# RESEARCH AND CONSTRUCTION OF A MATHEMATICAL MODEL USING DISCRETE PROGRAMMING METHODS FOR THE MIXING AND MELTING OF COPPER CONCENTRATES

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This paper describes the construction of an optimal schedule for a metallurgical workshop using discrete programming, and in particular, the method of branches and boundaries. In this regard, a heuristic approach to solving this problem is proposed, which includes: building an initial graph that satisfies the constraints of the optimization problem, as well as sequential search optimization of the initial graph according to a given criterion. To test the effectiveness of using the task of forming a melting schedule as part of the operational control subsystem in the converter department, experimental studies were conducted. Considering that the creation of the automated process control system of the copper plant provides for the introduction of systems using modern software and hardware controls, cargo flow control, and an automated conversion process control system, the efficiency of using optimal melting schedules will significantly increase.

**Keywords.** Copper raw materials, blending, smelting.

# МЫС КОНЦЕНТРАТТАРЫН ШИХТАУ ЖӘНЕ БАЛҚЫТУ ҮШІН ДИСКРЕТТІ БАҒДАРЛАМАЛАУ ӘДІСТЕРІМЕН МАТЕМАТИКАЛЫҚ МОДЕЛЬДІ ЗЕРТТЕУ ЖӘНЕ ҚҰРУ

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Бұл жұмыста дискретті бағдарламалау арқылы, атап айтқанда, бұтақтар мен шекаралар әдісімен металлургия цехының оңтайлы графигін құру сипатталған. Осыған байланысты осы мәселені шешуге эвристикалық тәсіл ұсынылады, оған мыналар кіреді: оңтайландыру мәселесінің шектеулерін қанағаттандыратын бастапқы графикті құру, сондай-ақ, берілген критерий бойынша бастапқы графикті дәйекті іздеу жүйесін оңтайландыру. Конверторлық бөлімшеде жедел басқару кіші жүйесінің құрамымен балқыту кестесін қалыптастыру міндетін пайдаланудың тиімділігін тексеру үшін эксперименттік зерттеулер жүргізілді. Мыс зауытының баж ТП құру заманауи бағдарламалық-техникалық басқару құралдарын, жүк ағынын бақылауды, айырбастау процесін басқарудың автоматтандырылған жүйесін қолдана отырып жүйелерді енгізуді көздейтінін ескере отырып, балқымалардың оңтайлы кестелерін пайдалану тиімділігі айтарлықтай артады.

**Түйін сөздер:** мыс шикізаты, араластыру, балқыту.

# ИССЛЕДОВАНИЕ И ПОСТРОЕНИЕ МАТЕМАТИЧЕСКОЙ МОДЕЛИ МЕТОДАМИ ДИСКРЕТНОГО ПРОГРАММИРОВАНИЯ ДЛЯ ШИХТОВКИ И ПЛАВЛЕНИЯ МЕДНЫХ КОНЦЕНТРАТОВ

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В данной работе описывается построение оптимального графика металлургического цеха с помощью дискретного программирования, и в частности, методом ветвей и границ. В сзязи с этим предлагается эвристический подход к решению данной задачи включающий в себя: построение исходного графика, удовлетворяющего ограничениям оптимизационной задачи, а также последовательную поисковую оптимизацию исходного графика по заданному критерию. Для проверки эффективности использования задачи формирования графика плавки с составе подсистемы оперативного управления в конверторном отделении были проведены экспериментальные исследования. Учитывая, что созданием АСУ ТП медь завода предусматривается внедрение систем с применением современных программно-технических средств управления, контроля грузопотоков, автоматизированной системы управления процессом конвертирования, эффективность использования оптимальных графиков плавок существенно повысится.

**Ключевые слова.** Медное сырье, купажирование, плавка.

**Introduction.** The solution of the formulated problem of constructing an optimal graph using discrete programming methods, and in particular, the method of branches and boundaries, involves a large amount of calculations, difficult when implementing the system. At the first stage of the procedure, an initial graph is constructed that satisfies all the constraints of the task. i.e., it is valid [1].

Restoration of the process state in each unit of the site (at the time of the start of the algorithm) based on the initial information and using a mathematical model of the process: formation of the initial section of the graph by entering the first heats of each unit into the Gantt table, calculation based on a mathematical model of the characteristics of an exemplary melting with a given average blast consumption and an average number of buckets of loaded matte, assignment of the characteristics of all swimming trunks (except the first ones) to the values of the characteristics of an exemplary melting, filling in the Gantt table with swimming trunks, taking into account the restrictions and if the condition is met, the first stage of the procedure is completed [2].

Checking the possibility of changing the average flow rate of the blast in the required direction and calculation of the required value by which the average blast consumption must be changed and adjustment of

the average blast consumption by this value. Checking the possibility of changing the matte loading of the smelts [3]. If possible, the transition to is carried out, otherwise at the end of the first stage of the procedure. The choice of melting, which can change the matte loading in the required direction and adjust the number of loaded matte buckets [4].

**Materials and methods.** At the second stage of the procedure, a direct search for the optimal schedule is carried out by step-by-step improvement of the original schedule. The search step is to select a pair of swimming trunks for which it is possible to redistribute the material (matte) or temporary (duration of the first period and downtime after melting) resource, redistribute the selected resource, evaluate the newly obtained schedule option and, if unsatisfactory, return to the old option. The choice of two melting points in the redevelopment of the schedule, for which it is possible to redistribute the resource [5]:

1. Adjustment of the characteristics of the selected melts in accordance with the redistribution performed.

2. Checking for violation of the condition. If this condition of redistribution is violated, the transition to paragraph 7 is rejected and made, otherwise to paragraph

3. The schedule (Gantt table) is adjusted in accordance with the production redistribution of the

resource.

4. Evaluation of the change in the criterion ΔF. If ΔF < 0, then the step is considered successful and the transition is made to point 1, otherwise to point 6.

5. Return to the previous version of the schedule (reverse adjustment of the Gantt table).

6. Return resource redistribution for previously selected swimming trunks.

7. Checking for a decrease in the value of the criterion after conducting cycles of redistribution of all types of resources. If the decrease in the criterion value is not marked, the optimization procedure is completed, and the cycle is repeated from point 1.

We present an algorithm for forming the work schedule of the converter department together with a semiotic model, which form a system for forming the optimal work schedule of the converter section [6].

The purpose of the research was: to determine the feasibility of optimal schedules of converter melts generated by the system; identification of the reasons causing the deviation of the actual values from the specified melting schedules (start and end times of operations, the amount

of processed and received materials, etc.), development of recommendations to increase the degree of use of optimal melting schedules [7].

The development of an algorithm for operational control of the converter department involves testing the control algorithm together with the control object. However, conducting experiments with an algorithm that has not yet been debugged at the facility is not possible due to the strenuous operation of the separation units in industrial conditions. The output of the latter's operating modes beyond the scope of the regulated one entailed significant production losses. In addition, there are difficulties caused by the need to simultaneously measure a large number of parameters involved in evaluating the operability and effectiveness of the control algorithm. In real production conditions, this can only be done with a long delay, low accuracy and insufficient data collection frequency [8].

**Results and discussion.** In these conditions, it is advisable to debug the control algorithm based on experiments with a simulation model of the converter compartment [9]. The process of forming and using a simulation model includes the following steps: clarification of information flows into the modeling system and schemes of their transformation; assessment of the probabilistic characteristics of the material flows

of the converter unit in order to form a model of compensating effects; development of the structure of a software system that simulates the functioning of a control object based on a mathematical model of the process, development of a software system simulating the functioning of an object (with active disturbances) in conjunction with a control system; conducting simulation experiments with the software system; evaluation by a specialist of the results of the simulation experiment; adjustment of the parameters (structure) of the control algorithm [10]:

Block 1 organizes a cycle for all units in operation.

Block 2 generates the initial information for simulating the process at the time interval $\tau$ in the *i-th* unit of the site. For this purpose, values characterizing the state of the process at the end of the *t1* time interval (composition, quantity and temperature of the mass and slag in the bath), as well as the values of control actions on the time interval $\tau$ (flow rate of blast, ore, amount of poured matte and drained slag, the moment of commencement) are rewritten into the working array from the general memory area of the system or the end of blowing). These values are considered as mathematical expectations of the corresponding values.

To obtain noisy values, each of the listed parameters is exposed to interference according to the following Equation 1.

$$\Theta_j = M_{\Theta j} + \xi_{\Theta j} \qquad (1)$$

where $\xi_{\Theta j}$ - is a random variable distributed according to a normal law with zero mathematical expectation and a variance equal to the variance of the real "played" parameter obtained by statistical processing of experimental data.

The value of $\xi_{\Theta j}$ - is generated by block 8, which implements a pseudorandom number sensor with a given distribution law.The compositions of materials loaded into the converter are also subjected to noise.

Block 3 contains a mathematical model of the conversion process described in section 2, and the initial state of the process is transformed into the final one, taking into account the specified control actions.

Block 4 generates the output technological parameters of the process (temperature, amount and composition of the exhaust gas). It is assumed that the air sucked into the exhaust gas is directly proportional to the amount of converter gas to the following Equation 2.

$$M\left\{G_p[\tau]\right\} = K_p G_g[\tau] \qquad (2)$$

The value of the $K$ coefficient was found during the identification of the mathematical model. In this case, the amount and composition of the gas mixture is determined by to the following Equations 3-4:

$$G_m[\tau] = G_g[\tau] + G_p[\tau] + \xi G_p[\tau] \qquad (3)$$

$$\alpha_{so_2}^m[\tau] = \alpha_{so_2}^2[\tau]G_g[\tau]100\%/G_m[\tau] \qquad (4)$$

In addition, the block updates the values characterizing the state of the process located in the general memory area of the system, thereby preparing for the simulation of the next time interval.

In conclusion, we return to block 1 to simulate the operation of the next unit.

Block 5 calculates the parameters of the converter gas flow from the converter compartment by to the following Equations 5-6:

$$G_{\overline{m}}^{\Sigma}[\tau] = \sum_{i=1}^{n} G_m^i[\tau] \qquad (5)$$

$$\alpha_{so_2}^{\Sigma}[\tau] = \sum_{i=1}^{n} \alpha_{so_2}^i[\tau]G_m^i[\tau]G_{\overline{m}}^{\Sigma}[\tau] \qquad (6)$$

After that, the calculation of the current statistical characteristics of the total gas flow, the average downtime of the units, the average deviation of time parameters, melting parameters from those set by the graph is performed by to the following Equations 7-8:

$$\overline{X}[n] = \overline{X}[n-1] + \frac{1}{n}\overline{X}[n] - \overline{X}[n-1] \qquad (7)$$

$$\sigma_X^2[n] = \sigma_X^2[n-1] + \frac{1}{n-1}\left\{X[n] - \overline{X}[n-1])^2 - \sigma_X^2[n-1]\right\} \qquad (8)$$

The results generated by block 5 are recorded in the general memory area of the system.

Block 6 is used to simulate random disturbances on the process, reflecting fluctuations in the flow rate of blast and ore into the converter, the amount and composition of the loaded matte and other materials, the duration and moments of the beginning and end of the smelting purges. For these purposes, a standard procedure for generating pseudorandom sequences distributed according to a normal law is used. The variances of the corresponding parameters to be noisy are transmitted to block 2 and 4 when accessing block 6.

The next stage consists in the development of a software system, providing simulation of the operation of the control object together with the control system, the developed system functions as follows.

Block 1 prepares the initial values of the system time counter τ and the control time interval l. Block 2 organizes a cycle for all units of the department that are in operation. Block 3 generates the initial state of the process in the i-th unit necessary to start the system in operation, the following parameters are generated: the start time of the current melting, the average consumption since the beginning of the current melting, the number of matte buckets loaded into the current

melting by the time the system starts, the compositions of materials loaded into the current melting. This sets not only the initial conditions for the i-th unit, but also the integral control actions applied before the start of the system.

Block 4 generates a micro description of the current technological situation at the site in the language of a systematic model, thereby preparing information for the operation of the situational management unit. Information for the formation of a micro description is selected from the general memory area of the system sequentially for each unit of the site.

Block 5 generates a solution for managing the converter department based on the semiotic model of the latter. Depending on the chosen solution, a transition can be made to block 6, 8 or 9 (AB). The selected solution(s) are recorded in the general memory area of the system.

Block 6 generates the optimal work schedule of the department for a given time interval, taking into account the management decisions developed in block 5. The generated schedule is fixed in the general memory area of the system. Block 7 organizes the cycle according to the melts scheduled in block 6 for a specified time interval. Block 8 generates the optimal schedule for the next melting, in addition, if block

5 makes a decision to adjust the schedule of some melting, it generates a new schedule for it, taking into account the changed situation in the department.

Block 9 (AB) contains a simulation model of the converter compartment.

Block 10 increases the values of the accounts $\tau$ and l by one, preparing the output for the next simulation cycle. Block 11 analyzes the value of the system time. If the simulation of the next shift has ended, a transition is made to block 12, otherwise to block 14. Block 12 prints the results of the simulation of functioning during the last shift. Block 13 resets the counter values to zero, thereby switching to simulating the next shift. Block 14 analyzes the value of the counter l. If the l value is equal to the control cycle time set when the system is started, the transition is made to block 15, otherwise to block 9. Block 15 resets the l counter values to zero.

The developed simulation system allows checking the operability and effectiveness of the proposed system of operational management of the converter department in various modes of its operation. The data obtained as a result of the next cycle of the experiment is evaluated by a specialist who makes a conclusion about the quality of the control system and decides whether to adjust the control algorithm aimed at eliminating the identified shortcomings, or to end the experiment if satisfactory results are obtained, both the structure of the control algorithm and the values of its objects, the field can be adjusted then a series of experiments is repeated.

Simulation modeling of the control system showed the operability of the system and the possibility of a significant increase in the efficiency of technological processes of the metallurgical workshop during its implementation presented in Table 1.

Table 1 - System performance results

| № | The name of the indicator | Significance in current practice | Importance in situational management |
|---|---|---|---|
| 1 | Dispersion of SO content in converter gases | 2,89 | 0,36 |
| 2 | Downtime variance | 212 | 36 |

The functioning of the operational management system of the converter department is aimed at the formation of work schedules of the department, which regulate the conditions of the process and are issued as written instructions to the technological staff. It is shown above that the algorithm for forming the work schedule of the converter department ensures that the schedule is optimal from the point of view of coordinating the operation of individual units and is most appropriate to the current situation in the metallurgical workshop. The size of the planned period in the formation of the department's work schedule is determined by the established management practice, is limited by the dimension of the optimization task solved at the Central computer and is assumed to be equal to one day or less (depending on the moment of the beginning of planning). The results obtained in this case could be issued for execution once a day. However, the non-stationarity of the control object, as a rule, leads to the need to revise the schedule during the day. The main reasons for non-stationarity are:

- failures of the converter compartment units, resulting in the need to force the operating modes to perform the production program with a smaller number of operating units;

- deviations of the qualitative and quantitative characteristics of the raw materials of copper matte) from the regulated norms due to violations in the operation of the electric furnace and charge departments, leading to the need to force or artificially reduce the pace of operation of the converter department;

- disturbances in the operation of the electric furnace compartment, leading to excessive downtime of the converter compartment units, leading to excessive downtime of the converter compartment units in anticipation of the next portions of matte.

- the effect of the "human factor" - staff errors in fulfilling planned schedules, the inability to reach the planned blast consumption due to a decrease in the intensity of the work of the shapers, etc.;

- the drift of the characteristics of aggregates due to their aging, the listed factors, on the one hand, lead to significant deviations from the specified schedule, which do not allow using it in the future, on the

other hand, to the inadequacy of the mathematical models underlying the algorithm for selecting modes and, consequently, to the non-optimality or even inadmissibility of the management decisions being formed. Under these conditions, the effectiveness of the control system can be ensured by introducing a rational frequency of submission of control actions, as well as on the basis of the application of the principle of adaptation, involving the introduction of feedback on the structure and parameters of the control system.

Under these conditions, the appropriate task is to select algorithms for adapting the mathematical model of the control object and to develop a general algorithm for functioning that regulates the sequence and frequency of operation of individual algorithmic blocks of the control system.

The mathematical model of the control object is presented, as well as the structure of the predicate system. The adaptation of the control system should be reduced to adjusting the parameters of the analytical model and the structure of the predicate system based on current information about the functioning of the facility and the control system. The first task is solved on the basis of the use of probabilistic interactive adaptation algorithms, the type and characteristics of which should take into account the statistical features of the current information and is selected during a special study. The algorithm of the current correction of the structure of the predicate system is based, ultimately, on the correction of the values of the weighting coefficients appearing as arguments in the corresponding predicates, which, in turn, connect the concept of different levels of description.

The structure of the general algorithm for the operation of the control system. The main blocks of this algorithm are:

Block 1 converts the information generated by the subsystem of centralized control of the automated control system into a form convenient for further use (in other words, the block restores a micromodel of the current situation in terms of language) $\left\{a_i^j\right\}$, $\{\tau v\}$.

Block 2 performs, based on the predicate system $\left\{P_S^K\right\}$, the selection of a management solution $U$ that is optimal for this situation. If the developed solution is immediately ready for implementation, then it is issued to the site for execution, otherwise other blocks of the system are launched in order to specify the sequential one.

Block 3 is started if the management decision relates to the formation (adjustment) of the work schedule of the converter department. At the same time, the initial state of the converter department is fixed and, taking into account the previously developed management decision of the department. At the same time, the initial state of the converter department is fixed and, taking into account the previously developed management decision, $U_\Psi$ the formation of a work schedule for the converter department for a day (until the end of the day from the moment the unit is put into operation);

Block 4 implements a system of equations, which is an analytical mathematical model of the conversion process.

The set of blocks 1-4 is a system of operational control of the converter department by deviation. The frequency of operation of the system units is 3-4 hours, which corresponds to the dynamics of the most "rapid" disturbances (failures of aggregates, the action of the "human factor", etc.), the control object in this case is considered as quasi-stationary. Accounting for the non-stationarity of the control object, which allows to increase the efficiency of the control system, is provided by the introduction of blocks 5-7. Block 5, comparing the characteristics of converter melts obtained on the basis of an analytical model with the fixed block 1, adjusts the parameters of the model by implementing a probabilistic interactive algorithm by to the following Equation 9:

$$A[n] = A[n-1] + \gamma[n]\nabla_A[Z^0[n] - Z(Q[n], A[n-1])^2 \tag{9}$$

where A is the vector of model parameters; $Z_0$- output of the control object; $Z$- output of the model; $Q$ is the output of disturbances; $U$ is the vector of control actions;

Block 6, based on the process model (block 4), digitally simulates a certain production situation in the converter department, sequentially simulates the

adoption of each of the available management decisions by to the following Equation 10:

$$U_\Psi(\Psi = 1, 2 \ldots) \tag{10}$$

based on the criterion $Q(x, u)$ the effectiveness of each management decision is evaluated, after which the optimal management, in the sense of the specified

criterion, is selected; Block 7 captures the situation $[n]$, generated by block 6, selects the optimal management solution based on the predicate system $\{P_S^K\} \rightarrow \overline{U}_{on}[n]$, compares both $U_{on}[n]$ and $\overline{U}_{on}[n]$ in case of their discrepancy, corrects the predicate system in order to eliminate the resulting mismatch.

The implementation of blocks 5-7 is associated with significant computational difficulties. The need to launch blocks 5-7 is due to changes in technology (for example, the transition to new types of raw materials) or changes in the organization of work and should be carried out with a periodicity of about a month.

**Conclusion.** In the process of long-term operation of the system for the operational formation of an optimal work schedule for the converter department, the need to improve individual units of the system has been identified. In particular, the technological staff of the metallurgical workshop expressed the wish that it was necessary to take into account the raw materials and energy limitations of the electric furnace electronic department (FED).

To implement these wishes, the following changes were made to the algorithm for forming the work schedule of the converter department: a fragment of an algorithm has been developed that corrects a given plan for the production of rough copper, taking into account the energy and raw material constraints of the FED, as well as the schedule of the latter's PPD; the procedure for creating a schedule at time intervals corresponding to the FED's PPR has been changed. At these intervals, it is planned to reduce the intensity of the converters, the melts are spaced over time so that they can be provided with matte from one furnace; an algorithm has been developed for the formation of an application plan for the issuance of a matte FED with the development of the latter for shift tasks, which specify the time the output of each stein bucket, as well as the total number of buckets per shift and per day. The required number of pellets to be processed and the cost of electricity are also indicated.

The listed changes and additions are made in the form of separate fragment programs and independent programs and will be included in the system software being developed.

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