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# ADAPTIVE MODELING OF MINING SCHEDULE USING GENETIC ALGORITHM IN A DYNAMIC ENVIRONMENT

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**Abstract.** The operation of large mining clusters faces significant challenges, as long-term planning is often based on constant environmental conditions, ignoring uncertainties in the economic environment, geological uncertainty, and the mutual influence of enterprises. However, the current realities of the global market and the challenges of the industrial crisis require consideration of dynamic conditions, such as price and demand fluctuations, during mining operations. This study proposes a method for multi-factor optimization of mining operations based on a genetic algorithm. The methodology involves the mathematical formalization of a mining cluster system combining open pit mines and industrial deposits, using an evolutionary approach to solving nonlinear optimization problems that take into account ore quality and mining costs. The study identified optimal parameters for the optimization algorithm – specifically, a crossover value of 0.7–0.8 and a mutation probability of 5% – to ensure the accuracy of design decisions and prevent optimization from drifting toward local minima. The proposed model determines annual production blocks, storage volumes, and processing of man-made deposits, enabling dynamic adjustments to cutoff ore grade values to minimize overall costs. Unlike traditional deterministic approaches, the proposed methodology provides flexibility in planning, enabling long-term reductions in production and storage costs while maintaining stable ore quality. The results obtained can be used by engineering design organizations for adaptive, dynamic long-term design of mining facilities and regional clusters, as well as for improving the specialized software used for this purpose.

**Key words:** mathematical modeling, regional mining cluster, open-pit, тechnogenic deposits, ore quality, adaptive design

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## ДИНАМИКАЛЫҚ БАСҚАРУ ОРТАСЫНДА ГЕНЕТИКАЛЫҚ АЛГОРИТМ АРҚЫЛЫ ТАУ-КЕН РЕЖИМІН БЕЙІМДЕУ

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**Аннотация.** Ірі тау-кен өндіру кластерлерінің қызметі елеулі қиындықтарға тап болып отыр, өйткені ұзақ мерзімді жоспарлау көбінесе қоршаған ортаның тұрақты жағдайларына негізделіп, шаруашылық жүргізудің экономикалық ортасындағы белгісіз факторларды, геологиялық белгісіздікті, сондай-ақ кәсіпорындар арасындағы өзара ықпалды ескермейді. Алайда жаһандық нарықтың қазіргі шынайы жағдайлары мен өнеркәсіптік дағдарыс мәселелері тау-кен жұмыстарын жүргізу барысында баға мен сұраныстың ауытқуы сияқты динамикалық жағдайларды есепке алуды талап етеді. Осы зерттеуде генетикалық алгоритмге негізделген тау-кен жұмыстары режимін көпфакторлы оңтайландыру әдісі ұсынылады. Әдістеме карьерлер мен техногендік кен орындарын біріктіретін тау-кен өндіру кластері жүйесін математикалық формализациялауды қамтиды және кеннің сапасы мен өндіру шығындарын ескеретін сызықтық емес оңтайландыру есептерін шешу үшін эволюциялық тәсілді қолданады. Зерттеу барысында жобалық шешімдердің дәлдігін қамтамасыз ету және оңтайландырудың локалдық минимумдарға түсуін болдырмау мақсатында оңтайландыру алгоритмінің параметрлері, атап айтқанда кроссовер шамасы 0,7–0,8 және мутация ықтималдығы 5 % деңгейінде анықталды. Ұсынылған модель жылдық өндіру блоктарын, қоймалауға жіберілетін көлемдерді және техногендік кен орындарын қайта өңдеуді айқындайды, бұл жалпы шығындарды азайту үшін кен құрамының борттық мәндерін динамикалық түрде түзетуге мүмкіндік береді. Дәстүрлі детерминистік тәсілдерден айырмашылығы, ұсынылған әдістеме жоспарлауда икемділікті қамтамасыз етіп, ұзақ мерзімді перспективада кен сапасының тұрақтылығын сақтай отырып, өндіру мен сақтау шығындарын төмендетуге мүмкіндік береді. Алынған нәтижелер тау-кен өндіру кәсіпорындары мен өңірлік кластерлерді бейімделмелі динамикалық ұзақ мерзімді жобалау үшін инженерлік жобалау ұйымдарында, сондай-ақ қолданылып жүрген мамандандырылған бағдарламалық қамтамасыз етуді жетілдіруде пайдаланылуы мүмкін.

**Түйін сөздер:** математикалық модельдеу, өңірлік тау-кен өндіру кластеры, карьер, техногендік кен орындары, кен сапасы, бейімделмелі жобалау

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# АДАПТИВНОЕ МОДЕЛИРОВАНИЕ РЕЖИМА ГОРНЫХ РАБОТ ПОСРЕДСТВОМ ГЕНЕТИЧЕСКОГО АЛГОРИТМА В ДИНАМИЧНОЙ СРЕДЕ ХОЗЯЙСТВОВАНИЯ

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**Аннотация.** Работа крупных горнодобывающих кластеров сталкивается со значительными проблемами, поскольку долгосрочное планирование часто основывается на предположении о неизменности условий внешней среды и при этом недостаточно учитывает неопределённость экономической конъюнктуры, геологическую неопределённость, а также взаимное влияние предприятий внутри кластера. Однако современные реалии глобального рынка и кризисные явления в промышленности требуют учёта динамических факторов, таких как колебания цен и спроса, при планировании и ведении горных работ. В данном исследовании предложен метод многофакторной оптимизации режима горных работ на основе генетического алгоритма. Методология включает математическую формализацию системы горнодобывающего кластера, объединяющей карьеры и техногенные месторождения, и применение эволюционного подхода для решения нелинейных задач оптимизации с учётом качества руд и затрат на добычу. Определены оптимальные параметры алгоритма, в частности коэффициент кроссовера 0,7–0,8 и вероятность мутации 5%, что повышает точность проектных решений и снижает риск «скатывания» оптимизации к локальным минимумам. Предложенная модель определяет годовые блоки добычи, объёмы складирования и параметры переработки годовые блоки добычи, объёмы складирования и параметры переработки техногенных месторождений, позволяя динамически корректировать бортовые содержания руды для минимизации совокупных затрат. В отличие от традиционных детерминистических подходов, разработанная методология обеспечивает гибкость планирования, позволяя в долгосрочной перспективе снижать затраты на добычу и хранение при сохранении стабильного качества руды. Полученные результаты могут быть использованы инженерно-проектными организациями для адаптивного долгосрочного проектирования горнодобывающих предприятий и региональных кластеров, а также для совершенствования специализированного программного обеспечения, применяемого для решения соответствующих задач.

**Ключевые слова:** математическое моделирование, региональный горнодобывающий кластер, карьер, техногенные месторождения, качество руды, адаптивное проектирование

**Introduction.** In the course of studying the design of open-pit mining scheduling within a mining cluster under uncertain initial data, it becomes evident that a comprehensive understanding of the interactions between various geological, geotechnical, and economic factors is a necessary requirement (Hryhoriev et al., 2023a, Lutsenko et al., 2024). The experience of mining and processing enterprises in the Kryvbas region under crisis-driven dynamic conditions demonstrates a shift in the logistical connections between enterprises (Khomenko, V.L. et al., 2024). Numerous instances of transporting minerals from the open-pit mines of one combine to the processing plants of another have been recorded. Such intensification of logistical connections confirms the formation of an anthropogenic-mining complex of the third order – a mining cluster – based on the Kryvyi Rih Iron Ore Basin (Hryhoriev et al., 2023a). The uncertainty in initial data, such as ore grade, rock mass properties, and market conditions, complicates the already complex process of mining design and adds a dynamic component to its determination.

Essentially, designing open-pit mining operations under conditions of uncertain initial data requires a holistic approach that goes beyond traditional deterministic frameworks. By acknowledging inherent uncertainties and utilizing advanced mining scheduling modeling techniques, designers can develop more robust and adaptive production systems. These systems are based on the principles of dynamic design (Hryhoriev et al., 2023b) and are better prepared to operate in the modern dynamic environment of mining production. The search for and justification of new methods for evaluating and selecting mining scheduling strategies necessitates a thorough analysis of the development of the scientific foundation on this issue.

The relevance of selecting a mining scheduling strategy for open-pit mines emerged in the 1930s with the development of large-scale mining complexes. This was primarily due to the fact that the production capacity of open-pit mines cannot remain constant throughout their operation, mainly due to the varying volumes of overburden removal. Subsequently, the process of determining the mining scheduling strategy was long considered under deterministic conditions. With the advancement of mathematical knowledge and the capabilities of computer technology, methods for automatic design of intermediate pit outlines began to develop. In 1965, Lerchs and Grossmann, using graph theory and dynamic programming methods, developed an algorithm for determining the mining scheduling strategy, which was later named after them (Lerchs et al., 1965). In 1991, Denby and Schofield introduced a methodology based on a genetic algorithm, which allows for the simultaneous combination of pit limits and mining schedules, leading to the maximization of the net present profit from the exploitation of the deposit. These and several other algorithms (Denby et al., 1991) were primarily implemented in powerful geographic information systems used by large design enterprises.

At the same time, the described scientific approaches are relevant primarily under conditions of deterministic initial data available during the design process. Some of these approaches were developed under a directive economy, while others were based on the relative stability of prices for products from mining enterprises. Similarly, geological information about deposits was considered deterministic, and risks associated with geological uncertainty were not taken into account. However, in practice, numerous cases of unconfirmed reserves (Okhunov et al., 2022, Jelvez et al., 2023) have been encountered, highlighting the shortcomings of such an approach.

The article (Dimitrakopoulos et al., 2002) examines the development and application of stochastic optimization for strategic mine planning, highlighting the advantages of this approach specifically under conditions of uncertain initial data. The primary tools discussed in the article include stochastic simulation and stochastic optimization. The authors rightly note that traditional methods of reserve estimation and production planning often result in single-point forecasts, which may be biased due to the failure to account for uncertainties. To address this issue, the authors propose integrating stochastic simulation and stochastic optimization to model ore body uncertainties during the design of open-pit mining and production planning. The article also provides statistical information based on project work experience: stochastic optimization increases the efficiency of mining scheduling by 25% and can expand pit limits by 15%, adding approximately 10% to the net present value of the project (Dimitrakopoulos et al., 2011).

In particular, stochastic simulation tools are used to create a series of models that reflect the probabilistic mine production schedule. Sequential simulation generates a series of models that are statistically equivalent to the probabilistic distributions of the ore (Dimitrakopoulos et al., 2011). High-order sequential simulation with spatial cumulants allows for modeling complex nonlinear geological structures by using high-order statistical characteristics (Mustapha et al., 2010). In further research, stochastic optimization integrates uncertainty into the optimization process of mining scheduling and pit productivity. For these tasks, researchers employed methods such as Simulated Annealing or Stochastic Integer Programming (SIP). The first approach involves a heuristic method that includes iterative improvement, where blocks with lower probabilities are rescheduled across production periods to minimize deviations from production targets (Godoy et al., 2004). Stochastic Integer Programming ensures optimization of the mine production schedule, accounting for uncertainty by using a series of simulated orebody models. The primary goal is to maximize the project's NPV while minimizing deviations from planned production targets (Rakishev et al., 2015). A similar approach for a copper mine, considering uncertainties in ore quality and waste dump capacity, is examined in (Ramazan et al., 2014). The study (Hryhoriev et al., 2024c) proposes a technological solution to minimize geological uncertainty when exploiting a technogenic deposit.

The study (Groeneveld et al., 2019) provides an in-depth analysis of existing approaches to open-pit design under conditions of uncertainty. However, the authors do not consider the changes in the production system that involve stockpiling temporarily substandard raw materials.

The authors of (Buelga et al., 2021) confirm the relevance of considering the dynamics of commodity prices as one of the key factors influencing the boundaries and scheduling of open-pit mining operations. However, in (Das et al., 2023), the authors also conclude that a gap still exists in research concerning the development of an optimization model for mining scheduling that takes into account the management of overburden and associated minerals under conditions of uncertainty.

Thus, a substantial scientific and methodological foundation has been accumulated for the search for optimal mining scheduling and production capacity (Hryhoriev et al., 2023d) under uncertain dynamic conditions. However, the emerging trends toward the formation of mining clusters necessitate considering the mutual influence of individual extraction enterprises on the overall mining scheduling of the cluster.

Therefore, the aim of this study is to scientifically substantiate and develop a methodological approach to adaptive optimization of the mining scheduling within a mining cluster under dynamic operational conditions.

**Materials and methods.** Planning the mining scheduling and production capacity in such a complex system is a non-trivial task and requires appropriate mathematical support. However, we first need to formulate and mathematically formalize the approach to solving the problem of determining the mining scheduling for a mining cluster that includes several open-pit mines and technogenic deposits.

Let us consider that the open-pit mines are extracting steeply dipping ore deposits of variable quality. Low-grade ore, which is not economically feasible to process at the moment, is stockpiled in technogenic deposits for future processing. Consequently, technogenic deposits can operate in modes of accumulating mineral raw materials and subsequent extraction.

To ensure the continuous operation of the processing plant, it is planned to supply the plant with a steady quantity and quality of ore, blended from ores extracted from different open-pit mines. The ore production rate of each mine may vary over time, while the overall rock mass extraction rate must remain constant. In this context, the objective function (1) aims to minimize the total costs of extraction and storage while ensuring minimal deviations from the target values for ore quality and volume.

$$\min\left(\alpha\sum_{x,y,z,t}(e^t{}_{xyz}+s^t{}_{xyz})C^t{}_{xyz}+\beta\left|\sum_{x,y,z,t}e^t{}_{xyz}V-V^t{}_{\text{target}}\right|+\gamma\left|\frac{\sum_{x,y,z,t}e^t{}_{xyz}Q_{xyz}V}{\sum_{x,y,z,t}e^t{}_{xyz}V}-Q^t{}_{\text{target}}\right|\right) \quad (1)$$

where x,y,z – coordinates of a block in three-dimensional space;

$Q_{xyz}$ – the content of the valuable component in the block by coordinates. $x,y,z$;

$C^t{}_{xyz}$ – the cost of extracting the block at coordinates $x,y,z$ in year $t$, monetary units;

$V$ – constant volume of each block, m$^3$;

$Q^t{}_{\text{target}}$ – target content of the valuable component required for the processing plant in year $t$, %;

$V^t{}_{\text{target}}$ – target volume of ore to be delivered to the plant over a specific period in year $t$, m$^3$;

$\alpha$, $\beta$, $\gamma$ – weighting coefficients for balancing between costs and quality indicators of mining operations;

The variable parameters will be:

$e^t{}_{xyz}$ – binary variable indicating whether the block is removed at the given coordinates $x,y,z$ in year $t$;

$s^t{}_{xyz}$ – binary variable indicating whether the block at coordinates $x$, $y$, $z$ is stored in the technogenic deposit in year $t$.

When searching for the optimum, certain constraints must be considered. First, a block can only be removed if there is no other block directly above it:

$$e^t{}_{xyz}\le 1-e_{x,y,z,t+1} \quad (2)$$

It should also be considered that the volume of material extracted from the technogenic deposit cannot exceed the volume that has been stockpiled:

$$\sum_{x,y,z,t}s^t{}_{xyz}V\le\sum_{x,y,z,t}\left(1-e^t{}_{xyz}\right)V \quad (3)$$

The ore mass delivered to the processing plant must maintain consistent quality and quantity, taking into account the selection from both open-pit mines and technogenic deposits:

$$\left|\sum_{x,y,z,t}e^t{}_{xyz}V-V^t{}_{\text{target}}\right|\to\min \quad (4)$$

$$\left|\frac{\sum_{x,y,z,t}e^t{}_{xyz}Q_{xyz}V}{\sum_{x,y,z,t}e^t{}_{xyz}V}-Q^t{}_{\text{target}}\right|\to\min \quad (5)$$

This problem formulation allows for a comprehensive approach to mining planning, considering not only the economic but also the technological aspects of ore extraction and processing.

Let us consider rational methods for solving the problem we have formalized.

The classical method for solving a similar problem, albeit under deterministic initial data, has been simulation modeling followed by optimization (Jelvez et al., 2023). This approach involves first creating a detailed simulation of the mining operations and then applying optimization methods to the simulation results to achieve optimal solutions.

Simulation involves modeling the development of mining operations for various extraction strategies, taking into account all technological processes and potential changes. Then, during the data analysis phase, analytical methods are used to identify optimal patterns and strategies. The next step is to apply mathematical optimization methods to the simulation data to select the best strategy.

We consider this approach impractical, as the first step – namely, the modeling of the development of mining operations – is a rather complex and resource-intensive process, and this method requires numerous iterations of that process.

Another well-known method for solving such problems is the Integer Linear Programming (ILP) method. This method allows the problem to be addressed as an optimization problem with binary variables that indicate whether a block should be extracted or left in situ. ILP is used for a wide range of engineering and management tasks and can be effectively applied to our case as well. The modeling of the problem's solution is performed using specialized mathematical software for linear programming, such as IBM CPLEX or Gurobi (Ramazan et al., 2014). All constraints (geometrical, resource balance, ore quality) are formulated as linear inequalities. ILP solvers efficiently find the global optimum, provided that the constraints and the objective function are linear.

The advantages of this approach traditionally include the accuracy of the solution. Additionally, ILP is a well-established field with a vast body of literature and tools, which simplifies the implementation of the approach. Today, there are many highly efficient commercial and open-source solvers available that can quickly solve large ILP problems.

However, for very large problems or problems with a large number of variables and constraints, ILP can become excessively resource-intensive or even unsolvable due to the exponential growth of computational requirements. ILP is also limited to problems that can be formulated with linear constraints, which does not always accurately reflect the real-world situation.

In recent years, genetic algorithms have gained increasing popularity in solving optimization problems (10, Paithankar et al., 2019). They are part of a broader class of evolutionary algorithms that utilize natural selection methods to solve optimization and search problems. Genetic algorithms are well-suited for solving optimization problems that involve a large number of possible solutions and a high level of complexity.

Next, let us consider how genetic algorithms can be applied to solve our formalized problem of optimizing the mining scheduling within a mining cluster. The key components of applying genetic algorithms can be summarized as follows. In this method, each individual in the population represents a possible plan for the extraction of blocks from the open-pit mine – a specific mining schedule. An individual can be represented as a vector of binary variables $e_{xyz}$ and $s_{xyz}$, where each element reflects the status of a block (extracted, left in situ).

The fitness function evaluates the quality of the block extraction plan, taking into account the quantity and quality of the ore delivered to the processing plant, as well as the extraction and storage costs, in accordance with the objective function.

Next, according to the classical interpretation of this approach, selection methods, such as tournament selection or roulette wheel selection, are used to choose individuals that will reproduce and form the next generation. Individuals with higher fitness have a greater likelihood of being selected. In our context, individuals refer to the different solutions to the optimization problem.

Two selected individuals (parents) are combined to create one or more offspring (crossovers). In the context of determining the mining schedule, this involves combining the initial solutions to generate new ones. Typical methods include single-point, two-point, or uniform crossover.

To prevent premature convergence to a local optimum and to introduce diversity into the population, random changes are made to the genome of the offspring (mutation mechanism). For example, this could involve changing a binary value from 0 to 1 in a randomly selected block.

The first significant advantage of this approach is that genetic algorithms can be applied to a wide range of problems, including those that do not lend themselves to linear formulation. Given the complex configuration of ore deposits, the constraints and the objective function of the problem are rarely described by a linear equation. Practical experience in design suggests that the initial data for planning are often incomplete or not entirely reliable. This method can effectively handle problems where optimal solutions are rare, difficult to determine, or based on incomplete initial data. Experience with this approach indicates that genetic algorithms can find global optima in problems where other methods might get stuck in local optima.

At the same time, it is known that genetic algorithms typically do not guarantee finding the best possible solution, and the time required to find a solution can vary significantly. It should also be noted that the choice of algorithm parameters (such as population size, mutation probability, and crossover probability) can significantly impact the outcome.

Given the advantages and disadvantages outlined, the most appropriate approach appears to be the use of genetic algorithms for solving the optimization problem of mining scheduling within the structure of a mining cluster.

**Results and discussion.** In accordance with the chosen solution method, the mathematical interpretation of the genetic algorithm will include several stages through which the algorithm evolves to find the optimal solution.

Let $P(g)=\{u_1(g),u_2(g),\ldots,u_N(g)\}$ be a population of $N$ individuals at the $g$-th step (iteration) of the algorithm. Each individual $u_i(g)$ is a possible solution to the problem, represented by a vector of variables $e_{xyz}^{\ t}$ and $s_{xyz}^{\ t}$.

$$u_i(g)=\left[e^{t_1}{}_{x_1y_1z_1}\ldots,e^{t_n}{}_{x_ny_nz_n},s^{t_1}{}_{x_1y_1z_1},\ldots,s^{t_n}{}_{x_ny_nz_n}\right] \tag{6}$$

At the beginning of the algorithm, P(0) is generated randomly or based on heuristics.

Next, for each individual $u_i(g)$ the value of the objective function f($u_i(g)$) is calculated, which takes into account costs, volumes, ore quality, as well as the year of extraction for each block:

$$f(u_i(g))=\alpha\sum_{x,y,z,t}(e^t{}_{xyz}+s^t{}_{xyz})C^t{}_{xyz}+\beta\left|\sum_{x,y,z,t}e^t{}_{xyz}V-V^t{}_{\text{target}}\right|+\gamma\left|\frac{\sum_{x,y,z,t}e^t{}_{xyz}Q_{xyz}V}{\sum_{x,y,z,t}e^t{}_{xyz}V}-Q^t{}_{\text{target}}\right| \tag{7}$$

The fitness function is calculated as the inverse of the objective function, since the objective function is being minimized:

$$\text{fitness }\left(u_i(g)\right)=\frac{1}{1+f\left(u_i(g)\right)} \tag{8}$$

At the selection stage, individuals are chosen to participate in the crossover and mutation processes. The selection is based on the fitness function, with individuals having better fitness values having a higher chance of being selected:

$$P_{\text{selected}}(g)=\text{Selection }\left(P(g),\ \text{fitness }\left(u_i(g)\right)\right) \tag{9}$$

At the next step, the crossover process combines the parental chromosomes to create new offspring. In our interpretation, new variants of mining schedules are generated. Let $u_p(g)$ and $u_q(g)$ be the two selected parent individuals. The new individuals are created as follows:

$$u_{\text{new}}=\text{Crossover }\left(u_p(g),\ u_q(g)\right) \tag{10}$$

The mutation process alters some genes of the new individuals with a certain probability \( p_m \). If the selected gene is $e_{xyz,t}$ or $s_{xyz,t}$, its value can be changed as follows:

$$u_{\text{mut}}=\text{Mutation}\left(u_{\text{new}}\right) \tag{11}$$

For example, if $e_{xyz,t}$=0, it can change to $e_{xyz,t}$= 1 with a probability of $p_m$.

The new individuals replace the old ones in the population. The replacement can be partial or complete. For example, the new individuals replace the worst-performing ones in the population.

$$P(g+1) = \text{Replace}\left(P(g),\ \{u_{\text{new}}\}\right) \tag{12}$$

The algorithm terminates the optimization process when one of the following criteria is met: a specified number of iterations $G_{max}$ is reached, or the improvement in the fitness function remains insignificant over several iterations. The overall structure of the genetic algorithm for determining the mining scheduling within the structure of a mining cluster is presented in figure 1.

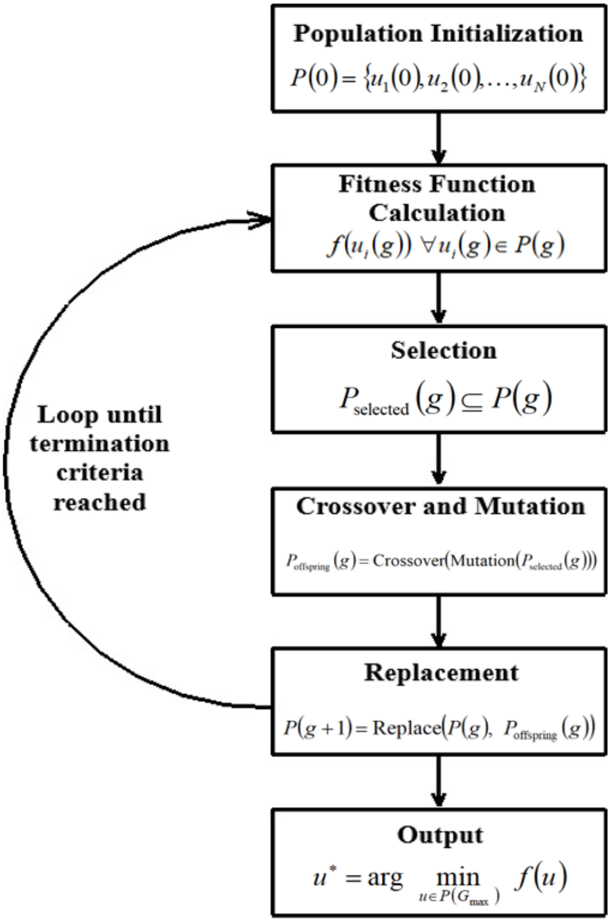


Figure 1 - General structure of the genetic algorithm for determining the mining scheduling within the structure of a mining cluster.

The implementation of the algorithm can be carried out in the PyCharm IDE using the Python programming language, which is well-suited for such tasks and has the necessary libraries. After compiling the program code, it is necessary to input the array of geological and techno-economic data for the enterprises being designed, as well as the technological parameters $Q^{t}_{\text{target}}$, $V^{t}_{\text{target}}$, $\alpha$, $\beta$, $\gamma$, which are set according to the conditions of the dynamic mining environment.

Equally important is the selection of genetic algorithm parameters, as this impacts the accuracy of the results. The crossover probability *cxpb* controls the combination of already determined mining schedules to create new ones (offspring variants) and determines the frequency of this process. A value in the range of 0.7-0.8 effectively combines different solutions and maintains diversity within the population.

The mutation probability *mutpb* introduces random changes into the mining schedules, helping to avoid local minima and maintain variation within the population. A value around 5% is generally accepted. A high value might lead to excessive random searching and the loss of useful solutions, while a value that is too low could result in the algorithm getting stuck in local minima.

The number of generations *ngen* determines how many times the population will evolve before the algorithm terminates. The more generations, the more time the algorithm has to search for the optimal solution. The specific value depends on the complexity of the project, with a minimum of 50 generations recommended. However, if improvements in the results are still observed in the later iterations, the number of generations can be increased to 100 or more.

**Conclusions.** The present study has theoretically substantiated and practically developed a methodological approach to the adaptive optimization of mining scheduling within a mining cluster operating under conditions of market uncertainty. A key result of the research is the formulation of a mathematical model that, unlike traditional deterministic frameworks, integrates distinct open-pit mines and technogenic deposits into a single, unified production system. This holistic integration facilitates the rigorous optimization of material flows – balancing direct extraction, stockpiling, and the reprocessing of previously accumulated raw materials – thereby minimizing operational costs while strictly adhering to the quality constraints imposed by the processing plant.

Furthermore, the research has demonstrated the efficacy of employing a genetic algorithm to address the formulated non-linear optimization problem, which typically challenges standard linear programming methods. Through extensive experimental modeling, rational parameters were established to ensure the reliable identification of the global optimum: specifically, a crossover probability in the range of 0,7–0,8 and a mutation probability of approximately 5%. These parameters provide the critical balance between maintaining population diversity and ensuring convergence speed, effectively preventing the algorithm from stagnating in local minima.

From a practical perspective, the proposed methodology enhances the resilience of mining operations against the volatility of global commodity markets. By enabling the dynamic annual adjustment of cut-off grades and production volumes, the model mitigates the economic risks associated with long-term planning in a dynamic environment.

Future research will focus on developing this approach by expanding the optimization solver. This will reduce the size of the model's elementary block, reduce the time required for optimization calculations, and improve the accuracy of the results.

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