sets $N_1 \div N_9$ are elements serviced in renovation system, service elements belong to the sets: D - diagnostic stands that identify renovation range and allocation to renovation stands; - O - renovation stands; Dk - diagnostic stands that check correctness of renovation. Furthermore, in renovation systems, we distinguish a set of elements awaiting renovation (OR), and a set of elements awaiting to be reintroduced to operation (R). It should be noted that renovation system of a structure as shown in Fig. 5 may concern: an arbitrary set ofram sets $N_1 \div N_9$,

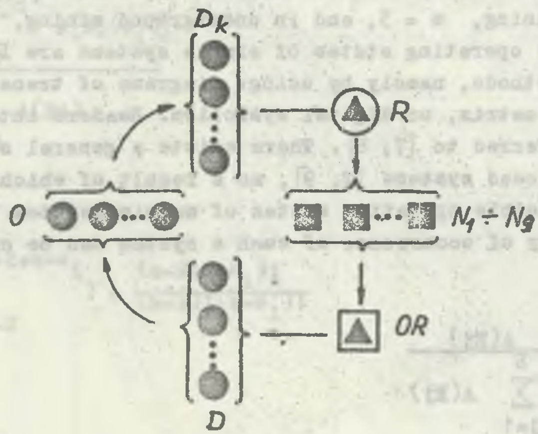

Fig. 5. Diagram of the structure of regeneration of elements of winning-and-transport system

Rys. 5. Schemat struktury odnowy elementów systemu urabiająco-transportowego

a set of elements (parts, sub-units, units) belonging to one or several sets, or some of these sets. Therefore, by combining the structures of systems as in Figs. 3 or with the structures of renovation systems, we obtain a complex structure of multiple hierarchical systems [6]. The principle of calculating this type systems consists in successive calculation of systems that occupy the lowest place in formal hierarchy and in combining single dynamic systems into multiple systems in order to calculate systems that occupy a higher place in formal hierarchy [4].

3. ANALYTICAL METHOD OF CALCULATING SINGLE SYSTEMS - BASIC RESULTS OF INVESTIGATIONS

The outset problem in each form of calculation and analysis of systems is identification of technically possible operating states of systems and determination of boundary probabilities of occurrence of such states.

The number of technically possible operating states of a system can be established from the formula

$$E = \binom{m-1+w}{m-1} = \frac{(m-1+w)!}{(m-1)!\,w!} \tag{1}$$

where: m is the number of system states; w is the number of serviced devices (eg power of sets N_5 or N_9). As it results from Figs. 3 and 4, in transport systems employed in mining, m = 4; whereas in winning systems in open-cast mining, m = 3, and in underground mining, m = 4. Technically possible operating states of single systems are identified by one of the three methods, namely by using: diagrams of transition, graphs, transpose of a matrix, or digital symbolism. Readers interested in these methods are referred to [7, 8]. There exists a general solution for multistage cyclic closed systems [2, 9], as a result of which for definite technically possible operating states of machine system (Ej), the boundary probability of occurrence of such a system can be calculated from the formula

$$p(Ej) = \frac{A(Ej)}{\sum_{j=1}^{E} A(Ej)} \tag{2}$$

in which

$$A(Ej) = \prod_{i=1}^{m} \frac{\bar{\Theta}_i^{w_i}}{\binom{w_i}{N_i}_{\circ}} \tag{3}$$

$$\binom{w_i}{N_i}_{\circ} = \begin{cases} w_i & ; \text{ for } w_i \leq N_i \\ N_i!N_i^{(w_i-N_i)} & ; \text{ for } w_i > N_i \end{cases} \tag{4}$$

where: w_i is the number of serviced devices (eg wheel cars, working faces) on the ith stage at the time of occurrence of state Ej; N_i is the number of service devices on the ith stage; $\bar{\Theta}_i$ is the mean time of service of devices serviced by service devices on the ith stage.

The technique of calculating $\bar{\Theta}_i$ in the case when engineering characteristics of serviced or service devices are different is given in [2, 7, 8]. An important problem to solve is determination of the degree of utilization of machines and devices of the system and its throughput. For this purpose we must calculate:

- boundary probability $p(w_i)$ that on the ith stage there are w_1 serviced machines or devices;
- boundary probability $p(k_i)$ that the kth service machine or device on the ith stage is engaged by a serviced device.

Respectively:

$$p(w_i) = \frac{\sum_{j=1}^{E_i(w_i)} A[Ej(w_i)]}{\sum_{j=1}^{E} A(Ej)} \quad (5)$$

where:

$$Ej(w_i) = \binom{m-2+W-w_i}{m-2} = \frac{(m-2+W-w_i)!}{(m-2)!(W-w_i)!} \quad (6)$$

and

$$p(k_i) = \sum_{w_i=k}^{W} p(w_i) \quad (7)$$

The mean boundary number of machines or devices of the ith stage which service the serviced machines of devices can be calculated from the mula

$$\bar{N}_i(p) = \sum_{w_i=1}^{N_i-1} w_i\, p(w_i) + N_i \sum_{w_i=N_i}^{W} p(w_i) \quad (8)$$

The mean boundary number of serviced machines and devices which await servicing on the ith stage will be calculated from the formula

$$\bar{u}_{i(o)} = \sum_{w_i=N_i+1}^{W} (w_i-N_i)\, p(w_i) \quad (9)$$

The system throughput equals that of any stage of the system, while throughput of a stage is equal to the sum of throughputs of devices that service that stage. Throughput of the ith device on the ith stage will be calculated from the formula

$$W(k_i) = p(k_i) \cdot Td\, \mu_i\, \bar{V} \quad (10)$$

where: Td is time of readiness; $\overline{V}$ is a mean number of medium (mineral of definite quality, overlay, etc.) contained in one serviced device (working face, wheel car, etc.); μ_i is a mean intensity of servicing a device operated by a service device on the ith stage; μ_i is calculated from the formula

$$\mu_i = (\overline{\theta}_i)^{-1} \tag{11}$$

Formula (11) holds for stationary processes of service of the Markov type. Because of (10), throughput of the system is calculated from the formula

$$Ws = \sum_{k=1}^{N_i} \underline{W}(k_i) \tag{12}$$

It is worth noticing that in formula (10)

$$p(k_i) \cdot Td = Tef. \tag{13}$$

is an effective time of handling the ith device on the ith stage.

On the grounds of the given formulae, a nomogram was developed (Fig. 6) for the calculation of machine systems. Using this nomogram one can:
a) calculate the throughput of the system for a given set of machines and devices, the procedure being illustrated in Fig. 7; for a determined throughput of the system and known engineering characteristics of machines and devices included in the system, one can select their number, the relevant procedure being illustrated in Fig. 8.

Using the given formulae or nomogram, one can optimize the selection of a system with regard to maximal utilization of machines and devices, or expanding this problem - with regard to minimal operating costs. When we use the nomogram, maximal utilization of machines and devices will be achieved if all throughput Q_o determined by means of nomogram for wheel cars (Q_{ow}), loading devices (Q_{oz}), and unloading devices (Q_{or}) are practically equal to one another, ie

$$Q_{ow} = Q_{oz} = Q_{or} \tag{14}$$

at simultaneous achievement of required throughput of the system. In order to illustrate the influence of the number of wheel cars (w) on the system throughput (w_s) and the number of machines awaiting service on the stage "loading" of wheel cars (stage 1), ($\overline{U}_1(0)$)Fig. 9 shows an example of analysis of a system consisting of two loading devices, one unloading

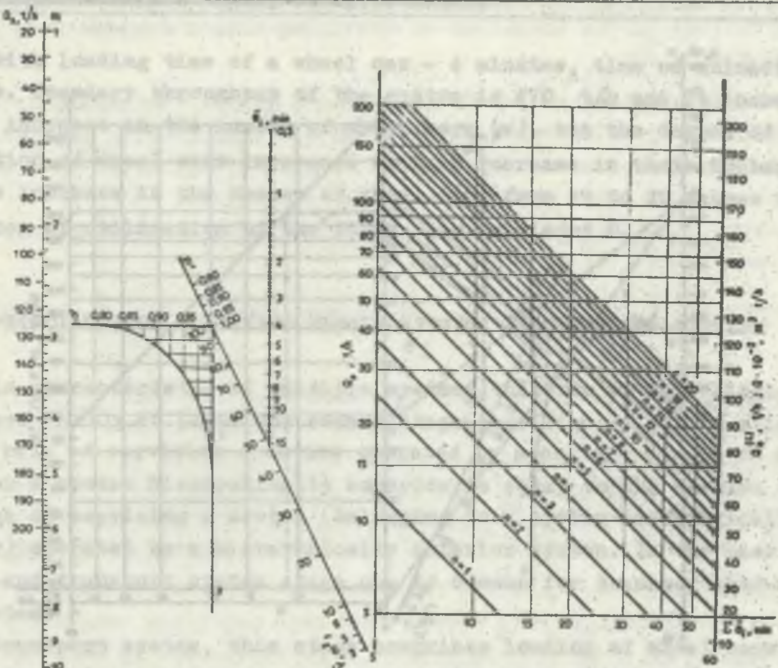

Fig. 6. Nomogram ofor calculation of machine systems
Rys. 6. Nomogram do obliczania systemów maszynowych

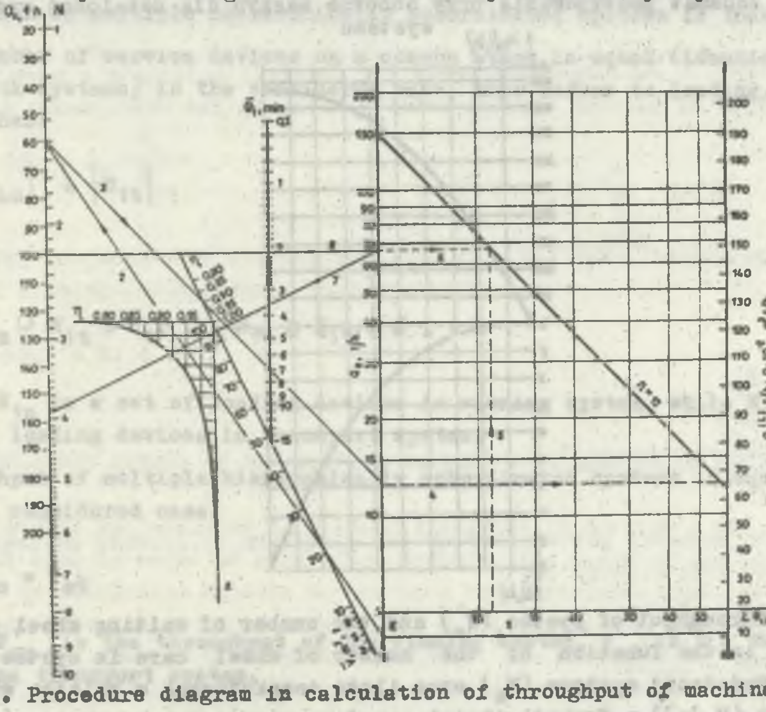

Fig. 7. Procedure diagram in calculation of throughput of machine systems
Rys. 7. Schemat postępowania przy obliczaniu wydajności systemów maszynowych

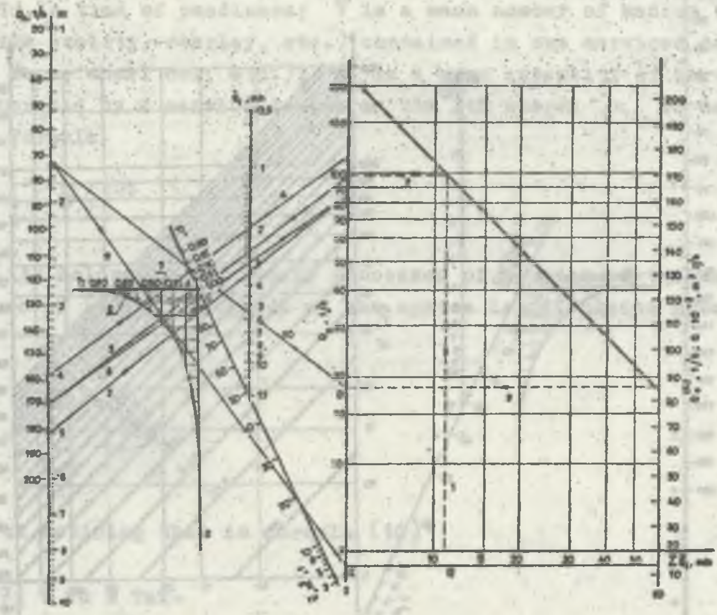

Fig. 8. Procedure diagram in selection of machines for a determined throughput of system

Rys. 8. Schemat postępowania przy doborze maszyn dla ustalonej wydajności systemu

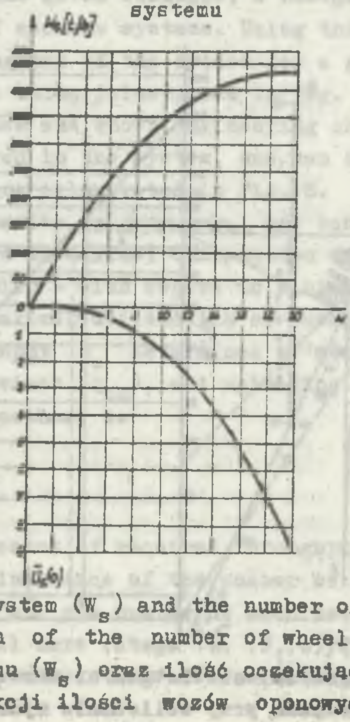

Fig. 9. Throughput of system (W_s) and the number of waiting wheel cars ($U_1(0)$) in the function of the number of wheel cars in system (w)

Rys. 9. Wydajność systemu (W_s) oraz ilość oczekujących w kolejce wozów oponowych ($U_1(0)$) w funkcji ilości wozów oponowych w systemie (w) device with loading time of a wheel car - 4 minutes, time of unloading - 1 minute. Boundary throughput of the system is 470 t/h and it increases with an increase in the number of wheel cars (w), but the degree of non-utilization of wheel cars increases with an increase in their number, and thus the increase in the number of wheel cars from 19 to 20 causes that the degree of utilization of the 20 th car is almost 0.

3. THE PRINCIPLES OF COMBINING SINGLE SYSTEMS INTO COMPLEX SYSTEMS

It is characteristic of multiple systems that two or more single systems have jointly at least one common stage (see Figs. 1÷4), in which intensity rate of servicing a device operated by a service device on a common stage for a system hierarchically superior is equal to the reverse of mean time of servicing a device (belonging to a system hierarchically superior) operated by a hierarchically inferior system. In the case of winning-and-transport system stage one is common for transport-and-winning system.

For transport system, this stage comprises loading of wheel cars, and for winning system, this stage comprises servicing of working faces by transport system, more precisely - by loaders. An obvious condition of cooperation of multiple hierarchically subordinated systems is that:

- the number of service devices on a common stage is equal (identical) for both systems; in the considered case, this refers to loading, devices, then:

$$\left|N_{1u}\right| = \left|N_{1t}\right| \tag{15}$$

in which

$$N_{1u} \cup N_{1t} = N_1; \qquad N_{1u} \cap N_{1t} = \emptyset \tag{16}$$

where: N_{1u} is a set of loading devices in winning system, while N_{1t} is a set of loading devices in transport system;

- throughput of multiple hierarchically subordinated systems is equal: in the considered case,

$$W_{su} = W_{st} \tag{17}$$

where: W_{su} is the throughput of the winning system, W_{st} is the throughput of the transport system.

The essence of the principle of combining single systems into multiple systems is:

- to determine the mean time of servicing a device (belonging to a hierarchically superior system) operated by a hierarchically inferior system; in the considered case, this refers to the determination of a mean export time of fired winning from the working face ($\bar{\Theta}_{1u}$);
- to select machines and devices for a hierarchically superior system so that condition (17) be fulfilled.

Proceeding to determine $\bar{\Theta}_{1u}$, let's note that

$$C = \text{ent}\left[\frac{\bar{Q}}{\bar{V}}\right] \tag{18}$$

where: $\bar{Q}$ is the mean amount of winning fired in the working face; $\bar{V}$ is mean carrying capacity of wheel cars; C is the number of loading cycles of wheel cars. Mean service time of the working face operated by transport system equals

$$\bar{\Theta}_{1u} = C\ \bar{\Theta}_{1t} + \bar{T}_o \tag{19}$$

where: $\bar{\Theta}_{it}$ is mean loading time of wheel car; T_o is mean waiting time of loading machines for wheel cars during loading of winning in the amount of $\bar{Q}$.

In order to calculate the value $\bar{T}_o$, we shall calculate a mean boundary probability of waiting time of loading machines for wheel cars; it equals

$$p_{o1} = 1 - \frac{\sum\limits_{k=1}^{N_1} p(k_1)}{N_1} \tag{20}$$

where:

$$\frac{\sum\limits_{k=1}^{N_1} p(k_1)}{N_1} = p_{ko} \tag{21}$$

is a mean boundary probability of the operation of loading devices.

Taking into account that:

$$\frac{p_{ko}}{p_{o1}} = \frac{C\ \bar{\Theta}_{1t}}{\bar{T}_o}$$

hence

$$\bar{\tau}_o = p_{o1} \frac{C \bar{\Theta}_{1t}}{p_{ko}} \tag{22}$$

After introducing (22) into (19) and transformation, we obtain

$$\bar{\Theta}_{1u} = \frac{C \bar{\Theta}_{1t}}{p_{ko}} \tag{23}$$

which results from the fact that $p_{ko} + p_{o1} = 1$.
Formula (23) and conditions (15) and (17) basically establish the principle of combining single systems into multiple systems. It follows from condition (17) that for a known value of $\bar{\Theta}_{1u}$, one must select such a set of machines and devices in a hierarchically superior system so that this condition be fulfilled.

In the case of winning-and-transport systems, the above consideration and conclusions resulting from them should have an additional correction that the time of occupation of a loading machine by a particular working face is greater than that given by formula (23) by mean travel time of loading machines between successive working faces ($\bar{T}_m$). It is a time when a loading machine does not work; therefore, the number of loading machine determined according to the procedure as in section 2 should be increased by

$$\Delta N_1 = N_1 \frac{\bar{T}_m}{\bar{\Theta}_{1u}} \tag{24}$$

Finally, the number of loading machines required for a determined throughput of winning-and-transport system will be

$$\Delta N_{1o} = N_1 + \Delta N_1 \tag{25}$$

4. SIMULATION METHOD OF CALCULATING SYSTEMS - PRINCIPLES OF PROCEDURE

Selection and analysis of systems discussed in section 2 can,be accomplished also by means of simulation methods. The range of pro lems to be solved by simulation methods may be much more extensive than he range of problems solved by analytical methods, depending on the range of problems fed into the simulator of system operation. The developed simulation model [5] included: utilization of system elements, regeneration of system elements, magnitude of standby machines and devices their influence on stabilization of operation and throughput of system. The developed simulation of system operation [5] permits to:

- select the most optimal analysed system as regards throughput, degree of utilization of machines and devices and magnitude of stand-by;
- assess the operation of existing and designed systems as a result of determining weak elements of system and excess;
- test variations in output magnitude and stabilization of output in time depending on standby magnitude;
- test the influence of characteristics of operating parameters of system elements on output magnitude and variations in time depending on standby magnitude.

Diagrams of system structure and the structure of system regeneration were discussed in section 2. On the basis of a detailed analysis of system functioning, a general formal model was developed for that class of systems [5] for a known structure of utilization (Figs. 3 and 4) for the needs of simulation of utilization and regeneration processes. A general block diagram of simulator is shown in Fig. 10.

Without getting into details of the principles of simulator construction or characteristics and parameters of the operation of system elements and standards [5, 10, 11], we shall give only some results of a representative solution of machine system.

It was assumed that at the outset: $N_1 = 2$, $N_2 = N_1$, $N_3 = 1$, $N_4 = N_1$, $N = 5$, $N_6 = 2$, $N_7 = 3$, $N_8 = 2$, $N_9 = 28$ (for denotations of N_i, see Fig. 3). As a result of simulation of 240 working shifts, stabilization of practically all calculated characteristics was obtained, the more important ones include: demand for standby machines and devices (system throughput) waiting time of working faces for servicing by service devices, waiting time of wheel cars for service devices, utilization calendar time for servicing working faces by service devices, degree of utilization of service devices in time, waiting times of service devices for working faces. Some of the results are illustrated in Figs. 11÷14.

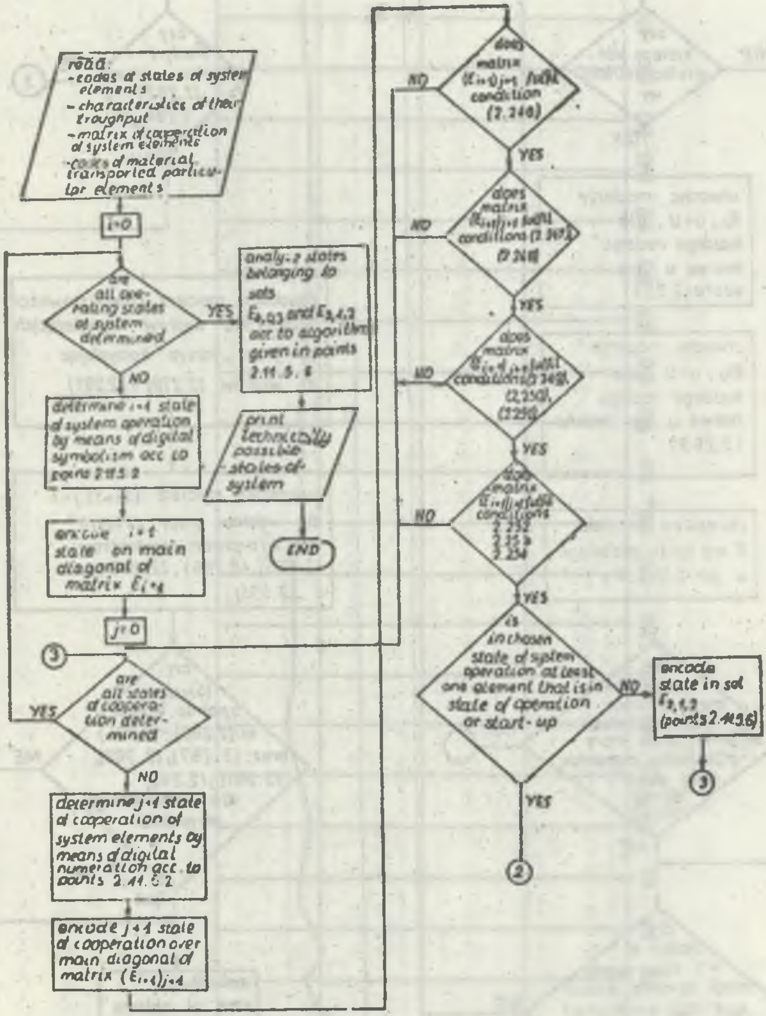

Fig. 10.1. Block diagram of simulator

Rys. 10.1. Schemat blokowy symulatora

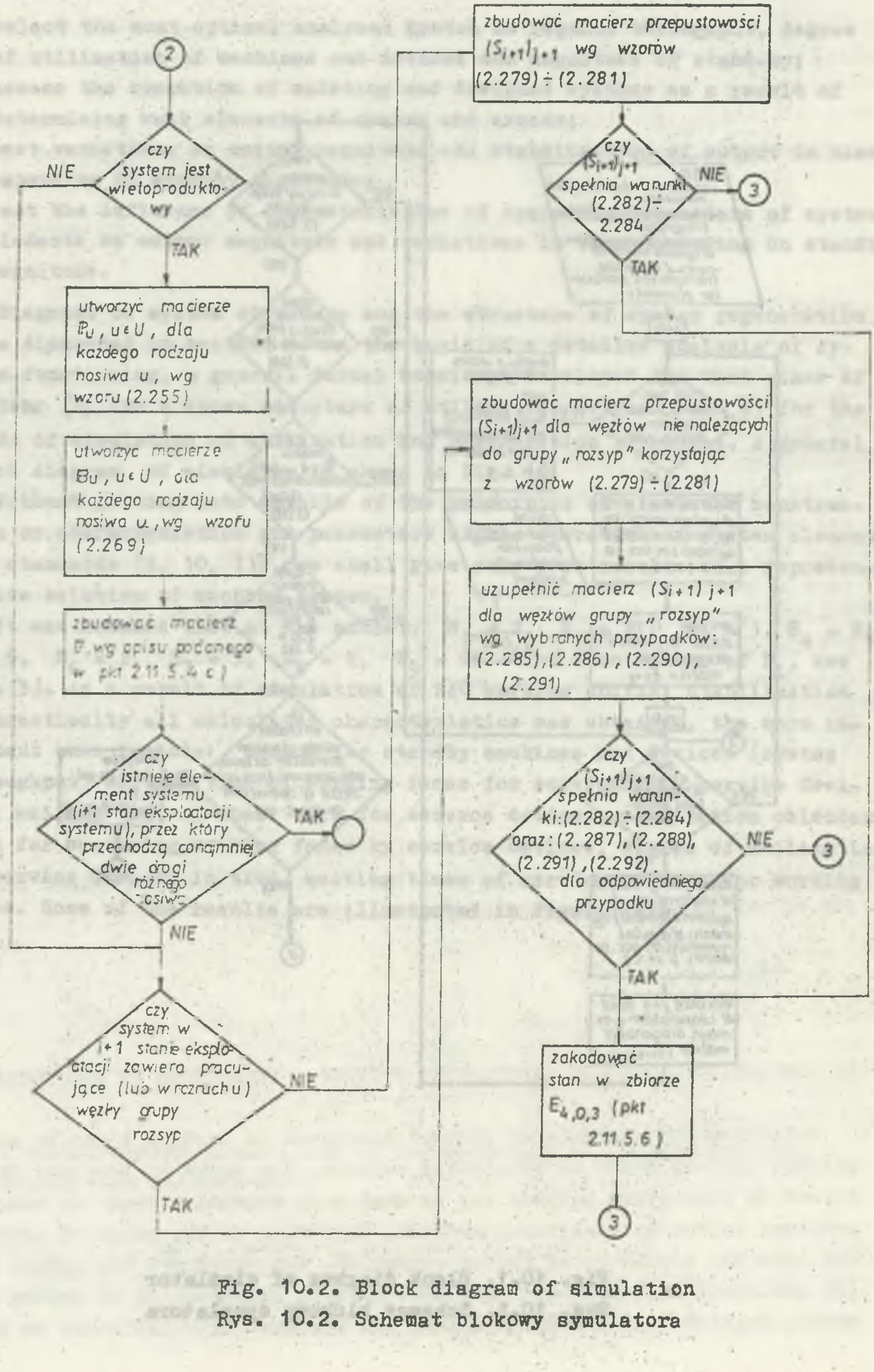

Fig. 10.2. Block diagram of simulation
Rys. 10.2. Schemat blokowy symulatora

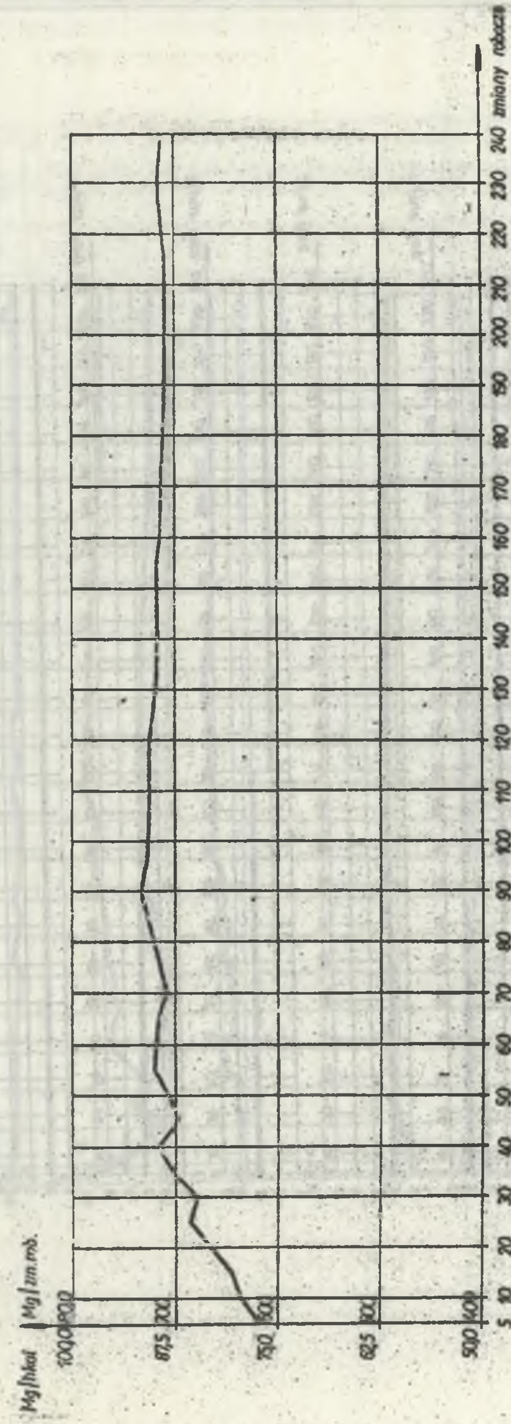

Fig. 11. Throughput of system
Rys. 11. Wydajność systemu

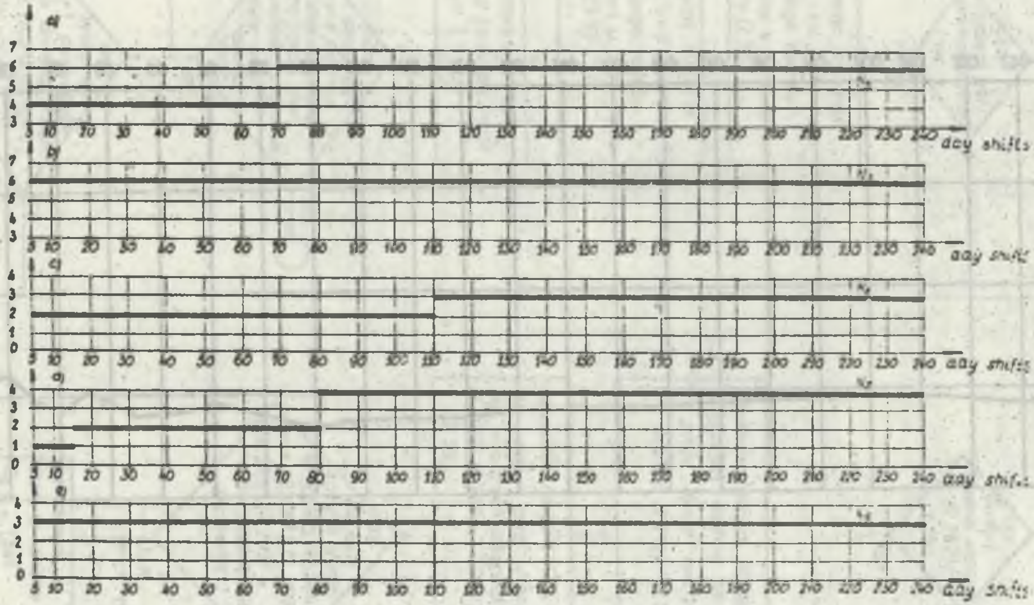

Fig. 12. Demand for standby elements

a) anchoring elements, b) gadding cars, c) firing gang, d) loading machines

Rys. 12. Zapotrzebowanie na elementy rezerwowe

a) kotwiące, b) wozy wiertnicze, c) brygady strzałowe, d) ładowarki, e) wozy oponowe

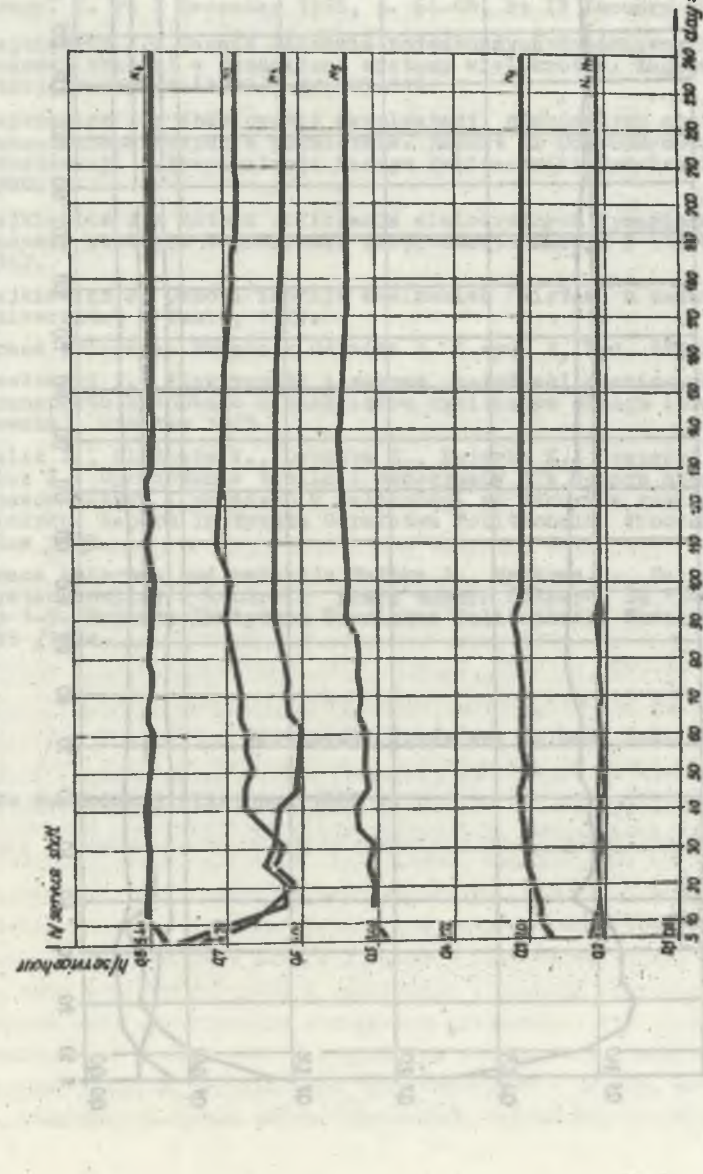

Fig. 13. Degree of utilization of set elements of system
Rys. 13. Stopień wykorzystania elementów zbiorów systemu

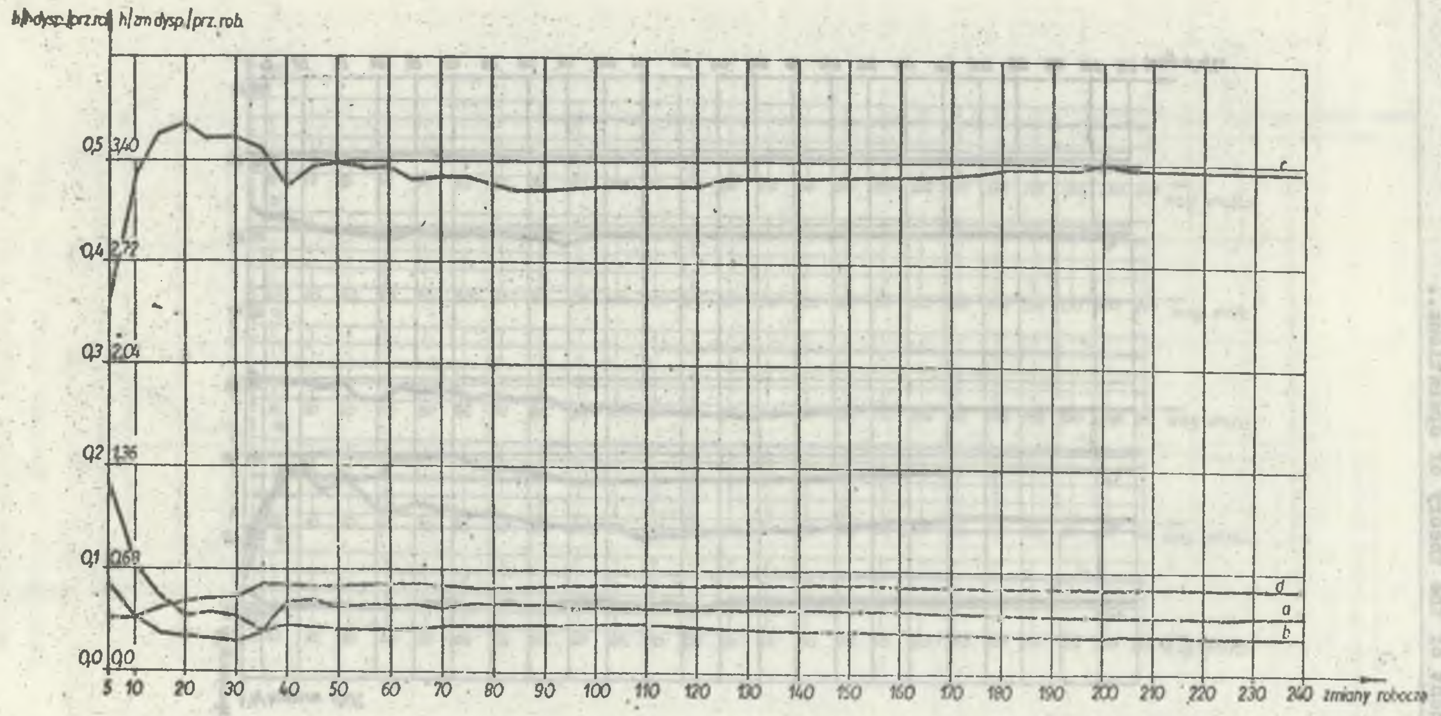

Fig. 14. Waiting of working faces for service by a) anchoring cars, b) drill cars, c) firing gangs, d) loading cars

Rys. 14. Oczekiwanie przodków roboczych na obsługę przez a) wozy kotwiące, b) wozy wiertnicze, c) brygady strzałowe, d) ładowarki

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ROZWÓJ TEORII EKSPLOATACJI GÓRNICZYCH SYSTEMÓW MASZYNOWYCH O NIECIĄGŁYCH STRUKTURACH TECHNOLOGICZNYCH - PODSTAWOWE WYNIKI PRAC

S t r e s z c z e n i e

W pracy podano: podstawowe wyniki prac z zakresu obliczania i analizy metodami analitycznymi dynamicznych wieloetapowych wielokanałowych, cyklicznych systemów maszynowych, które są formalnym modelem systemów transportowych i urabiających eksploatowanych w górnictwie, a także systemów odnowy; nomogram do obliczania tych systemów; zasadę łączenia systemów pojedynczych w systemy wielokrotne, które są formalnym modelem systemów urabiająco-transportowych oraz systemów urabiająco-transportowych z odnową, w tym przypadku uwzględniono specyfikę systemów stosowanych w górnictwie; podstawowe wyniki prac z zakresu opracowanej metody symulacyjnej oraz z symulatorem eksploatacji systemów urabiająco-transportowych z odnową.

РАЗВИТИЕ ТЕОРИИ ЭКСПЛУАТАЦИИ ГОРНЫХ МАШИННЫХ СИСТЕМ С НЕСПЛОШНЫМИ ТЕХНОЛОГИЧЕСКИМИ СТРУКТУРАМИ - ОСНОВНЫЕ РЕЗУЛЬТАТЫ РАБОТЫ

Р е з ю м е

В статье представлены основные результаты работ с области расчёта и анализа аналитическими методами динамических многоэтапных, многоканальных циклических машинных систем, которые становятся формальной моделью транспортных и разрабатывающих систем эксплуатированных в горном деле, и систем реставрации. Представлена номограмма для расчёта этих систем, принцип связи единичных систем во многократные, которые являются формальной моделью систем разработывающе транспортных и разрабатывающе транспортных с реставрацией. В этом случае взято во внимание специфику систем применяемых в горном деле. Основные результаты работ с области разрабатываемого симуляционного метода с симулятором эксплуатации систем разрабатывающе транспортных с реставрацией.