Доклади на Българската академия на науките
Comptes rendus de l'Académie bulgare des Sciences
Tome 77, No 1, 2024

ENGINEERING SCIENCES
Mechanics

OPTIMIZATION OF TECHNOLOGICAL SCHEMES FOR CONSTRUCTION OF OPEN MINE ROADS

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Received on June 29, 2023
Presented by Ch. Roumenin, Member of BAS, on November 28, 2023

Abstract

Optimization of haul roads is a critical aspect of open-pit mine design, directly impacting operational costs. While computer software tools are increasingly employed for haul road optimization, there is a growing need for additional analytical models in this field. This research study compares and analyzes some of the commonly used modern methods for optimization, using the hypothetical example of optimizing haul roads in a typical open-pit mine scenario. The selection of a particular optimization method depends largely on the unique characteristics of the open mine, including its geographical location, current raw material market conditions, and other local factors. Given the complexity of the problem and the multitude of parameters involved, potential simplifications are also discussed. By examining and evaluating different optimization approaches, using the example of haul road optimization, this research aims to enhance the understanding of haul road optimization and provide insights into effective strategies for improving operational efficiency and reducing costs in open-pit mining operations.

Key words: open-pit mining, haul road optimization, operational efficiency

Introduction. A key element in the design of open-pit mines is the construction of mine roads, which serve as complex engineering facilities that require careful planning and individualized design solutions long before the mine enters its operational phase. Whether these roads are temporary, providing access to a

https://doi.org/10.7546/CRABS.2024.01.12

specific horizon, or permanent, with a lifespan that coincides with or extends beyond the life of the mine, it is crucial to consider a combination of factors. These factors include the geographic location of the mine, geological and hydrogeological conditions, and the integration of heavy mechanization and associated design requirements. Furthermore, with the growing focus on environmental and economic considerations, challenges related to climate change, rising fuel prices, and the development of zero-emission transportation have become increasingly important.

One of the primary challenges encountered in designing mine roads is the presence of unacceptably high longitudinal slopes in certain sections. These problematic slopes not only pose an additional risk of traffic accidents but also contribute to the accumulation of residual deformations in the road, resulting in increased maintenance and operating costs. Additionally, inadequate pavement thickness design can lead to subgrade icing, causing significant deformations that render the road unusable. Addressing these issues requires a comprehensive investigation into the functioning of drainage systems, proper consideration of frost heights, and the construction and maintenance of the road's cross-section.

The presence of a non-functioning drainage ditch can impede the proper flow of water and exacerbate road deterioration. Neglecting frost heights can lead to frost heave, further damaging the road surface. Moreover, an improperly constructed and poorly maintained cross-section can significantly impact the road's load-bearing capacity, surface condition, and overall durability. These circumstances necessitate thorough investigation and accurate decision-making to ensure the optimal design and construction of mine roads, with the goal of minimizing risks, reducing maintenance costs, and enhancing operational efficiency. By addressing these challenges and incorporating appropriate design solutions, the optimization of technological schemes for open mine road construction can ultimately contribute to the success and sustainability of mining operations.

At least more than 50% of the total operating costs in open-pit mines that rely on trucks are attributed to transportation costs [1]. This significant portion of expenses serves as a strong motivation for the development of methods aimed at optimizing the technological schemes for the construction of open-pit mine roads. By minimizing transportation costs through efficient road design and layout, mines can achieve substantial savings and improve overall operational profitability.

The incorporation of real-world case studies and computational modelling techniques in this study holds paramount importance within our overall methodology. Real-world case studies bring a practical dimension, illustrating the application of theoretical principles in concrete scenarios. They serve as crucial benchmarks, validating the effectiveness of optimization approaches in diverse contexts. Concurrently, computational modelling offers a quantitative lens, enabling a systematic evaluation of these approaches. By seamlessly integrating these elements, our methodology aspires to not only enrich the empirical foundation of the research but also provide a nuanced understanding of the intricate

dynamics shaping open-pit mine road construction optimization.

The research methodology will involve a review and synthesis of relevant literature to establish a comprehensive understanding of the current state of knowledge in open-pit mine road optimization.

Models variety. In order to effectively reduce transportation costs, numerous authors have focused on addressing the challenges associated with the construction of mining roads. Several approaches have been employed in the quest for optimization solutions for open-pit road construction. When formulating different types of models, two commonly used parameters are the minimum physical distance and transport energy consumption. The minimum physical distance parameter aims to optimize the spatial dimensions, specifically the distances between significant points within the open-pit mine. On the other hand, transport energy consumption takes into account subjective factors such as the skills of drivers and encompasses various elements.

Despite the increasing utilization of computer software products like AutoCAD Civil 3D [2], GEMS [3], and Maptek's Vulcan [4] in the field of transport road optimization, the development of additional analytical models remains highly relevant. These software tools have provided valuable support, but there is a growing need for further advancements in analytical modelling techniques to address the complexities and specific challenges encountered in open-pit road construction.

In their work, Liu and Chai [5] focus on optimizing open-pit roads with the goal of minimizing time-varying energy consumption during transportation. To simulate the characteristics and constraints of this complex system, they formulate a mixed-integer programming model that incorporates time-varying parameters. These parameters encompass various aspects, including resistance functions between neighbouring nodes, the amount of waste transported to the dumps along the route, traffic density, road capacity of the selected route, and more. The time-varying parameters primarily account for the process of road damage resulting from the frequent passage of heavy trucks on the road surface. To validate the applicability of their model, the authors utilize raw data obtained from the Zhahanaoer open-pit mine, ensuring that their findings are grounded in real-world scenarios.

Zlatanov [6] conducted an extensive examination of the significance of roads in open-pit mining operations. His work not only included his own analyses but also incorporated findings from studies conducted by other research teams. Zlatanov's focus was specifically on the condition of roads in large open-pit mines such as "Mini Maritsa Iztok", "Mini Bobov dol", "Asarel", among others. He identified several key problems related to technical, transport, and economic aspects of these roads.

One of the major difficulties highlighted by Zlatanov pertained to improperly installed and maintained drainage facilities, particularly culverts. Issues such as insufficient depth and unfavourable slopes in relation to the road axis were found

to have a significant impact on road conditions and overall functionality. These challenges underline the importance of proper design and maintenance practices for drainage infrastructure within open-pit mine roads.

In their research, Zhang et al. [7] investigate the optimal truck-shovel configuration for open-pit mine transportation systems. By analyzing experimental results, it was observed that the overall transportation volume and profit of the optimal truck-shovel configuration significantly increased compared to the original mine scheme. When not considering the output requirement of a single loading point, the transportation volume and profit increased by 7.84% and 7.73% respectively. However, when considering the ore output requirement of a single loading point, the increase was slightly lower at 3.75% for transportation volume and 3.85% for profit. The optimal schemes evenly allocated trucks among loading points, with shovels possessing the largest bucket capacity positioned closest to the unloading point. This allocation strategy effectively reduced queuing and maximized truck transportation capacity. Furthermore, the study demonstrates that arranging shovels with high-shovelling efficiency and trucks with strong-loading capacity at the nearest loading point further improves the total transportation volume. The paper also outlines the contributions of this research, which include the proposal of a mathematical model-guided simulation experiment for selecting the optimal truck-shovel configuration.

Thompson [8] summarized that over the past decade, augmented design and management guidelines have been formulated to meet the demands of mine operators for safer and more efficient haulage systems, as well as the requirements of truck manufacturers for a predictable and controlled operating environment. These developments have been informed by an analysis of surface haulage accident records, identifying key factors contributing to accidents. Geometric and functional design issues were found to be the primary substandard design factors, with inadequate structural design also playing a significant role. While improved mine haul road design can mitigate haulage accidents, it is important to consider the human factors that contribute to these incidents. Human factors encompass the interactive effects of geometric, structural, and functional design components. A well-designed road should accommodate human error, aiming to prevent accidents or minimize their severity. Knowledge of human error in the context of mine haulage enables the design of roads that can accommodate non-standard practices or actions that would otherwise escalate errors into accidents. By considering both design improvements and human factors, mine haul roads can be optimized for safer and more efficient operations.

As technological capabilities continue to advance and economic conditions constantly evolve, the optimization tasks associated with open-pit mine roads become increasingly complex. The inherent instability of the raw material market further compounds the challenges faced in optimizing haul roads. With a growing number of factors influencing the optimization process, such as changing

production requirements, environmental considerations, and cost fluctuations, the formulation and solution of this pressing problem in open-pit mining become even more intricate and demanding.

This necessitates a comprehensive and holistic approach that accounts for the interplay between various factors to arrive at effective and sustainable road optimization strategies. By addressing these complexities, researchers and practitioners in the field of open-pit mining can contribute to improved road design, enhanced operational efficiency, and reduced costs in transportation, ultimately promoting the success and longevity of mining operations.

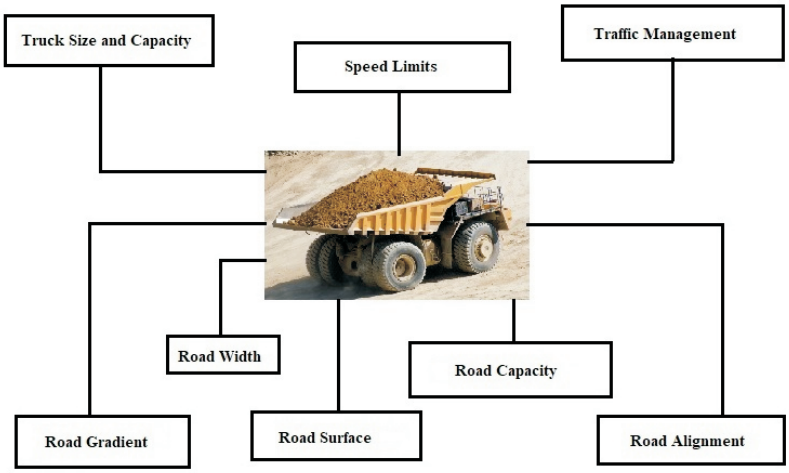


Fig. 1. The main parameters associated with haul roads and trucks in the context of mine operations

Figure 1 provides a comprehensive overview of the key parameters associated with haul roads and trucks in open-pit mines. The diagram illustrates the interplay between various factors that influence the design and operation of haul roads for efficient and safe truck transportation. The main parameters are road gradient, width, alignment, surface condition, and capacity, which collectively determine the road's functionality and ability to accommodate truck traffic. Additionally, Fig. 1 highlights the importance of truck size and capacity, as well as speed limits and traffic management measures, in ensuring smooth and controlled movement of trucks on the haul roads.

The key parameters depicted in Fig. 1 can be optimized through careful consideration and engineering practices. Road gradient can be optimized by minimizing steep slopes through suitable alignment and engineering solutions. Road width should be determined based on anticipated traffic volume and vehicle size, allowing for safe passing and maneuvering. Smooth road alignment with well-designed horizontal and vertical curves enhances safety and comfort for truck drivers. Op-

timal road surface materials and construction techniques ensure good traction, durability, and resistance to environmental conditions. Road capacity optimization involves analyzing traffic flow, structural design, and implementing measures to minimize congestion. Advanced engineering tools and collaboration among experts aid in analyzing scenarios, evaluating design options, and monitoring ongoing operations for continuous improvement. By optimizing these parameters, open mine roads can achieve enhanced safety, efficiency, and productivity.

Including specific case studies and examples is paramount for validating and refining open-pit mine road optimization models. These real-world instances serve as empirical evidence, validating the efficacy of optimization methods across diverse mining environments. Demonstrating cost reductions, increased operational efficiency, and improved safety through actual applications provides tangible proof of the models' effectiveness. Moreover, incorporating environmental considerations and integrating safety technologies directly into optimization frameworks ensures a comprehensive approach that aligns road design with economic, environmental, and safety objectives.

Problems and possible solutions. The optimization of technological schemes for the construction of open mine roads involves addressing various problems to improve the efficiency and effectiveness of road construction processes. Some of the key problems are summarized in Table 1.

The general guidelines for optimizing technological schemes for the construction of open mine roads may vary depending on the specific context and requirements of each project due to several factors. These factors include variations in geological conditions, terrain characteristics, available resources, local regulations and standards, environmental considerations, and project-specific goals and constraints.

Optimal solution and discussions. In order to incorporate the problems mentioned in Table 1 into a mathematical model for optimizing the technological schemes for the construction of open mine roads, it is essential to consider a multitude of parameters. These parameters encompass various aspects related to terrain constraints, road layout optimization, traffic flow, safety considerations, environmental impact, and cost optimization. Each problem requires the inclusion of specific parameters that capture the unique characteristics and requirements of the different projects. Factors such as surface drainage patterns, traffic variations, safety measures, environmental mitigation strategies, and cost analysis all play significant roles in the modelling process. By comprehensively incorporating these parameters into the mathematical model, a more accurate representation of the complex interplay between the problems and their respective solutions can be achieved, facilitating informed decision-making for the construction of optimal open mine roads.

The complexity of mathematical modelling in haul road optimization is determined by the fact that each parameter carries a different weight or significance in

T a b l e 1

Challenges and solutions in the optimization of technological schemes for construction of open mine roads

Problem	Description	Solution
Selection of optimal road layout	Determining the most suitable alignment, slope gradients, and curves for safe and efficient transportation routes for heavy vehicles.	Conduct comprehensive geological surveys and terrain analysis. Utilize computer-aided design software and simulation models to evaluate different road layout options. Consider factors such as terrain stability, haul distances, and operational requirements.
Efficient resource allocation	Optimizing the allocation of equipment, materials, and manpower to minimize costs, reduce construction time, and ensure timely completion.	Utilize project management techniques to schedule resources effectively. Implement lean construction principles to minimize waste and improve productivity. Consider outsourcing certain tasks and leveraging technology for efficient resource utilization.
Construction techniques and technologies	Implementing innovative methods to enhance construction efficiency, quality, and durability.	Utilize advanced construction techniques such as mechanized earthmoving, prefabrication, and modular construction. Explore the use of alternative materials and technologies for road construction. Adopt efficient compaction and paving methods.
Environmental considerations	Addressing concerns such as soil erosion, dust generation, and habitat disruption through erosion control and reclamation strategies.	Develop and implement erosion control measures, such as terracing, revegetation, and sediment control structures. Utilize dust suppression techniques and dust monitoring systems. Implement land reclamation plans to restore the environment after mining activities.
Safety and risk management	Prioritizing the safety of workers and implementing measures such as proper signage, road markings, and traffic management protocols.	Develop and enforce comprehensive safety protocols and procedures. Implement proper road signage, markings, and lighting. Provide training and awareness programmes for workers. Conduct regular safety audits and inspections.
Cost optimization	Balancing quality, durability, and cost considerations by minimizing expenses, optimizing material usage, and considering life-cycle costs.	Conduct cost-benefit analyses to evaluate different construction methods and materials. Implement value engineering principles to identify cost-saving opportunities. Optimize material usage and explore recycled or alternative materials. Consider long-term maintenance and life-cycle costs.

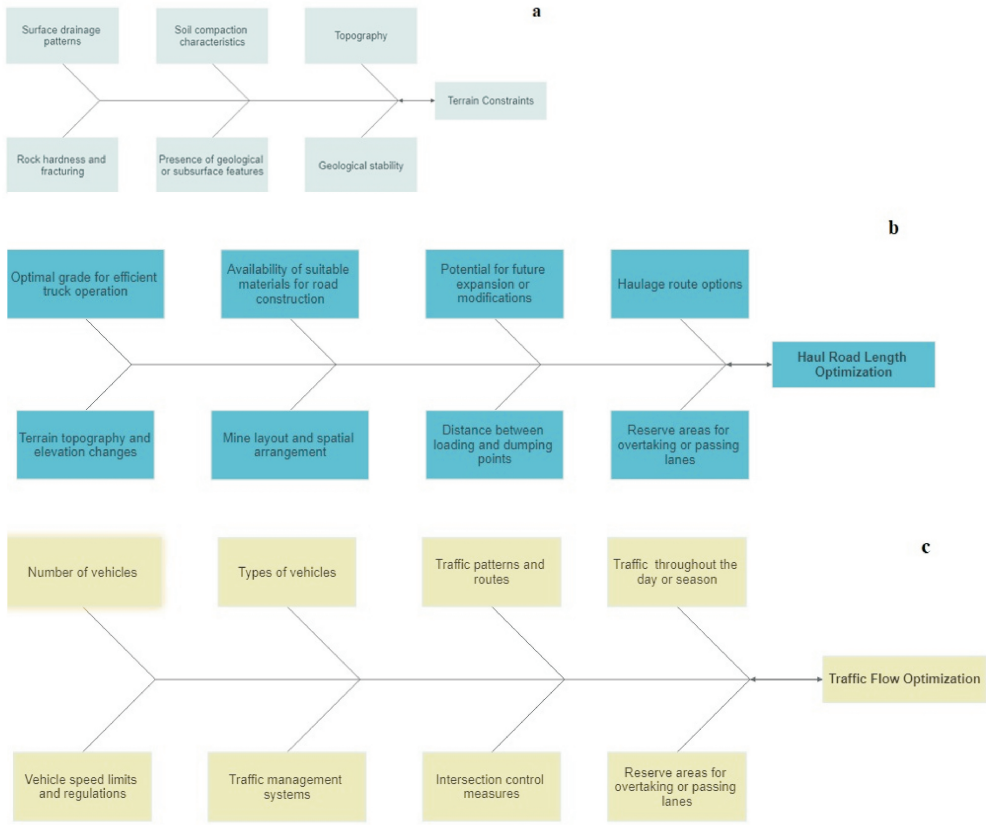


Fig. 2. Schematic view of key problems and parameters in haul road optimization: a – Terrain constraints; b – Haul road length optimization; c – Traffic flow optimization

the overall system. Each parameter represents a specific aspect of the road design, such as terrain constraints, haul road length, traffic flow, or other related factors. The weight of each parameter is influenced by its impact on the efficiency, safety, and cost-effectiveness of the haul road system. Balancing and integrating these parameters into a cohesive mathematical model requires careful consideration of their individual weights and interactions. The varying weights of parameters introduce complexity as their relative importance must be accurately captured to develop an effective optimization solution. Consequently, the modelling process needs to account for the unique characteristics and priorities of each parameter, ensuring that the final model reflects the real-world complexities and produces optimal results for haul road design and operation.

The intricate nature of haul road optimization arises from the diverse array of parameters, each carrying distinct weights that significantly influence the efficiency, safety, and cost-effectiveness of the system. Addressing the intricate interplay of parameter weights is crucial, as their dynamic influence shapes the

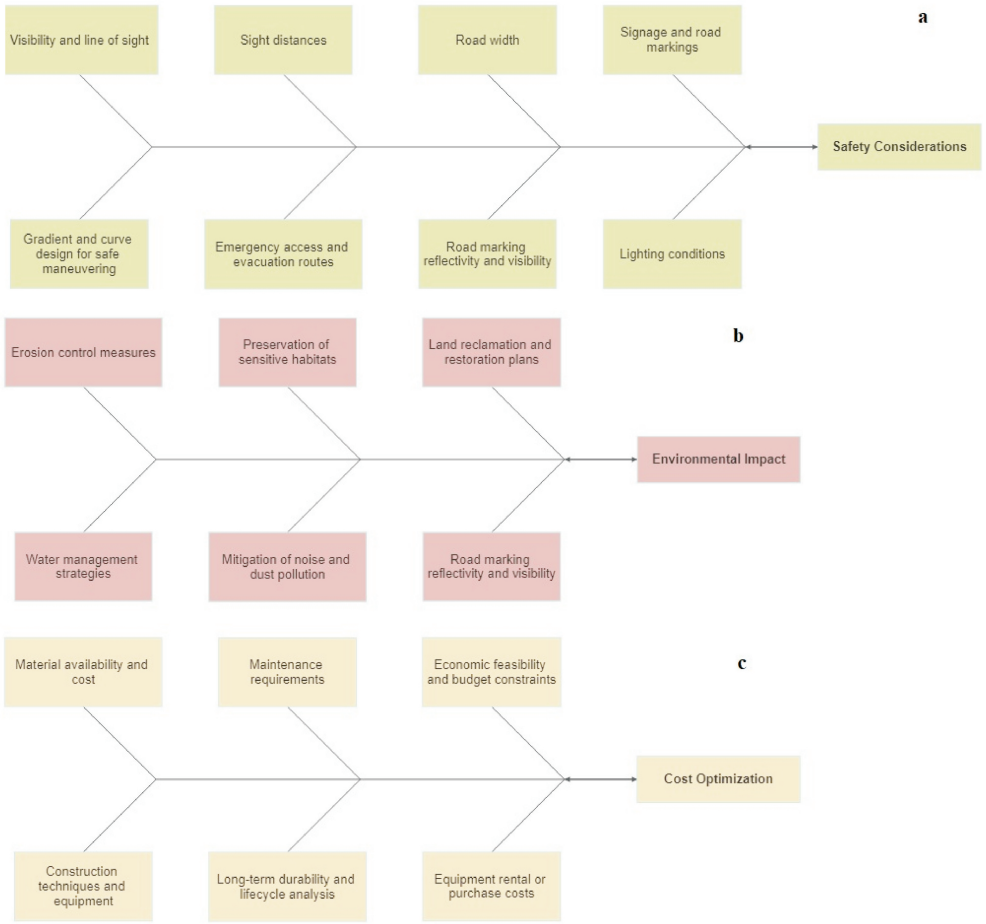


Fig. 3. Schematic view of key problems and parameters in haul road optimization: a – Safety considerations; b – Environmental impact; c – Cost optimization

optimization process, impacting the overall effectiveness and economic viability of open mine road construction.

Achieving optimal results in haul road design necessitates meticulous consideration of the distinctive characteristics and priorities of each parameter, emphasizing the critical requirement for a balanced and integrated approach in the development of a cohesive mathematical model. The intricate task of balancing and integrating parameters in the mathematical model underscores the importance of harmonizing their unique attributes and priorities to ensure a comprehensive and effective solution for open mine road construction.

Conclusions. This paper on the optimization of technological schemes for the construction of open mine roads serves as a comprehensive examination of various parameters and associated problems, providing valuable insights and rec-

ommendations for improving haul road design, efficiency, and overall operational performance. By synthesizing and analyzing the findings from multiple sources, a holistic overview of the parameters, problems, and optimization techniques discussed in the literature is presented. The examination of various papers allows for the identification of common trends, best practices, and innovative approaches utilized in different mining contexts. Various parameters are described and analyzed that play a crucial role in the optimization of haul road design and operation. Each parameter, including terrain constraints, haul road length optimization, traffic flow optimization, material selection, maintenance scheduling, and cost management, has been related to specific problems encountered in open-pit mining operations.

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