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Decision Support for Ore Transportation in Mining Enterprises – a Systematic Literature Review

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Abstract
Excavated material transportation is crucial in mining operations, requiring optimal efficiency. Since the early 2000s, various aspects of transportation network optimization have been researched, often producing methods with overlapping objectives and outcomes. This work consolidates and analyzes existing methods and artifacts related to decision support for optimizing ore transportation networks. A systematic literature review, following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, was conducted using sources such as Scopus, Web of Science, and Google Scholar. Out of 170 initial research papers, 46 were selected for detailed analysis. The review highlights the current state of decision support in ore transportation, focusing on supported decisions, optimized processes, and applied methods. It also identifies research gaps and future trends in this field.

Keywords
decision support, ore transport optimization, systematic literature review, mining enterprises.

Introduction

One of the key challenges of mining companies is the optimization of production processes. In practice, the issue is complex and involves a series of tasks. The key ones include the placement of mining faces in time and spatial domain, the selection of mining equipment (e.g., haulage machines, auxiliary machines) and their management. Fundamentally, all processes of a mining company, especially the most crucial one – extraction and production process, commence with planning. The scope of the production plan (e.g., annual) pertains to the objectives that mining areas will be obligated to achieve. Key variables to consider in estimating the production potential of mining units are quantitative and qualitative parameters of the deposit, exploitation capabilities and methods, transport capabilities, and the availability of the machinery fleet (Cao et al., 2021). The preparation of the production plan itself is a complex and time-consuming process that requires teamwork. The developed production plan then serves as the basis for supervising and evaluating the work progress and capacity, which is often a challenging task for miners, particularly due to poorly recognized geological conditions (e.g., the exploited deposit turned out to be uneconomical) or the occurrence of random events (e.g., seismic threats or equipment malfunctions). In such cases, higher supervision in the mining department personnel are obliged to make changes to the mining operations, which, despite the challenges, will ensure the achievement of the set production goals. Especially challenging are extensive underground ore mines, where it is necessary to define a new ore logistics system as well as eliminate factors causing slowdowns and production stoppages. In critical situations, relocating the extraction to another area or mining areas appears to be the most optimal solution. It is also crucial to prevent bottlenecks by minimizing machinery downtime resulting from damages or inadequate selection of machinery configurations for wheeled haulage process. Decision-making under conditions of uncertainty is an integral part of the mining industry. Therefore, it is essential to strive to minimize intuitive decision-making or reliance on catalog data through current technology. Hence, it is necessary to continuously develop and improve monitoring, specialized computational-engineering, analytical, simulation, and optimization environments to harness the full operational potential of the transport network (Campeau and Gamache, 2020; Alfort et al., 2007).

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Mining transport constitutes one of the most critical assets in the technological process of every mine. Therefore, this article aims to focus on reviewing available IT solutions that support decision-making in the area of mining transport. Generally, the technological advancement of such solutions over the years has been driven by the development and availability of computers, the increase in their computing power, and the interest of users on the mining side. The first solutions mentioned in the literature focused on planning and scheduling of extraction, dating back 50 years. During this period, the first simulation models also emerged. The development of specialized analytical environments occurred from the mid-1990s to 2005, and they became widespread in the subsequent years. Since 2013, specialized cyber-physical systems utilizing digital twins have become an integral part of transport process management in mining (Temkin et al., 2020; Karami and Szymanski, 1997).

The initial analytical solutions were based on simplified analytical methods. Many input data consisted of catalog data or averaged statistics. Due to the strongly stochastic nature of the transport process, it is difficult to speak of their accuracy. Access to data measured under real conditions and the ability to track the ore flow in the transport network in time and space with an awareness of exploitation contexts are crucial elements in decision-making. A key breakthrough was the introduction of monitoring equipment in mining, especially the construction of broadband teletransmission networks using fiber optic technology. In the case of underground mines, this solution appeared in the last decade. Since then, there has been the possibility of full information exchange between the underground and surface of the mine. Acquiring a fraction of this data in the past would have required a huge amount of manual measurements, involving human resources that are difficult to estimate. Such an effort still would not have resulted in the availability and quality of data achievable today in real-time through Operational Technology – OT, which in the case of mines is mostly SCADA software. Initially, the location of movable assets in the mine was also impossible. In the case of open-pit mines, the advent of GPS technology was a breakthrough, while in the case of underground mines, RFID technology seems to be the optimal solution. However, tracking the flow of ore mass on conveyor belts remains a significant limitation. For instance, in the case of an underground mine with an extensive conveyor transport system, strain gauge scales or vision-based ore analyzers are installed at critical locations, mainly at the dump points. Therefore, access to this data is limited and spatially dispersed. Consequently, numerical tracking of the flow of ore mass is impossible. As a result, a comprehensive analysis and evaluation of the transport process are not directly attainable, necessitating the development of simulation models (Bardzinski et al., 2020).

The analysis of transport processes is inseparably linked to issues such as geological modeling, planning and designing the mineral extraction process, exploitation of technical facilities, and the organization of machine work and maintenance. Due to the holistic nature of the issue, in order to ensure optimal operating conditions for transport, the development of computational models should be conducted on multiple levels, necessitating the development of comprehensive decision support tools, which, in turn, call for the application of simulation models. Depending on the size and type of the mine, the ore logistics system creates a more or less complex functional structure in the form of vessels connected with their own topology, hierarchy, and cooperation rules. Therefore, in the case of a large mine, the development of IT tools supporting the reproduction and understanding of technological processes can be a significant challenge. The digital modeling of the ore logistics process requires an understanding of natural (e.g., geological), operational (e.g., mining method, transport system layout, shift work system), and technical (e.g., machine availability, structure, technical condition, risk of failure) conditions (Jurdziak et al., 2019).

The aforementioned lack of monitoring and data transmission methods contributed to the proliferation of a planned preventive machinery maintenance strategy. Machine diagnostics in the mining industry relied on basic methods for many years, and due to the extensive spatial distribution of the transport network, it mostly concerned critical machinery (Zimroz et al., 2014). Planning of maintenance and repair work was mostly based on reliability models or strictly defined inspection periods. The observed development of the Internet of Things in the last decade has accelerated the mining industry's interest in technical diagnostics, as well as the widespread application of the current trend – Predictive Maintenance. Current technological solutions allow for the development of a DSS class system which, in an integrated and systematic approach, ensures the assessment and prediction of the effectiveness of the transport system in the mine in the functions of planning, organizing, controlling, and monitoring the process of ore hauling – Advanced Process Control (APC). Moreover, it should be emphasized that a mine is a highly dynamic ecosystem that necessitates continuous changes in the layout of ore hauling (Stefaniak et al., 2020). This also considers issues such as modifying ore hauling routes (e.g., expansion, elimination) or requirements regarding the configuration of machine work, their purpose in the system, or the method of machine maintenance itself. Therefore, the development and continued maintenance of a comprehensive DSS system in many cases pose a significant challenge, often limited only to individual areas of belt transport management.

Related Works

Systematic literature review is a research method that involves a comprehensive and structured search of relevant literature to identify and analyze existing knowledge on a specific topic. In the case of mining companies, several such reviews have been found that can provide valuable insights into the current state, research gaps and future research directions in the field. They pose these issues from a variety of perspectives.

Osanloo and Paricheh (2020) presented a literature review of all aspects of technical, economic and sustainable development of in-pit crushing systems (IPCC) along with a statistical analysis of the systems since 1956 to the present. It included a total of 105 papers. The authors analyzed the advantages and disadvantages of different types of IPCC systems, as well as their impact on the environment, safety, and productivity. The main conclusion from the systematic literature review is that IPCC systems have the potential to reduce mining costs and improve productivity compared to traditional truck and shovel systems. The selection of an appropriate IPCC system depends on various factors, including the size and shape of the pit, the type of material to be mined and the distance between the pit and the processing plant. Moreover, the implementation of IPCC systems can have a significant impact on the environmental, safety and social aspects of mining operations, and these factors should be considered in the decision-making process.

Pimentel et al. (2016) provided a systematic analysis of the literature devoted to the development and application of quantitative decision-support methods with sustainability considerations in the mining industry. The authors identified key elements of decision support models, such as life cycle assessment, real options and externalities analysis, and discussed their applications in the mining and mineral processing industries. In particular, they found important gaps in elements such as project portfolio optimization, operations and waste management, and mine closure and rehabilitation, and even more so when social targets and impacts are considered. They also identified the challenges associated with the integration of sustainability considerations into decision-making processes and the need for new methods and tools to address these challenges. The paper highlights the importance of integrating social and environmental factors into decision-making processes and the challenges associated with data availability and quality. The authors also expressed the complexity and uncertainty of sustainable mining networks and the need for decision-support models that can handle these challenges.

Rakhmangulov et al. (2022) conducted a systematic literature review to gather information on possible strategies and methods for the development of a mining enterprise. The authors identified five main areas of multi-criteria decision making methods (MCDM) used in mine supply chain management: capacity planning, logistics, inventory control, network design, and sustainable development strategies. The article focuses on the last area, sustainable development strategies, and proposes a method for selecting a strategy for mining and technical system sustainable development using combined fuzzy Analytic Hierarchy Process (AHP) and Measurement of Alternatives and Ranking according to COmpromise Solution (MARCOS). The authors extracted data from 25 articles, including the MCDM methods used, the criteria used for decision-making, and the sustainable development strategies proposed. The review highlights the importance of considering multiple criteria and stakeholder perspectives in decision-making for sustainable development in the mining industry. The proposed method for selecting a strategy for mining and technical systems sustainable development using a combined fuzzy AHP-MARCOS multicriteria decision method provides a useful tool for decision-makers in the mining industry.

A similar systematic literature review concerning sustainable deep-sea mining transport plans identified 23 studies that used MCDM methods for sustainable deep-sea mining transport plan assessment (Ma et al., 2022). The review found that the AHP was the most commonly used MCDM method, followed by the Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS) method and the Simple Additive Weighting (SAW) method.

Also, Sitorus et al. (2019) identified 122 studies that used MCDM methods for the choice problem, but only in mining and mineral processing. The studies covered a wide range of decision problems, including mining method selection, equipment selection, mineral processing plant design, and waste management. Similar to the previous review, the AHP was the most commonly used MCDM method, TOPSIS, and the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE). The authors identified several trends in the use of MCDM methods in mining and mineral processing, including the increasing use of sustainability criteria, the integration of expert knowledge and stakeholder preferences, and the use of novel MCDM methods such as fuzzy logic and grey relational analysis.

Risk management and assessment in the mining sector was the subject of the last literature review presented in this section (Tubis et al., 2020). The authors selected 94 of the most relevant articles in this field published over the past decade and based on the concept of human engineering systems. Most of the selected studies were published in the last 5 years, which proves that this research direction is only in its growth phase and should develop in the coming years. The authors emphasize that, when analyzing risk management/risk assessment issues in the mining sector, one should not forget about the possible different factors and aspects of risk occurring at different stages of the mine life cycle (MLC). The MLC encompasses six phases: exploration and feasibility, design and planning, construction and installation, mineral exploitation and processing, mine closure, and post-mining land development. Selected articles on risk management and assessment in the mining industry have mainly addressed the last three phases of MLC.

The above-described literature shows that the use of the SLR (Systematic Literature Review) method is not new in the mining area, and several such reviews have already been performed. While some of them were focused on researching decision support or optimization methods, the authors see a lack of review that will connect three areas: decision support, optimization methods, and excavated material transportation. The ore transportation procedure covers four of the seven main stages of mining operations (Matsui, 2009) and can cover up to 70% of total production costs (Xiwen and Zhongling, 2010). For this reason, in the authors' opinion, such a review is necessary to summarize and indicate directions for further development in order to further improve this area of mine operation.

Materials & Methods

To conduct a systematic literature review, one needs to follow a clearly defined method that describes the process of searching, collecting, and analyzing research papers in search of the answers to the questions asked. The review presented in this article meets all the criteria for a systematic review and was developed using the PRISMA method (Moher et al., 2009). The study began by posing research questions and developing a protocol that would adequately gather and synthesize information to provide the answers. The literature included in this research was gathered from three different sources using carefully formulated queries during the search process, and was then filtered in the selection process by all of the authors. Finally, on that sample, a descriptive and in-depth review of the selected research was performed.

Research Questions

Research questions were created to guide the review and describe the current state of research in the field of material transport optimization in mining enterprises. A total of five questions were asked, with the first one being the main research question for the review. The role of questions R2–5 was to go in-depth into the solutions found in the literature and provide answers on specific methods used and areas of application. The research questions are:

– *R1. What is the current state of the research regarding decision support for ore transportation in mining enterprises?*
– *R2. What are the decisions supported that are relevant to the ore transportation process in mines?*
– *R3. What are the methods used to support decision-making concerning ore transportation?*
– *R4. What parts of the ore transport process are being supported?*
– *R5. What are the goal-objective functions used in ore transport optimization?*

Search & Selection Process

To answer the research questions, a systematic literature review was performed. The articles of interest were initially searched with the use of multiple keywords that can be divided into three categories: decision support, mine, and ore transport. All keywords used in this process are presented in Table 1. For any article to be initially selected for the sample, one keyword from each category needed to be present in its title, abstract, or keywords.

It was decided that the articles included in this study should come from recognized scientific literature sources such as Scopus and WOS, as well as from grey literature sources such as Google Scholar. Therefore, three queries, one for each source, were built and run on July 25, 2023. In each of them, additional inclusion criteria were added, such as document language, which was English, and document type, which was either an article or conference proceedings. The final form of each of the queries, as well as the quantity of articles selected by them is presented in Table 2. The querying process resulted in 57 documents from the Scopus database and 52 from the Web of Science database. As for Google Scholar, only the first 100 positions, sorted by default in order of relevance, were included in this study. After joining results from all three sources and the removal of duplicates, the initial sample of review was created from 170 documents.

The sample was subjected to further screening, first with the use of titles and abstracts and then with full texts. Because of the small size of the initial sample, only four criteria were used in this process. All of the criteria are presented in Table 3. The first was a straight-forward extension of the keywords used in database querying, while the rest were more technical. The fourth one, although not standard, was added because some of the documents present in the sample were not digitalized due to their significant age and therefore not available to the authors.

At the beginning of the screening process, the sample consisted of 170 unique documents. In the first stage of the selection, where only the title and abstract were under review, 89 documents were excluded, in majority because they did not meet C1. At the second stage, where full texts were examined, another 35 documents were removed from the sample. Finally, only 46 documents were included in the final sample. The selection process in the form of the PRISMA diagram is presented in Fig. 1. During the selection process, the authors found out that a large number of articles were referring to decision support in the case of ore transport, but the area of support was beyond the mine. Most commonly, the documents were referring to the situation of ore transport between mines and a specific power plant or shipment port.

Table 1
Keywords selected in search of relevant literature

Decision Support	Mine	Ore Transport
Decision Support System, DSS, Decision Making, Decision Support	Copper Mine, Coal Mine, Underground Mine, Open Pit Mine	Ore Transport, Spoil Transport, Transport Optimization, Ore Haulage, Spoil Haulage, Haulage Optimization

Table 2
Queries used in database search

Database	Quantity	Query Content
SCOPUS	57	TITLE-ABS-KEY((“Decision Support System” OR DSS OR “Decision Making” OR “Decision Support”) AND ((copper OR coal OR underground OR “open pit”) AND min*) AND ((Ore OR Spoil OR “Optimization”) AND (Transport* OR Haulage))) AND LANGUAGE (english) AND (DOCTYPE(ar) OR DOCTYPE(cp))
WOS	52	TS=((“Decision Support System” OR DSS OR “Decision Making” OR “Decision Support”) AND ((copper OR coal OR underground OR “open pit”) AND min*) AND ((Ore OR Spoil OR “Optimization”) AND (Transport* OR Haulage))) AND LA=(english) AND (DT=(Article) OR DT=(Proceedings Paper))
Google Scholar	Over 21,000	(“Decision Support System” OR DSS OR “Decision Making” OR “Decision Support”) AND ((copper OR coal OR underground OR “open pit”) AND min*) AND ((Ore OR Spoil OR “Optimization”) AND (Transport* OR Haulage))

Table 3
Criteria used in the selection process

Criterion	Description
C1	the main subject of the document had to be decision support strongly embedded in the area of ore transport or the development of the ore transport at the mine.
C2	The document needed to be a scientific article or conference proceeding written in English.
C3	The document is not a literature review.
C4	The document needed to be available with the use of standard means.

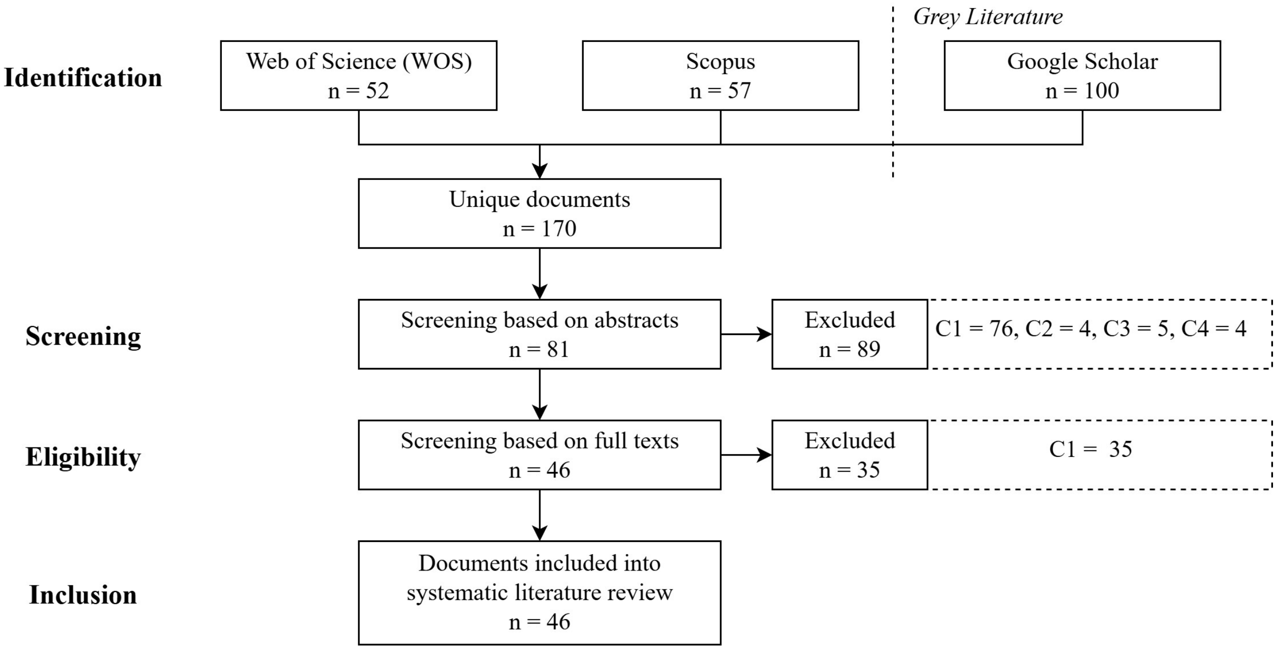

Fig. 1. PRISMA diagram of systematic literature review

Such articles were rejected from the review on the basis of C1, because, in the authors' opinion, their scope of work is not related to mine itself.

The final 46 documents included in the review were then collected, grouped, and characterized in terms of answering the research questions. During this process, the quality of the described work was also assessed. Unfortunately, a small number of researchers (< 10) failed to meet quality standards, in the authors' opinion. However, because of the limited sample size, it was decided not to exclude their work but rather to describe it only briefly.

Descriptive Analysis

A descriptive analysis was performed to give an initial look at the content of 46 publications that have been the source of this review. First, all documents have been compared based on their year, which is shown in Fig. 2. Two periods of excitement in the topic area can be marked, first from 2010 to 2016 and second from 2017 to 2021. Before 2010, the research interest was minimal, with one article being published every few years. Currently, the maximum has been reached in 2022, and 2023 should be excluded from this analysis as it was performed before the year ended.

The second stage of descriptive analysis was performed using a popular tool called VOSviewer. This software is used to visualize bibliometric networks, the analysis of which allows one to find and explore relationships between publications, authors, keywords, etc. In this particular example, the most informative was the network created from the combined keywords declared by the authors of the documents in the sample, which is shown in Fig. 3. Nine clusters have been found, of which three are of interest. The first one (green) shows that AHP and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) are connected to tasks of equipment selection and event simulation with regard to the haulage system. The second one (blue) shows a triangle of relationships, pointing out that integrated models are used to support decisions with regard to energy efficiency. Finally, the third one (red) shows a close relationship between MCDM methods like MARCOS or Fuzzy AHP that can be used to enhance strategies in mining enterprises, especially the open-pit ones. From the rest of the clusters, it can be learned that fuzzy sets and metaheuristics play a vital role in the solutions.

The final component of the descriptive analysis was the categorization of publications performed during the selection process. From each publication, four different pieces of information were extracted: type of mine, type of ore being excavated in this mine, type of

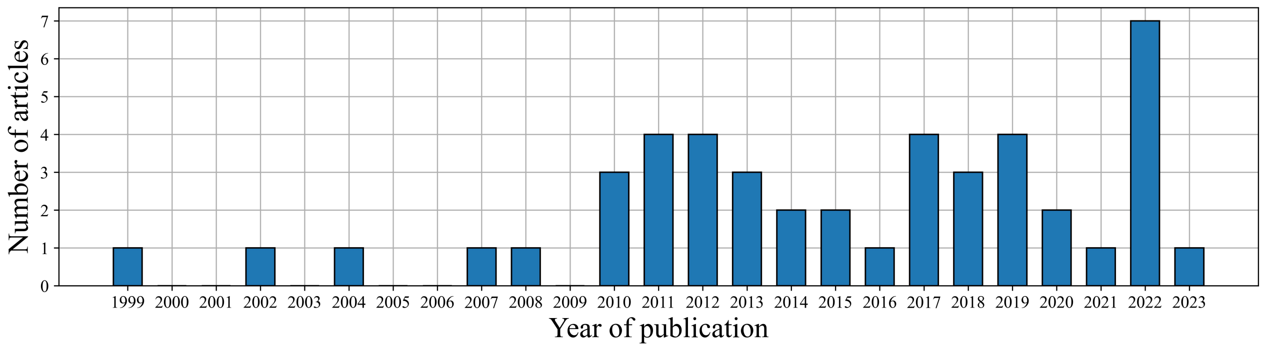

Fig. 2. Number of publications selected to review by year of their publication

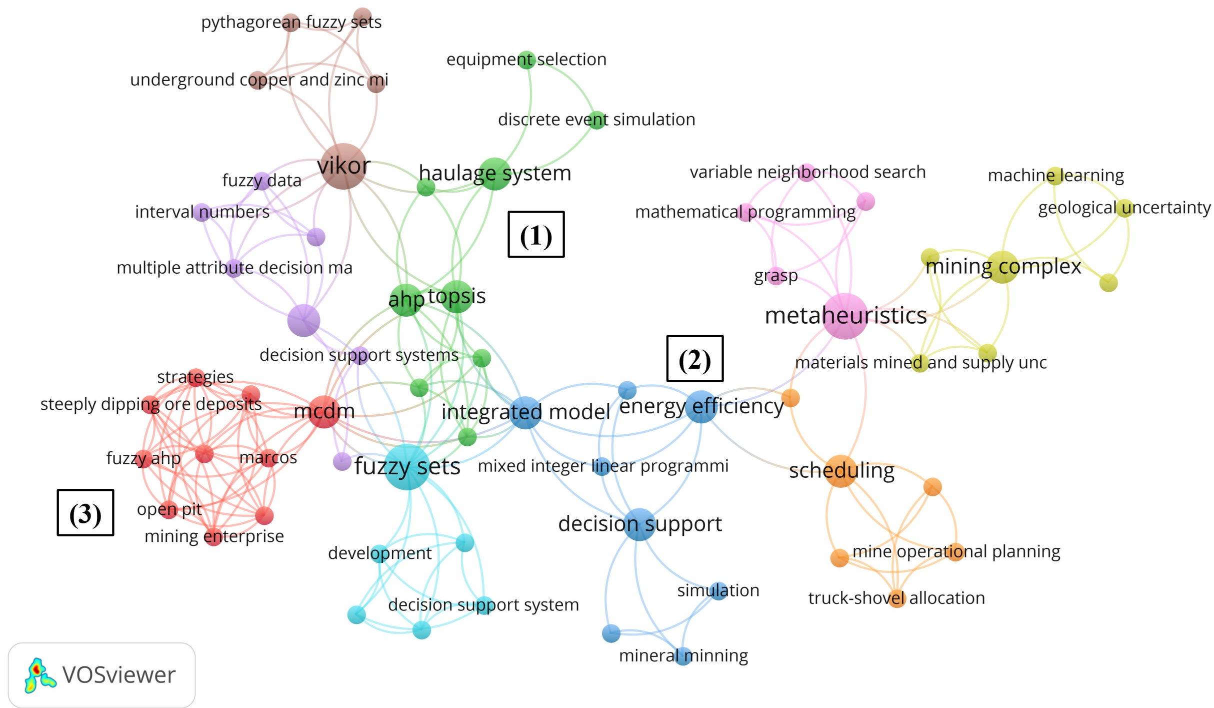

Fig. 3. VOSviewer network created based on keywords specified by authors

transport being supported by the described solution, and methods used to perform the decision support. Results in each category are presented in the form of donut plots that are shown in Fig. 4. From these graphs, it can be deduced that most of the publications describe a solution for decision support in the transportation process: using tire machines (2/3), in open-pit mines (2/3), and the top 3 ores excavated are iron, coal, and copper (adding up to 1/3). In the case of means of ore transport, conveyors and various (i.e., two or more different) are also popular (15% each). As for the methods utilized, some (adding up to 1/3) are used more often than others (adding up to 2/3). Here, one can distinguish two general groups: the optimization methods (e.g., Integer Programming, Mixed Integer Linear Programming, Genetic Algorithm, and Linear Programming) and the decision making methods (e.g., AHP, VIKOR, Fuzzy Logic, and Sensitivity Analysis).

In summary, the descriptive analysis helped establish several facts with regard to the review sample. First of all, almost all of the documents were published in the last 13 years, between 2010 and 2022. Second, most of the research is done in the area of tire machines and open-pit mines. Third, the most popular

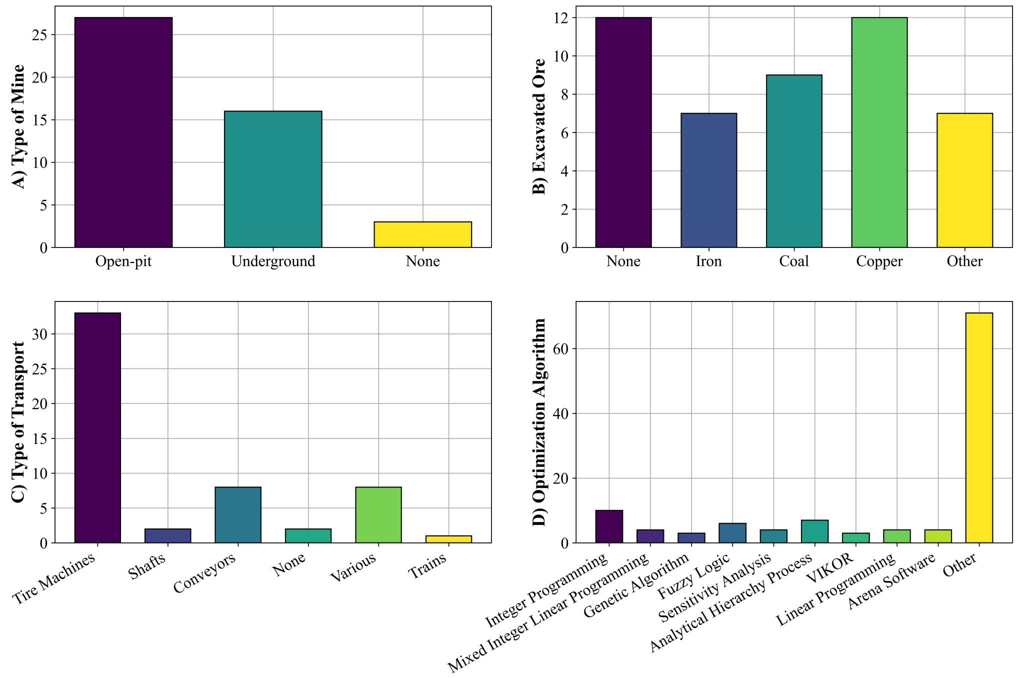

Fig. 4. Assessment of the number of articles in the sample based on: A) type of mine described, B) type of excavated ore, C) type of transport being supported, D) methods used in the articles Management and Production Engineering Review

methods to be utilized are: IP (Integer Programming) along with its variation MILP (Mixed Integer Linear Programming), AHP, and Fuzzy logic.

Decision Support for Ore Transportation in Mining Enterprises

In this chapter, results from the systematic literature review regarding decision support in ore transportation in mining enterprises are presented. During the full-paper review, the authors established eight different categories based on the decision-aided area. All of the papers will be presented in subchapters with regard to those categories, which are: predictive maintenance, efficiency assessment, mine simulation, scheduling and planning, equipment selection, mine development, machine allocation, and risk assessment. Each of the solutions will be presented in separate subchapters with respect to the categories in chronological order.

Predictive Maintenance

The category of predictive maintenance refers to solutions aimed at helping their users detect failures in the early stages of development. In addition, one item describing preventive maintenance was also included in this category due to the proximity of the areas.

For predictive maintenance, two documents from 2018 were found, both regarding transport with the use of conveyors. Wodecki et al. (2016) presented a method for long-term analysis of temperature data from the conveyor gearbox, which was aimed at detecting anomalies. Using data clustering algorithms such as k-means or EM clustering, the authors showed that the data are correlated with the days of the week, but they also found one group indicating an anomaly (e.g., potential damage). Stefaniak et al. (2016) raised the issue of building a DSS to support the management of an extensive network of conveyors in the area of predictive maintenance. The presented concept combines the readings from the automation (i.e., SCADA) with individual vibration characteristics collected using specialized equipment. The main tasks of the system would be: creating a repair and inspection schedule; identifying problematic elements for individual inspections; assessing the health of machinery before work; and early diagnosis of failures.

In terms of preventive maintenance, Jakkula et al. (2020) showed a method for utilizing the maintenance logbook of an LHD machine. In their work, they presented a method of analysis and creation of KPI's describing the health of the machine using methods such as MLE (Maximum Likehood Estimate), K-S Test (Kolmogorov-Smirnov) and RAM Modeling (Reliability, Availability and Maintainability). The method was tested on data from one accounting year for 4 machines, indicating the most and least unreliable machines and elements.

Efficiency Assessment

The efficiency assessment category includes works that present methods and ways of conducting a subjective assessment of process performance in relation to environmental conditions. Two documents were found that belong directly to this category.

Kozlowski et al. in 2019 described the method for automatic detection of work cycles for haul trucks. The information about work cycles has immense value in the calculation of some KPI's, mostly in regard to the assessment of operators work. The authors created an algorithm that used linear programming to detect unloading moments based on signals about engine rotations and pressure in the braking system. In 2022 Kuznetsov and Kosolapov (2022) analyzed the impact of several groups of factors on the operational efficiency of haul trucks. In their analyses, the authors included: environmental factors like temperature, the length and quality of the access road, the wear of working elements, and the operation scheme. With the utilization of mathematical programming, the authors showed a way to perform an assessment of up-to-date production efficiency and enable performance forecasting and technological decision-making.

Mine Simulation

The mine simulation category refers to solutions that are focused on reproducing real world mine operations in a digital format. Usually, such approaches rely heavily on two kinds of data: streaming (e.g., from SCADA systems) and stochastic (e.g., statistics regarding mine operation). If created correctly, mine simulation can be utilized, among others, for visualization of mine operations, carrying out what-if analyses, and predicting KPIs. The nature of the simulation is multipurpose, and therefore there are a variety of decisions that can be supported by it, which is why this is a separate category. The review found ten articles in regard to this matter, starting in 2012 and ending in 2022.

The first document published by Lin et al. (2012) describes, in a more general sense, the issues of creating a digital sibling for mine. In this paper, a general presentation of problems, possible branches of development, and technologies needed in the implementation process is presented. One year later, a data-driven simulation of an open-pit mine is presented by Meng et al. (2013). The authors modeled several types of machines in UML (Unified Modeling Language) and simulated them with discrete time in ARENA software. This simulation is based on a transport network, and some processes are not implemented, like ore extraction, milling, and blending. The main task of the simulation is to carry out what-if analyses that are each time specified by the user, and its accuracy is 95%. In 2014, Salama et al. presented a general discrete event simulation based on statistics (e.g., mean unloading time, mean time to the pit) with the sole purpose of selecting the optimal number of two types of machines used in ore haulage. The tool was used to estimate the work time, queues, and productivity of machines based on a set of initial criteria. After validation, the authors used a simulation on a practical case of an underground mine, and achieved a 20% increase in mean production value. In 2015 Upadhyay et al. presented a simulation based on interactions between tire machines in a mine. The authors mapped the connections between machines on a shared transportation network along with access route parameters (e.g., movement resistance, direction gradient) using MILP and ARENA software. In addition, a model for fleet management with a short-term horizon is proposed.

In 2017, two publications were found. Chen and Shi (2017) presented a system for planning and simulating complex transport networks with FlexSim software. The introduced tool takes into account actions such as loading, transport, machine allocation, unloading, and crushing. Another solution was showed by Goodfellow and Dimitrakopoulos (2017) who created a tool for stochastic modeling and optimization of the mining complex. The presented solution is a two-part model for: generating a life-of-mine production schedule; providing destination policies; and managing the use of available process streams. Simulation is based on material flows in the mining complex and non-linear transformations applying to it. This model, created with integer programming, is then tested on two use-cases, in which he is able to score an increase in NPV (Net Present Value) of about 23%

In 2018, Upadhyay and Askari-Nasab showed another discrete-time simulation of tire machinery in an open-pit mine. The solution provided by the authors is focused on reality, and therefore, among standard simulation elements like moving on a common transport network or traffic, the simulation includes road conditions, tire replacement costs, effects of accidents, accurate cost estimation, and multiple algorithms for machine allocation. Although accurate, the tool supports only short-term planning and was launched with the help of MILGP, MATLAB, Arena, and VBA. In 2019, Paduraru and Dimitrakopoulos raised the problem of allocating ore grades to different processes, which is usually done using decision thresholds. The authors point out that this approach may be insufficient because it creates queues, and the optimal solution could be to avoid queues and lose some of the final mineral. To verify that thesis, they have built a discrete-time simulation that generally presents the entire random process (i.e., including random events), and in this environment, they have placed a neural network to make decisions about the destination of excavated material. Using a reinforcement learning agent allowed a 7% increase in profits compared to the standard method. One years later, Abolghasemian et al. (2020) created a simulation of an open-pit mine, where places of interest, machines, and ore grades were reflected. The tool was created with the help of OptQuest and Arena software. Its main functionalities are excavation planning and shovel allocation with regard to mine restraints. The authors verified their solution over a 30-day period, which showed that the simulation estimation error is less than 5% and the new excavation plan allows for a 20% increase in profits. Finally, in 2022, Stepanova et al. showed a general simulation of a mine transportation network that allowed for the detection of bottlenecks. Using the model, the authors defined two bottlenecks in the described case and proposed a solution based on increasing the number of selected machines, which would help avoid queues.

Scheduling and Planning

In 2010, Qinghua et al. created a DSS for an open-pit mine based on GPS and GPRS technologies, whose main task was the optimization of ore extraction with regard to the blending process. The described system has several functions: operations on maps, management of stockpiles, drawing isolines of various ore grades, visualization of the location of excavators in real-time, reconstruction of historical views, communication with operators (e.g., dispatch instructions), creating an ore mixing plan, and some other smaller functions. This tool has been tested for about 2 years in a real mine, and its performance was assessed as good. The system was able to reduce the error in the resulting ore class from 15.82% to 4.35% and improve overall productivity. Two years later, Eivazy and Askari-Nasab (2012) showed a model for the long-term planning and short-term execution of extraction in an open-pit mine. The authors first used an algorithm to divide the entire mine into mining cuts. Then the proposed MILP model was able to create a long-term plan by optimizing the NPV, and on that basis, the short-term plan was created by optimizing the production costs.

In 2013, Bastos researched the problem of optimal shift change in an open-pit mine. The author created a TiMDP-based (time-dependent Markov decision process) model for aiding the decision of whether the operator should make one more trip and add overtime or return to the parking lot so the machine will stand idle until the next operator arrives. The main result of this work is the development of a method to calculate the impact of changing operators with regard to idle time. In the same year, Pascual et al. (2013) proposed an optimization tool for choosing an optimal number of vehicles for tire haulage, along with the number of active crew and maintenance stations operating. The model based on a closed queueing network performed optimization based on three criteria: machine availability, process efficiency, and global costs. In an exemplary section from the mine, the model allowed global cost savings of 20.6%, increased availability by 13.5%, and increased process efficiency by 7.1%.

In 2015, Nguyen and Bui presented a conception of a multi-agent decision support system for open-pit mining. The emphasis was put on accident handling: diagnosis, changing routes, and schedules for the rest of the machines. A year later, Patterson et al. (2016) present a MILP model for managing the work schedule and equipment. The model helps to trace the scenarios assumed by the user (e.g., a 10% faster delivery) in terms of optimality and energy efficiency. Another year later, in 2017, (Blachowski et al. show three examples of geoinformatics usage with regard to mining enterprises. While two of them are not related to transport, one example describes in a general sense a spatial management system for a large-scale conveyor network.

Equipment Selection

The equipment selection category contains five publications and refers to the problem of choosing an optimal amount or optimal ratio of machines for a given task. The focus here is usually on the equipment from the same category of transport, especially tire machines like haul trucks and loaders. The documents here can also be labeled as the scheduling and planning or mine development category, and only minor details distinguish this category. The main ones are: choosing alternatives, but from similar types of vehicles; and focusing not only on location and connection but also on the number of machines used on the shift.

The first paper, created in 1999 by Haidar et al., describes a decision support system that allows for choosing an optimal type of machine for ore haulage. The proposed solution was made using GA (Genetic Algorithms) and analyzed alternatives in terms of mine parameters and characteristics, operating conditions, equipment type, extraction rate, cost of ownership, operating costs, and equipment specifications. A similar problem was researched three years later by Samanta et al. (2002). The authors specified over 30 criteria in 7 different categories to make a selection. Then, using expert knowledge, two of those categories were chosen (i.e., production capacity and parameters of the mine) and a decision was made on that basis. The main technique used by the authors was AHP.

In 2011, Subtil et al. described a model for optimal resource planning and dynamic allocation. The main feature was the estimation of the number of machines needed on the shift, along with their allocation. The solution was done using linear programming in cooperation with Simplex software. The model, on the basis of two use cases, achieved an increase in productivity while reducing operating costs. One year later, Lashgari et al. (2012) created another tool for optimal equipment selection for load and haulage. The authors used a combination of fuzzy AHP and ANP for the initial weighting of the parameters, and on that basis, an alternative was chosen using TOPSIS in a fuzzy environment. The alternatives were assessed by 20 experts using a total of 30 criteria in four main categories: capital cost, operating cost, operational parameters, and technical parameters. Five alternatives were considered: backhoe loader, wheel loader, dragline, hydraulic shovel, and cable shovel, and the best one (i.e., the cable shovel) allowed for a reduction in operating costs and idle times while maintaining sufficient ore transportation speed.

Finally, in 2023, Navidi et al. proposed a G/M/C//M queuing model for shovel-truck systems in an open-pit mine. The main purpose of the described solution was to balance the ratio of loaders and haul trucks for profit maximization with regard to budget and environmental impact. The tool was also able to perform some what-if analyses for an increased number of vehicles.

Mine Development

Decisions in the mine development category can be further divided into two areas: transferring the mine from open-pit to underground and expanding the current transportation network of the mine. While the first one does not directly refer to ore transport, some of the solutions put a great emphasis on the transport issue and therefore were included in this review. A total of ten documents were granted the mine development category.

In 2004, Elevli and Demirci researched the problem of selecting suitable means of ore transportation for an open-pit mine evolving underground. The authors reduced this decision to six factors: production volume, investment cost, unit transport cost, NPV, difficulty in implementation, and the risk of deposit completion. The selection of the most suitable means of transport from the three given alternatives (i.e., shaft, truck, and loader) was made with the PROMETHEE method. After a 3-year break, Brazil and Thomas (2007) show a method for optimally creating a mine ore transportation network. In the proposed solution, the main transportation equipment (i.e., shafts, conveyors, and haul trucks) is represented on the graph, which is then optimized with regard to some restrictions (e.g., maximum inclination). On that basis, the authors created two products (i.e., Underground Network Optimizer and Decline Optimization Tool) that were successfully used in some practical cases. In 2008, (Yavuz et al. described a solution for the problem of choosing optimal mining supports for the mine's main access route for ore transport. The proposed solution consisted of 19 numerical models, each corresponding to one variant of support based on geological research on ore deposits. The optimal alternative was chosen using AHP, and this choice was further researched using sensitivity analysis.

Aghajani Bazzazi et al. (2011b) published two papers in 2011, both dealing with the problem of selecting the optimal alternative. In the first one (Aghajani Bazzazi et al., 2011a), the authors present a new method from the MADM (Multi Attribute Decision Making) area that allows for the optimal choice of transport. The method consisted of using the AHP and fuzzy-based expert opinion weighting and scoring. The criteria utilized in the process were divided into five categories: financial, safety, mine parameters, machine parameters, and reliability. Three different alternatives were taken into account: loaders with haul trucks, shovels with haul trucks, and haul trucks with conveyors, and the one selected (i.e., shovels and haul trucks) reached agreement among various groups of experts. The second work (Aghajani Bazzazi et al., 2011b) showed a modified VIKOR method, which was extended by an evaluation model based on fuzzy logic. The authors practiced their tool on the problem of choosing an optimal alternative from: a shovel and haul truck, a loader and haul truck, and a shovel with a haul truck and an in-pit crushed with a belt conveyor. The model showed that the shovel with haul truck is the best alternative, and the selection was made based on seven criteria: total costs, operating costs, working conditions, haulage distance, reliability, productivity, and life cycle.

Three years later, in 2014, Jovanovic et al. present another method for selecting the optimal mode of transport for the transitioning mine. The choice is made based on criteria associated with: construction costs, the scale of the transported output, the length of transport routes, and the unit cost of transport. The choice is made based on the model, which resembles transport operations as a weighted fuzzy network. The same problem was researched in 2019 by Ghasvareh et al., where the decision is made using combined AHP, TOPSIS, and VIKOR methods. The selection was made on the basis of a different set of criteria related to: availability, safety, failure rate, transportation costs, operator costs, purchase price, life expectancy, and flexibility.

In 2022, Rakhmangulov et al. researched the problem of an open-pit mine that has come to a significant point in its life and had to make a decision about the future. Four different scenarios for the mine were considered: change of mining parameters (i.e., mainly equipment), change of the form of mining (i.e., expansion of mine and equipment), change of mining mode (i.e., transition to the underground mine), and closure of the mine. With the use of Fuzzy AHP and MAROCS methods, the authors were able to select an optimal decision on the basis of 23 different criteria correlated to technological, economic, social, and environmental factors. In addition, the authors analyzed 107 mines to assess the form of excavation and the presence of external conditions. In the same year, Yang et al. (2022) describe a model for the optimal location of facilities utilized in the backfilling process. Six different places take part in this process from the extraction to the end. The proposed model combines the methods of PSO (Particle Swarm Optimization) and QNM (Quasi Newton Methods) in order to propose the optimal set of coordinates (i.e., one for each facility included in the process). Locations are selected to minimize transport costs while maintaining the highest efficiency. The authors declared a 42% savings in the cost of transport and improved efficiency. Finally, the year ends with Shamsi et al. (2022), who provide a solution for an open-pit mine for choosing an efficient alternative between loaders with haul trucks and a semi-mobile in-pit crushing and conveying system (SMIPCC). To solve this problem, the authors provided an integer programming model that was able to compare the two alternatives with regard to the production plan and select the best one by maximizing the NPV of the company. In addition, for the case of SMIPCC, the developed model indicates the proposed location of SMIPCC and the time of relocation, which involves a huge economic, operational, and technical effort. In the described case, based on the model results, the SMIPCC turned out to be a better alternative, with a 70% increase in the NPV.

Machine Allocation

Machine allocation is the action of assigning a machine, usually a haulage truck, to a place of work. This decision is usually made considering a number of different criteria, such as the availability of machinery or the category of material needed for the ore blending process. This review identified eight documents that concerned this type of decision, most of which also fell into another category of scheduling and planning.

In 2010 Souza et al. described a mathematical model solved by a metaheuristic aimed at selecting the optimal equipment (i.e., loaders, excavators, and trucks) for mining pits in an open-pit mine and adjusting the mining plan for those places. The metaheuristic created by the authors as a result of combining two methods, GRASP (Greedy Randomized Adaptive Search Procedures) and GVNS (Greedy Variable Neighborhood Search), allows them to find a solution close to the optimal one in an acceptable time, as operational decisions in this category usually have to be made in a limited time. In the same year, Nehring et al. (2010) presented a model for dynamic production planning and machinery allocation intended for underground mines. The model's objective function was to minimize the production deviation during each shift, and the model itself maps the mine operations in the MIP (Mixed Integer Programming) language. The model takes into account different classes of ore and is based on its flows, which have been divided into two categories: primary ore movements – from the place of extraction to the first point (i.e., crusher or ore pass) – and secondary ore movements – rehandling. The authors of the solution, based on 2 months of data, stated that the results obtained by their model are a significant improvement to the currently used plans that are created manually. A year later, Vasquez et al. (2011) presented a solution dedicated to operators of LHDs. Their authors presented a model based on IP for optimal assignment of the production plan and jobs for loaders. A decision-making process was also introduced to guide the operators who work with the system. In 2012 Ahangaran et al. published a document that also concerned the allocation of trucks, however, in an opencast mine. The authors proposed a dynamic solution (i.e., variability in the cooperation of loaders and trucks based on current requirements), which consists of two methods: a model that finds the shortest path between two points in mine and a model that determines the allocation of a truck to the workplace. The second one was created to minimize the costs of loading and transport and takes into account a number of criteria related to the characteristics of the workplace, loader, truck, etc.

Then, after a 5-year break in 2017, a document by Patterson et al. is created that concerns the problem discussed in this chapter, but with particular emphasis on energy efficiency. The authors present a solution for managing a heterogeneous fleet of vehicles, which adjusts the loaders to the mining parameters and schedules the vehicle to reduce wasted energy. The MILP model allowed for an increase in energy efficiency of 17.6% for a medium-sized enterprise and recommended vehicles that should be further optimized. Another 3 years later, in 2021, Li et al. created a tool for developing a weekly production plan in an underground mine and a dynamic allocation of machines for each shift. For this purpose, two models were built using IP and the following algorithms were used to optimize them: Artificial Bee Colony Optimization and NSGA-III (Non-Dominated Sorting Genetic Algorithm).

In 2022 Wang et al. presented a solution that is focused more on a machines and their cooperation. The described model is used to manage the operation of haul trucks, and, in addition to the tasks already mentioned (i.e., production planning and machine allocation), it also plans access routes for the tracks to follow. When building the model using IP, a number of previously omitted criteria were taken into account, such as a common place of operation through, for example, the criterion of the minimum safe distance between successive vehicles. Finally, in 2023, Yao et al. described the largest solution in this category. In the article, the authors presented the Decision Support System, whose main task is to develop a plan for mixing the output, maximizing production output, and minimizing the transport route. The developed plan is dynamic, so it is constantly adapted to changing conditions, such as a truck failure or inaccuracies in the estimation of output flows. The system itself is divided into 5 layers, two of which are used for planning (i.e., intelligent ore blending module, intelligent truck dispatching module), one for visualization (i.e., intelligent 3D digital geological module), and two technical (i.e., on-board terminals on machines and a 4G/5G communication network). The system, as the only solution from this chapter, was implemented in an open-pit mine, where it was responsible for approximately 70% of decisions regarding truck allocation. Due to the operation of the system, an increase in efficiency of 5.5% was noted over the year.

Risk Assessment

Risk assessment is a method for identifying, evaluating, and prioritizing potential threats related to mine operations. Only one document was directly related to risk assessment and was created in 2019 by Gul et al. The authors defined 333 different hazards in 38 areas of mine operation. Then, using expert knowledge (i.e., with 8 different experts), they weighted these threats with regard to the area of activity. Expert opinions utilized in this process were weighted by their years of experience. The overall process of risk assessment was performed with the use of the PFVIKOR (Pythagorean Fuzzy VIKOR) approach. On the risk assessment, a sensitivity analysis was also performed, and the article itself was accompanied by a list of control measures to counteract the threats.

Current Challenges and Future Trends

A thorough review of the literature selected in this SLR showed several current challenges and future research directions. The main challenge for the authors was the validation of their proposed solutions on real-world scenarios. This is clearly understandable, as most mines are not willing to implement new and experimental solutions. As it has been said earlier in the mining industry, the mines aim to always be the second, so they will not lose anything testing unknown and untested solutions. In addition, data from mines are not easily obtainable, and the quality of data can also be an issue. For this reason, as many as six articles directly state that their solutions need to be further assessed and validated, preferably on a real-world scenario (Upadhyay et al., 2015; Chen and Shi, 2017; Paduraru and Dimitrakopoulos, 2019; Eivazy and Askari-Nasab, 2012; Ahangaran et al., 2012; Patterson et al., 2017). In the authors' opinion, many other articles also dealt with this problem, but since they did not explicitly make this claim, these works were not included in this group. Another important aspect mentioned across multiple articles was the further development of solutions presented by them. Due to the high diversity of works and artifacts, it was decided to include all these solutions in one category instead of writing several individual development plans. Seventeen articles have been found that directly enlist their solution improvement as a possible further research plan (Meng et al., 2013; Goodfellow and Dimitrakopoulos, 2017; Paduraru and Dimitrakopoulos, 2019; Abolghasemian et al., 2020; Eivazy and Askari-Nasab, 2012; Pascual et al., 2013; Patterson et al., 2016; Samanta et al., 2002; Navidi et al., 2023; Jovanovic et al., 2014; Shamsi et al., 2022; Souza et al., 2010; Vasquez et al., 2011; Patterson et al., 2017; Li et al., 2021; Gul et al., 2019).

Various other authors proposed several challenges and trends. Three different categories have been established: simulating and optimizing mine processes, artificial intelligence, and highly specific ideas. In general regard to mine simulation and optimization, Brazil and Thomas (2007) indicate the need for further development of science in the area of transport and navigable networks so that more complicated scenarios can be optimized. Paduraru and Dimitrakopoulos (2019) argue for the incorporation of real sensory data from mines into the decision-making process. Shamsi et al. (2022) notes that further work is needed on the cooperation of the conveyors with the rest of the mine. Chen and Shi (2017) indicate that the FLEXIM software has only just been adapted to work in a mine and should be developed in this direction. Also, they propose to model the operation of sending employees and machines to work as a discrete-time simulation. Pascual et al. (2013) indicate the usefulness of creating an accurate model for simulating the repair of LHD machines. Patterson et al. (2017) points out that more solutions should provide a whole-of-mine perspective. Eivazy and Askari-Nasab (2012) propose to create a discrete-time mine simulation. Upadhyay et al. (2015) point out that simulation of mine can and be used to validate solutions in a larger time window. Meng et al. (2013) argue that mine simulation should be more general and presents the idea of creating a heuristic for selecting the detail of simulations according to user preferences. (Goodfellow and Dimitrakopoulos (2017) indicate the need to create simulations that will model more details of the technological process. In addition, the authors point out that optimizing interaction in the mining process in descrete event simulation helps to model interaction on a smaller scale, which is important for short-term production planning. Vasquez et al. (2011) suggested the need for better modeling of LHD operation in conditions of increased uncertainty (i.e., assuming multiple haul routes and possible grids). In the same matter, Abolghasemian et al. (2020) raise the need for further work in optimizing vehicle routes in an open-pit mine (i.e., vehicle routing problem), and propose the creation of an algorithm based on evolution to more effectively solve vehicle allocation. Li et al. (2021) use their example to show that vehicle allocation models should ideally optimize all equipment, not just the equipment responsible for transport. Finally, Patterson et al. (2016) simply highlight the need for better modelling of mining and transport.

In the domain of artificial intelligence, Haidar et al. (1999) find that linear programming is in recession, and new AI methods should be tested and implemented to optimize mine problems. Lin et al. (2012) point to the general need to develop all kinds of tools and models for the development of the "digital mine" concept. Yao et al. (2023) propose combining the solutions with autonomous machines according to the Industry 5.0 concept.

Finally, in regard to more specific ideas, Rakhmangulov et al. (2022) find the need for a multi-attribute and multi-objective model for selecting the optimal mine operation strategy throughout its life. Nehring et al. (2010) propose ore inventory tracking using automatic systems that would feed short-term scheduling and machine allocation models, which in turn would constantly update their recommendations.

Conclusions

The ore transportation process in mining enterprises is always one of the most critical aspects of their operations. Its efficiency has implications for every aspect of a mine's activities, like production output, operational costs, environmental impact, etc. For this reason, this issue is the subject of research for many authors, including those who attempt to optimize the process by creating solutions that have a positive influence on decision-makers involved in its management.

In this paper, a systematic literature review method was used in order to assess the current state of research in the area of decision support for ore transport in mines. SLR should be a repeatable, rigorous, and unbiased summary of selected parts of the literature that will describe the current research gaps and possible future directions in a selected topic. To achieve this, the review presented in this work was done according to the PRISMA statement guidelines. During this process, the initial sample of 170 articles acquired from 3 sources (Scopus, WoS, and Google Scholar) was created and then reduced to 46 articles that matched the review scope. On that sample, the descriptive analysis was done to catch the overall properties, followed by a thorough review of each article. Finally, the process allowed the authors to answer the initial research questions and shed some light on future research ideas. Below are the answers to research questions that were achieved with the SLR method.

R1. What is the current state of the research regarding decision support for ore transportation in mining enterprises?

The current state of the literature presents a picture in which various optimization problems have already been effectively solved using traditional methods. In particular, two branches of solutions can be distinguished here. The first of them addresses the issues of long-term tactical decisions and is usually supported by the use of Multiple Criteria Decision Making methods. The second branch is situated in the near-term time horizon and deals with operational decision-making issues. Solutions in this area mainly involve modeling mining operations as a set of variables and then seeking their optimal values within the created space. During the review, no entirely new areas or tasks requiring optimization were found. However, possible directions for development were identified, which were directly indicated by the authors or arose from their work. All of these directions are aligned with the concepts of Industry 4.0 and 5.0, particularly the concept of the "Digital Mine." Therefore, it can be concluded that this area naturally evolves in accordance with the path set by the industry and manufacturing companies; it is just slightly delayed.

R2. What are the decisions supported that are relevant to the ore transportation process in mines?

Decisions supported by solutions presented in the literature sample can be divided into two main categories with regard to the organizational level. On a tactical level, the main objective of the solutions was to aid in large-scale modifications of the transportation network. Tactical decisions were mostly referring to situations where the mine is expanding and new means of transportation are to be added or the old ones are to be modified or removed. In those cases, the solutions were mostly helping in choosing the most optimal means of transport and, in some cases, its location. On a strategic level, most of the artifacts were aiding in the production of long-term expansion plans or production plans. However, many of them do that alongside the operational level, where short-term decisions are being made. Optimization of operational decisions is quite popular in this environment, and there are also a large variety of decisions that can be supported. Most of the authors optimized one or more of the following problems: short-term production planning, allocation of machines and operators, transportation routes, and ore mixing schedules.

R3. What are the methods used to support decision-making concerning ore transportation?

The single most prevalent family of algorithms utilized in the researched literature were various forms of integer and linear programming. Their combination, mixed-integer linear programming, was also quite popular. Other commonly used techniques include genetic algorithms and fuzzy logic from the machine learning area and MARCOS, AHP, and VIKOR from the multicriteria decision-making domain. Often used were methods that combined two or more algorithms, like fuzzy AHP or fuzzy IP. In addition, some of the authors utilized commercially available solutions instead, like Arena or FlexSim software.

R4. What parts of the ore transport process are being supported?

The majority of solutions optimized the material transport between mining faces and the first stockpile, which is frequently the first point above the ground. A small percentage of authors moved further and included in their procedures the mixing, milling, and flotation characteristics. Therefore, most of the artifacts were researched in the area of tire machines (e.g., haul trucks and loaders), and almost any aspect of their operation was covered. Some solutions included other means of transport, such as conveyors, trains, and shafts, but mostly in terms of mine development, which does not cover their operation. Additionally, in some articles, a joint operation of various transportation means was included, at various stages of operation.

R5. What are the goal-objective functions used in ore transport optimization?

Commonly, objective goal functions were directly correlated with transport efficiency or operating costs. Most of the authors, as their metric of choice, used some form of production flow description, estimation of operating costs, or both. The main idea behind many solutions was to maximize the excavated material flow or production while simultaneously minimizing its transportation costs. In some cases, the opposite approach was used, in which profits from production or the enterprise value, expressed in NPV, were maximized. Other popular metrics include maximizing the availability of machinery, minimizing idle operation, and estimation accuracy in the case of simulation. In some works, a separate trend can be seen where the objective function is to minimize energy usage or environmental impact.

Overall, this review revealed several measurable improvements. Reported effects include up to 43% cost savings, a 69.8% increase in net present benefit, and productivity gains ranging from 7% to 20%. Several models improved equipment allocation, reduced idle time, and increased system availability by more than 13%. Validated simulations also enabled accurate short- and long-term planning, bottleneck detection, and enhanced decision-making, often outperforming manual or traditional methods. However, a major drawback is that many proposed solutions in the literature were never implemented in actual mining operations. This issue often stems from the dynamic nature of mine operations, where experimentation – especially if it carries the risk of even a temporary decrease in production – is typically avoided. Mines operate around the clock, and any production halt is costly; therefore, only thoroughly verified solutions are adopted.

Describing future directions is an essential part of each systematic literature review. After carefully evaluating the articles, a few of them can be described. First, there is a visible trend to create various simulations, usually discrete-time, that should only grow over time. Many of the authors point out that there is a need for large-scale simulations that will include various means of transportation and the joint aspects of their operation in one network. Second, a large quantity of artifacts utilize the same methods that are being applied to solve the same problems. This presents a rather traditional approach, creating a gap that can be filled with the application of new methods. Currently, one of such new methods can come from the artificial intelligence area, which is very promising and has been applied with much success in other industrial environments. Third, the biggest problem with many artifacts was their lack of sufficient validation in a real-world use case. One solution for this could be an open validation framework, but there is an extremely low probability that any of the mines will agree to share their data in this way. However, some authors point out that the general, large-scale simulation of mine can provide a sufficient solution.

Finally, the limitations of this study must be acknowledged. First and foremost, it is important to note that some of the literature was not included in the research. In the case of mining sciences or literature addressing mining-related aspects in general, the issue of decision support is relatively rarely explored. Even when a presented solution serves decision-support purposes, this aspect is often overlooked, causing certain sources to meet only 2 out of the 3 main query requirements. Secondly, the entire aspect of transportation extending beyond the mine's boundaries was omitted. This situation often arises when the internal transportation network transitions into an external one, for example, when a mine collaborates with another entity such as a coal mine supplying a power plant. In such cases, the problem shifts toward decision-making within heterarchies characterized by strong relations of interdependencies. This is generally recognized as a research problem of higher complexity that also warrants attention. Thirdly, the aspect of vertical transportation, primarily carried out using electric hoists, was also omitted due to a lack of relevant studies in the literature sample.

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