BADANIA OPERACYJNE W GÓRNICTWIE ODKRYWKOWYM

OPERATIONS RESEARCH IN OPEN-PIT MINING

Marcin Maksymowicz – „Poltegor-Instytut" Instytut Górnictwa Odkrywkowego, Wrocław

Dążąc do maksymalizacji zysków, maksymalizacji bezpieczeństwa oraz spełnienia wymagań środowiskowych, decyzje zarządcze podejmowane w górnictwie odkrywkowym powinny być zawsze optymalne. Badania operacyjne - jako dyscyplina wspierająca procesy decyzyjne, pomagają to osiągać. W artykule wyjaśniono podstawowe zagadnienia dotyczące badań operacyjnych w branży górnictwa odkrywkowego oraz podkreślono ich znaczenie, przedstawiając szeroki wachlarz zastosowań.

Słowa kluczowe: *procesy podejmowania decyzji, badania operacyjne, górnictwo odkrywkowe, optymalizacja, modelowanie i symulacje, planowanie długoterminowe i krótkoterminowe, zamknięta pętla w zarządzaniu, alokacja maszyn i urządzeń, oprogramowanie dla górnictwa*

In striving to maximize profits, maximize safety and to meet environmental requirements, management decisions being made in surface mining industry should always be optimal. Operations research, as a discipline supporting the decision--making processes helps to achieve this. In this paper, basic issues related to operations research in open-pit mining are explained. Significance of the operations research is emphasized, presenting the wide range of its applications in open-pit mining industry.

Keywords: *decision-making processes, operations research, open-pit mining, optimization, modelling and simulations, long-term and short-term planning, closed-loop management, equipment allocation, mining software*

Introduction

Decision-making processes should be aimed at making decisions as best as possible, most beneficial, and in other words – optimal. Management at any stage of planning or mining operation involves a sequence of decisions to be made, and this essentially comes down to picking one of the potential directions of action. According to [16], the meaning of optimality is different for different issues. Therefore, it is always necessary to specify certain criteria of optimality in order to define what is meant by it. In most industries including open-pit mining, it mainly boils down to maximizing profits and minimizing costs. In addition to the economic aspects, operations research methods as a tool supporting the decision-making processes in open-pit mining, may concern also environmental protection and safety issues. The open-pit mining industry is characterized by a large amount of optimization problems that are covered by a very wide range of applications. The proper design and effective operation of an open-pit mine require a very complex set of analyzes to be performed, capturing all their crucial features.

This paper is focused on contribution of operations research and optimization to the open-pit mining industry. At the beginning, basic issues related to operations research discipline are explained, including its general approach to problem solving. Subsequently, the complexity of open-pit mining industry is emphasized by showing a large number of problems to be solved and decisions to be taken at different stages of mining projects. Finally, the significance of operations research in open-pit mining industry is highlighted, by presenting its wide range of applications.

Operations Research

The term operations research (OR) can be described as a set of analytical methods focused on solving problems and thus supporting the decision making processes. However, OR does not exclude the non-quantifiable reasoning or human judgments, which should be harmonious with the analytical approach. It is possible to distinguish three main areas that OR discipline involves (fig. 1):

- optimization;
- modelling and simulations;
- probability and statistics.

Fig. 1. Main areas involved in operations research [own work; based on Taha, 2017]
Rys. 1. Główne obszary dotyczące badań operacyjnych [opracowanie własne; na podstawie Taha, 2017]

Optimization, which is actually the main goal of any OR, can be understood as seeking to achieve the best performance under specific circumstances. It mainly requires comparing, and thus narrowing down potential solutions. Modelling can be simply described as making any kind of representation of something. Modelling of any process can be performed in two basic ways - mathematically or using a simulation. A simulation is a more or less accurate, estimation of a process or system, representing its operation over time. According to [24], there is a large number of simulation types in use, including discrete event simulations (DES), stochastic simulations (using Monte Carlo technique for instance), deterministic simulations, continuous simulations, among others. Finally, in probability and statistics area, mathematical algorithms and data are used to reveal any insights and risks, to make predictions, and to test possible solutions [2], [14], [22].

Operations Research Approach

Generally in OR, problems should be broken down into elementary components and then be solved in determined steps. According to [22], an exemplary OR process (fig.2) can include the following steps:

- definition of a problem;
- construction of a model around the problem;
- application of various solutions to the model;
- validation of the model;
- implementation of chosen solution to the reality.

Some authors [14], distinguish also an orientation stage as the first phase of an OR process. A lot of emphasis is put on a fact that any OR study should be done by multifunctional team. The team should be constituted of members from the departments or functional areas affected or having an effect upon the problem.

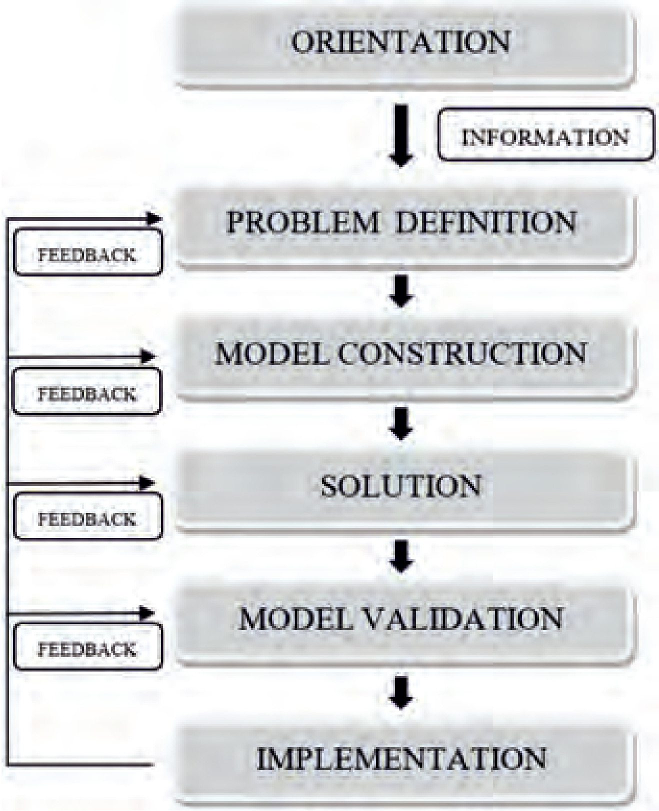


Fig. 2. General steps in OR process [own work; modified from Jakhar et al., 2013]
Rys. 2. Ogólne etapy badań operacyjnych [opracowanie własne; zmodyfikowano z Jakhar et al., 2013]

Defining the problem correctly is often considered as the most difficult and the most fundamental stage of any OR. Problem definition involves determining of the study objective, describing the decision alternatives and specifying the constraints and boundaries under which the system to be modeled operates. The correct problem definition helps to find the most important aspects of a system easier, in order to have it represented in the model. The created model should correspond to the real world and variability, capture all the key elements, but in the same time remain simple enough to be analyzed. According to [14], there are four categories of models:

- mathematical models, where characteristics of the modeled system is described by a set of mathematical relationships;
- computer simulation models, where the modeled system is abstracted into software;
- physical models, which are actually the scaled down versions of the reality;
- analogic physical models, which are models that use a physical analog in order to describe the system.

Since physical and analogic models are not commonly used in OR, we can describe model construction basically as assigning mathematical relationships to the defined problem, or as creating a simulation. The type, together with the complexity of the model, determines the solution method. The most common techniques to find the solution for mathematical models are: linear programming, integer programming, dynamic programming, network programming and nonlinear programming. Sometimes, the model solution phase involves sensitivity analysis, consisting in obtaining additional information about changes to the optimal solution when individual parameters in the created model change.

It is especially needed, when it is impossible to estimate some of the model parameters accurately enough. One of the ways to validate the model is comparing its solution output with historical data. Sometimes, especially for models of newly created systems or processes, the simulation itself can be used as a tool for models output validation. As the last step of an OR process, implementation requires to translate the solution into operating instructions. Implementation phase together with monitoring, gives the continuous feedback for the previous stages of the conducted OR [14], [22].

Open-pit Mining Value Chain

Mining industry is characterized by a very complex set of activities needed to be performed, hence many questions and problems arise at various stages of either planning of mining or the mining itself. Decision-making indispensably accompany the mineral resource extraction process chain all the time. According to [3], simplified steps in a mining value chain includes respectively: exploration, resource modelling, mine planning, operation of a mine, and processing and sale (fig. 3).

Tab. 1. Examples of decisions to be taken at different stages of open-pit mining projects [own work; modified from Bendorf, 2020]
Tab. 1. Przykładowe decyzje podejmowane na różnych etapach projektów górniczych [opracowanie własne; zmodyfikowano z Bendorf, 2020]

Time frame	Examples of decisions
Design stage	Definition of ultimate pit limits, mining method selection, infrastructure location, decisions on mining and processing capacities, decisions on financial risks
Long-term planning Medium-term planning	Pushback design, equipment selection, production sequencing
Short-term planning Day-to-day planning Shift-to-shift planning	Fleet management, equipment allocation, production scheduling, dispatching

Fig. 3. General steps in mining value chain [own work; based on Bendorf, 2020]
Rys. 3. Ogólna sekwencja działań w branży górniczej [opracowanie własne; na podstawie Bendorf, 2020]

Exploration includes data acquisition for the purpose of defining the range, geometry, geology, hydrogeology and geotechnical parameters of the deposit. This involves using many different techniques including geophysical methods and core drilling for direct sampling. Exploration data give the input for resource modelling, where 3D models of the deposit are created with the use of geostatistical methods. Taking into account technical, economic, legal and environmental aspects, the resource is subsequently classified to a reserve. Activities related to mine planning include at the beginning definition of the optimal open-pit shape, selection of mining method and mining system, extraction sequencing, equipment selection and long-term planning. The execution of the mine plan means basically operation of the mine. Mine operations are guided by short-term plans and controlled shift-by-shift. Depending on the type of extracted material, a significant issue can be the grade controlling, which aims to keep the material properties at the level acceptable for customers. Eventually, the last step of mining value chain is transportation of the extracted material to a customer, processing plant or power plant.

Closed Loop Management in Open-pit Mining

According to [3], the decisions supported by OR are being made in various areas and at different stages of the mining project (tab.1), They are based on different amounts of information available at the specific moment.

For planning and execution of the mine plan, [3] describes the Real-Time Mining approach. As previously mentioned, the implementation of solutions as the last step of any OR problem, together with monitoring give continuous feedback for previous stages of the conducted OR. The Real-Time Mining approach (fig. 4) is an iterative management cycle. Mine planning decisions are made, providing predictions on volumes of extracted materials, expected quality and process efficiency for instance. Subsequently, the mine plan is executed with implemented monitoring system, detecting discrepancies between predictions and actual measurements. Based on the updated models, the decisions made in the past should be reviewed and adjusted in order to optimize the process performance.

Sometimes, the optimization of existing mining systems can be not enough. Along with an increase in the life of a mine and changes within different economic, technical, environmental and safety conditions the application of mining operations techniques requires to be reconsidered. Possible situations that can convince mine planners to seek alternative solutions for current systems can be as follow:

- changed technical aspects of mining projects, for example increased production demand, decision on mine deeping, equipment unavailability or unplanned delays;
- changed economic aspects, for example increased operating costs due to the fuel price increase or spare parts prizes increase;
- new environmental restrictions in mining industry that must be followed such as reducing emissions, dust or noise restrictions;
- changed safety conditions which can affect the mining project;
- changed social circumstances [1].

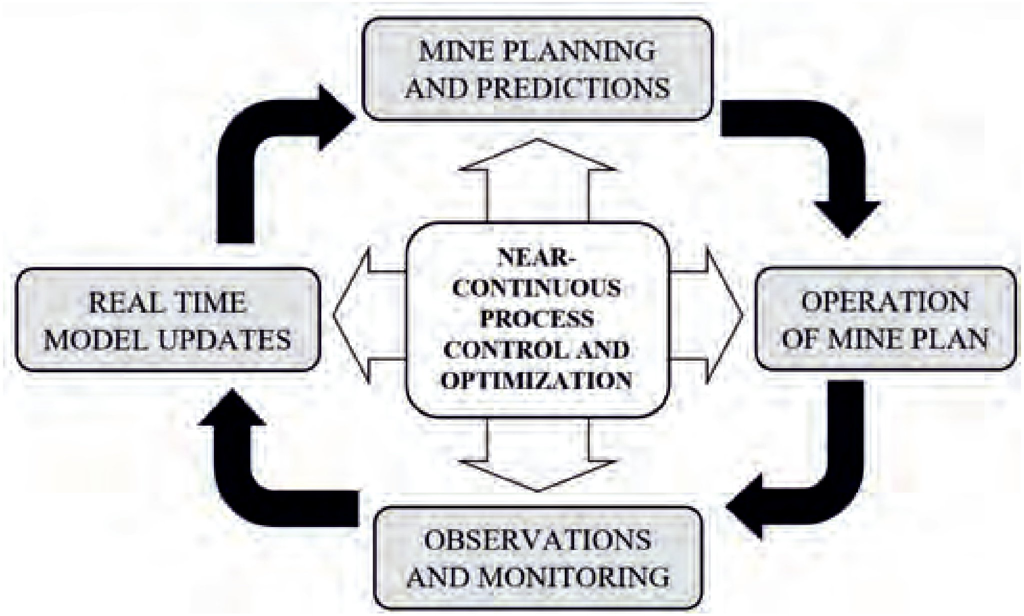


Fig. 4. Diagram of near-continuous process control and optimization [own work; modified from Bendorf, 2020]
Rys. 4. Diagram przedstawiający niemal ciągłą kontrolę nad procesem i jego optymalizacje [opracowanie własne; zmodyfikowano z Bendorf, 2020]

Operations Research in Open-pit Mining

In previous years, OR methodologies have been successfully applied to deal with many essential problems, arising in the planning or scheduling stage of open-pit mining. In [11], the contribution of OR is indicated in issues such as: economic evaluation, mine planning, operational and production and capacity planning. According to [17], the OR approaches in surface mining industry follow four main categories: open-pit mine design, mine production, material movement and mine evaluation. Both general and more detailed decisions on when and how to extract the material are made by mine planners. The techniques of OR are used firstly for the mine development and exploitation stages. This includes choosing the method of mining, estimating production capacities, performing detailed design of exploitation and transportation of the material. According to [21], the applications of OR related to open-pit mining can be grouped into three categories described by the models being created.

Ultimate pit limits and mine layout design models

Problem that arises early during the mine design is determination of the contours of an open-pit mine. Based on engineering constraints and available geological data obtained from exploration, it is aimed to design an open-pit mine in a way that maximizes the possible income. The general approach to design an open-pit starts with dividing the volume of interest into blocks and assigning the economic value to each of the blocks based on geological information. The crucial constraints in this process are so called precedence relationships (fig. 5). It is necessary to determine which blocks must be mined first, so that the next ones below can be mined. In parallel, the restrictions on geometry must be taken into account, including surface boundaries and limitations associated with the maximum slope of the pit. The general idea is to define a closed set of blocks, the mining of which will bring the maximum profit. The value assigned to each of the blocks can be either positive or negative. The value of the block is defined by useful mineral value and costs of excavating it.

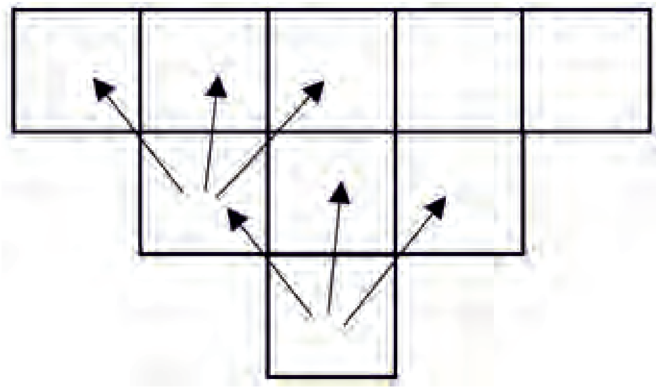


Fig. 5. General idea of the precedence relationship of blocks in 2D [own work]
Rys. 5. Ogólny zamysł pierwszeństwa wydobycia bloków w 2D [opracowanie własne]

In [18], a pioneering algorithm for finding the optimal open-pit mine design has been proposed, known as famous Lerchs-Grossmann algorithm. The problem can be represented as a directed network flow graph model, with its maximum closure being equivalent to the optimal solution. In [23], the Lerchs-Grossmann approach has been transformed by mathematical programming settings, representing the model by matrices and solving by generic linear programming. In [12], a broad research of comparing the push-relabel algorithm to the Lerchs-Grossmann algorithm has been presented. Another method developed to determine the optimum shape of an open-pit mine is floating cone method [10] and its modifications. Blocks which must be removed to allow the removal of the reference blocks, together form a cone with certain economic value that should be computed. Moreover, some authors claim that dynamic programming is the efficient way to decide on ultimate pit limits. Another methods are Korobov algorithm and genetic algorithm. Each of the methods for determining the contours of an open-pit mine has both advantages and disadvantages. Most of the commercial software packages being in use for finding optimal open-pit design (DataMine, Maptek Vulcan or Whittle for instance) are based on the above-mentioned methods [17], [21].

Block sequencing models

The block sequencing problems concern not only the question on which blocks to remove, but also when to remove it. The idea is to find the optimal sequence of material extraction. This allows to incorporate basic resource constraints like extraction volumes and processing volumes. Moreover, it is possible to use discounting to estimate the value of a block more accurately, taking into account time. In general, the goal of implementing OR techniques to block sequencing problems is to maximize the NPV of a mining project. For mine production sequencing problems, linear programming models or stochastic programming models can be applied. Moreover, a mixed integer programming model (MIP) has been proposed, receiving considerable attention [6]. Nonetheless, for large open-pit mines, large amounts of variables and constraints make MIP models impractical to use. Therefore, so called linear programming relaxation methods have been developed (Langragian relaxation for instance). Due to the complexity of the block sequencing problems, researchers often assume fixed cut-off grade for the whole life of mine. It is also possible to aggregate blocks or consider whole sets of strata instead of single blocks in order to simplify the problem. The others try to develop heuristic algorithms to sufficiently solve the biggest problems. Moreover, genetic algorithms and optimal solution strategies are in use to resolve large integer problems [17], [21].

Equipment allocation models

According to [21], there are two kinds of problems being solved by the equipment allocation models:

- tactical problems, concerning the type and size of the fleet;
- operational problems, including scheduling and dispatching strategies for instance.

Therefore, problems concern not only the production schedule itself, but also the determination of the equipment that can enable it. In the literature, the application of OR techniques concerns mainly shovel-truck systems, however, it is not limited to it. Nonetheless, it has been argued that shovel-truck systems corresponds to 95% of the global fleet for surface mining, due to their flexibility [8]. Main reasons to conduct OR for equipment allocation problems include maximizing profits, increasing safety and becoming more environmental friendly. There are two general possibilities of profit maximization [13]. It can be achieved either by production cost reduction while maintaining production rates, or by production rates increase while maintaining the same cost structure. Increase of safety may concern many different aspects like minimization of collision probability for instance. Becoming more environmental friendly can be achieved on many areas like striving to minimize diesel consumption for instance. The decisions can be based on constraints such as haul routes restrictions or equipment limitations. The problems regarding fleet management and thus, decisions to be taken may concern:

- equipment selection;
- matching;
- routing;
- scheduling;
- dispatching;
- and bunching among others.

The equipment should be chosen in such a way, to be able to meet the production volume requirements. Very important for the equipment selection problems (ESP) in surface mining is the match factor (MF), which describes the ratio of truck arrival rate to loader service time, hence indicating the efficiency of shovel-truck equipment [5]. Recently, a lot of attention has been focused on the optimization of mine haulage taking into account the fact that it often corresponds to the majority of mining costs [9], [20]. Queuing, as an undesirable situation occurs, when the equipment for shovel-truck system is matched improperly. Generally, the efficient use of haulage system is determined by the idling times of the equipment. In order to improve productivity together with operating costs reduction, dispatching strategies are applied. Real time consideration of alternative assignments of the machines increases efficiency of utilization of the equipment. Allocating optimal number of trucks to each of the loading units is essential. Furthermore, costs can be minimized by rerouting trucks when traffic congestion occurs. For the purposes of operational equipment allocation problems both deterministic and stochastic methods are in use. There are several methods, algorithms and software, being in use in order to solve truck allocation problems, thus to optimize haulage system, for example: shortest-path algorithms, discrete event simulations (DES), queuing theory, MIP models or heuristic algorithms. Fleet can be optimized either in terms of its performance increase, or in terms of costs reduction. The optimal level of productivity in open-pit mines relies on the observation, and then implementation of the adjustments to critical stages of operation. The data on equipment performances can be tracked in real time or noted at the end of shifts. Base on this data, so called key performance indicators (KPI) can be defined for the purposes of comparison of machines performance to hypothetical performance in perfect operating conditions. It opens many opportunities of implementing improvements to the processes in order to increase productivity, save money or improve safety. Among many adjustments to fleet management systems (FMS), an interesting example is an alert system [7]. The alert system detects performances of equipment that are different from the established values. Obtained results are automatically compared with predefined KPIs. Based on so called "as-is models" and the data obtained from the alert system it is possible to generate "to-be models" in order to optimize productivity and cost efficiency.

Long-term vs. Short-term Planning

In regards to production planning, it is possible to divide the planning activities in open pit mining into two main categories taking into account the period of planned mining activity. Many different authors apply OR techniques and methodologies both for long-term and short-term planning. Although, the boarder between long-term and short-term planning is not clearly defined in literature, it seems quite plausible to say that long-term planning concept, concerns mainly the sequence of mining production in years. Given that, some of the authors use the term "production sequencing" instead of long-term planning. On the other hand the term "production scheduling" can be used alternately to the short-term planning. A number of planning activities is necessary to be performed within the life of any mine. Starting from operational (day-to-

-day decisions) concerning the equipment allocation and truck dispatching for instance; to long-term strategies and decisions, concerning the building of new infrastructure, closing/opening new mining regions, among other; planning is indispensable element of any mining management [4].

Global Optimization Approach in Mining

A mining complex can be described as a value chain with multiple components such as: deposits, transportation systems, stockpiles or processing destinations, among others. Optimizing a mining complex requires the simultaneous optimization approach to all these components. For example, the haulage system cannot be optimized in matter of performance, without taking into account capacities of its destinations (crushers for instance). This kind of approach is often described in the literature as global mining optimization. Moreover, there are several methods developed for optimizing multiple components simultaneously, even concerning multiple deposits, multiple pits or multiple destinations of material. Another issue concerning the global optimization in mining is the concept of integrating mining and mineral processing [15], [19].

Mining Software

There are several different types of software available for the purposes of OR in open-pit mining industry around the world. In general, it can be used for visualization, integration, simulation and optimization (fig. 6). The main benefits of mining software can be as follow:

- it can provide a decision-making environment, while reflecting the reality;
- it gives possibility to connect mining data in different formats;
- it provides possibility to integrate different models and approaches of different areas such as design, geology, statistics, planning, scheduling, optimization and other;
- it gives visual confirmation (simulation for instance) of the modelling process.

The market of mining software supporting operational research has the structure of an oligopoly. HaulSim, Talpac, DataMine, Maptek Vulcan, Whittle, Runge and Blasor can be mentioned as the examples of software available for the general purposes of performing OR in mining [17]. An exemplary view on simulation created in HaulSim software is presented below (fig. 6) [25].

HaulSim

HaulSim is a product of RPM Global - one of the global leaders in providing simulation software for mining industry. HaulSim is a tool for creating computer models of mining activities. It allows to visualize, analyze and therefore, optimize mining production systems. HaulSim is the first ever DES software, created for the mining industry. High-level visualizations and very advanced analytical tools enables engineers to be more sure of real-life decisions made. The area, where HaulSim is developed the most is the simulation and analysis of truck-shovel systems [26].

Summary

In such a complex industry as open-pit mining, the operations research methodologies plays major role while aiming for optimization. Operations research techniques are in use among all the steps in mining value chain, especially in mine planning and operation of mines, by supporting the planning and management decisions. The applications of operations

Fig. 6. View on simulation created in HaulSim software [www.nationalresourcesreview.com.au]
Rys. 6. Pogląd na symulacje stworzoną w programie HaulSim [www.nationalresourcesreview.com.au]

research related to open-pit mining can be grouped into three categories described by the models being created, including Ultimate pit limits and mine layout design models, production sequencing models and equipment allocation models. Operations research methods are in use both for short-term and long-term planning. Moreover, the most of the open-pit mines utilizes so called real-time mining approach by implementing operation research and monitoring techniques, aiming to have near-continuous process control and optimization. Optimizing a mining complex requires the simultaneous optimization approach to many components, therefore global optimization approach in mining is being implemented. Optimization of mining often must be integrated with optimization of mineral processing. There is quite a few pieces of software available on the market, being helpful in operations research and optimization in open-pit mining. HaulSim software can be mentioned as one of the most interesting software, specialized mainly in simulation and analysis of shovel-truck systems.

Discussions

This article has been focused only on some of the issues related to open-pit mining industry. Mentioned examples on equipment allocation models concerned mainly the shovel-truck-systems, however operations research techniques are obviously not limited to it. All the issues concerning the operations research in underground mining has been omitted, although many methods are similar.

The research area, where operation research can be potentially very useful in the future is asteroid mining.

Literature

[1] ABBASPOUR H., DREBENSTEDT C. *IPCC Systems as a Bulk Material Handling Method in Mines: a Review Regarding the Technical, Economic, Environmental, Safety and Social Factors.* Katowice, Poland, Transport Problems, 2019, VIII International Symposium of Young Researchers [in English]

[2] BANKS J., CARSON J. S., NELSON B. L., NICOL D. M. *Discrete-Event System Simulation, Fifth Edition.* London, England: Pearson, 2010, 648p, ISBN 978-0-13-606212-7 [in English]

[3] BENDORF J. *Closed Loop Management in Mineral Resource Extraction. Turning Online Geo-Data into Mining Intelligence.* Cham, Switzerland: SpringerBriefs in Applied Sciences and Technology, 2020, 104p, ISBN 978-3-030-40899-2 [in English]

[4] BLOM M. *Short-Term Planning for Open Pit Mines: a Review.* International Journal of Mining Reclamation and Environment 33(9), 2018, University of Melbourne, Australia, ISSN 1748-0949 [in English]

[5] BURT C., CACCETTA L., WELGAMA P., FOUCHA L. *Equipment Selection with Heterogeneous Fleets for Multiple--period Schedules.* Journal of the Operational Research Society, 2011, 62(8), 1498–1509, ISSN 01605682 [in English]

[6] CACCETTA L., HILL S. P. *An Application of Branch and Cut to Open-pit Mine Scheduling.* Journal of Global Optimization, 2003, No. 27(2-3), pp. 349-365, ISSN 1573-2916 [in English]

[7] CORONADO P. P. V, TENORIO V. O. *Optimization of Open Pit Haulage Cycle Using a KPI Controlling Alert System and a Discrete-Event Operations Simulator.* Proceedings of the 37th APCOM Symposium, 37th APCOM Symposium, 2015, University of Arizona. Tucson, AZ, USA [in English]

[8] DeLEMOS PIRES D. *Surface Mining Technology: Managing the Paradigm Shift.* Mining Engineering, 2013, 65(12) pp. 36-41, ISSN 0026–5187 [in English]

[9] DZAKPATA I., KNIGHTS P., KIZIL M. S., NEHRING M., AMINOSSADATI S. M. *Truck and Shovel Versus In-Pit Conveyor Systems: a Comparison Of The Valuable Operating Time.* Coal Operators Conference, 2016, University of Wollongong, NSW, Australia [in English]

[10] ELAHI ZEYNI E., KAKAIE R., YOUSEFI A. *A New Algorithm for Optimum Open-pit Design: Floating Cone Method III.* Journal of Mining & Environment, 2011, No. 2, pp. 118-125, ISSN: 2251-8592 [in English]

[11] GUNN E. *A Brief Review of Operations Research in Mining.* Montreal, Canada: 40th Congrès Annuel SCRO - CORS Annual Conference, 1998 [in English]

[12] HOCHBAUM D. S., CHEN A. *Performance Analysis and Best Implementations of Old and New Algorithms for the Open--pit Mining Problem.* Operations Research, 2000, No. 48(6), pp. 894–914, ISSN: 1526-5463 [in English]

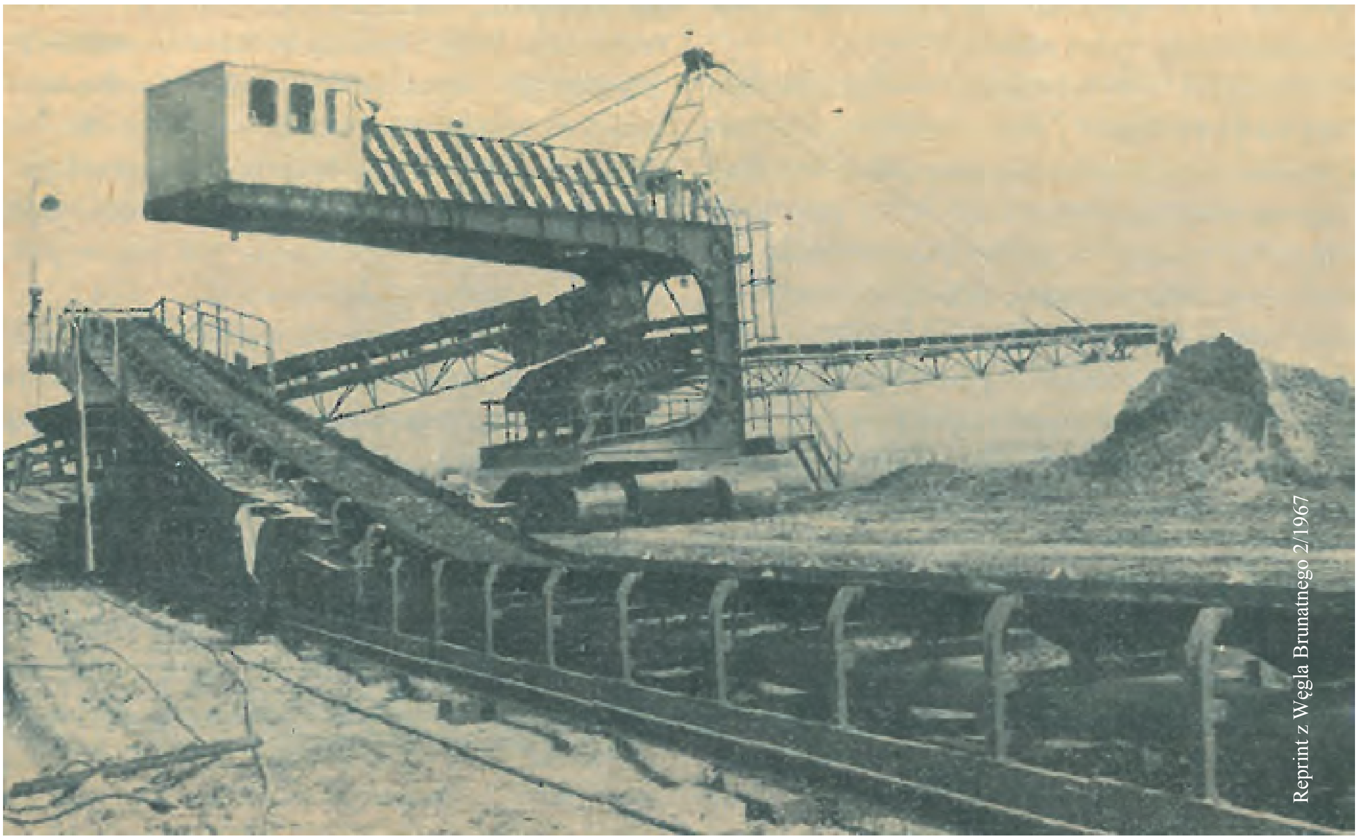
[13] INTHANONGSONE I., DREBENSTEDT C., BONGAERTS J. C. *Cost Estimation for Open-pit Mines: Tackling Cost Uncertainties.* Department of Mining Engineering, 2015, National University of Laos, 3166 Vientiane, Laos [in English]

[14] JAKHAR J., KUMAR V., KUMAR V. *Some Principles and Applications of Operation Research: A Historical Approach.* International Journal of Applied Science & Technology Research Excellence, 2013, Vol. 3, Issue 4, ISSN 2250-2718 [in English]

[15] KLEIN B., DUNBAR W. S., SCOBLE M. *Integrating Mining and Mineral Processing for Advanced Mining Systems.* CIM Bulletin, 2002, 1057, 63–67, ISSN 0008-4484 [In English]

[16] KOWALIK S. *Nowoczesne Metody Optymalizacyjne w Zastosowaniach Górniczych i Ekonomicznych.* Gliwice, Poland: Politechnika Śląska, Wydawnictwo Politechniki Śląskiej, 2004, 307s, ISBN 83-7335-241-4 [in Polish]

[17] KOZAN E., LIU S. Q. *Operations Research for Mining: A Classification and Literature Review.* Brisbane, Australia, 2011, Mathematical Sciences, Queensland University of Technology, ISSN 2008-1359 [in English]
[18] LERCHS H., GROSSMANN I. F. *Optimum Design of Open-pit Mines.* Canadian Mining Metallurgical Bulletin, 1965, No. 58, pp. 47 – 54, ISSN 0008-4484 [in English]
[19] MONTIEL L., DIMITRAKOPOLOUS R., KAWAHATA K. *Simultaneously Optimizing Open-pit and Underground Mining Operations under Geological Uncertainty.* Advances in Applied Strategic Mine Planning, 2017, Springer, p. 231, ISBN 978-3-319-69320-0 [in English]
[20] NEL S., KIZIL M. S., KNIGHTS P. *Improving Truck-shovel Matching.* Proceedings of the 35th APCOM Symposium, 35th APCOM Symposium, 2011, Wollongong, NSW, Australia, 24-30 [in English]
[21] NEWMAN A. M., RUBIO E., CARO R., WEINTRAUB A., EUREK K. *A review of Operations Research in Mine Planning.* INFORMS Journal on Applied Analytics, Interfaces, 2010, 40(3), 222-245, ISSN 0092-2102 [in English]
[22] TAHA H. A. *Operations Research: An Introduction, Tenth Edition.* London, England: Pearson Education, 2017, 843p, ISBN 13: 978-1-292-16554-7 [in English]
[23] UNDERWOOD R., TOŁWIŃSKI B. *A Mathematical Programming Viewpoint for Solving the Ultimate Pit Problem.* European Journal of Operational Research, 1998, No. 107, pp. 96-107, ISSN 0377-2217 [in English]
[24] ZEIGLER B. P., MUZY A., KOFMAN E. *Theory of Modeling and Simulation: Discrete Event & Iterative System Computational Foundations, Third Edition.* Amsterdam, Netherlands: Academic Press, Elsevier, 2018, 692p, ISBN 978-0-12-813370-5 [in English]
[25] www.nationalresourcesreview.com.au; accessed on November 20th 2020
[26] www.rpmglobal.com; accessed on November 20th 2020



Zwałowarka gąsienicowa.