Mining Optimization Laboratory

Report Twelve –2023/2024

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Executive Summary

This year, we have prepared a report including 23 papers under five main topics, as; 1) Strategic Mine Planning and Mine Design, 2) Implementation of In-pit Crushing and Conveying (IPCC) in Open Pit Mining, 3) Environmental Impacts and Sustainable Mining, 4) Operational Mine Planning, and 5) Other Topics. We continue to update all the research results on the MOL webpage https://sites.ualberta.ca/MOL/ on the members section. Sponsors have access to current and past research results and publications. Let's review the contributions in the MOL Report Twelve (2023/2024) by considering some of the main contributors.

The first group of papers in this year addressed the development and implementation of different mathematical programming frameworks for pit limit optimization, pushback design and strategic mine planning. The following four students have been the main contributors under this topic:

Emmanuel has proposed a stochastic MILP framework to optimize the open stope mine production scheduling, considering grade uncertainty and stockpiling strategy in **Paper 101**. He introduced a Stochastic Mixed Integer Linear Programming (SMILP) model, an advanced version of a previous Mixed Integer Linear Program (MILP). He enhanced the model to include various mining operations, such as decline development, ventilation, operational and ore pass development, stope design and extraction, backfilling, and stockpile management, all aimed at maximizing net present value (NPV). Emmanuel conducted six detailed case studies to assess and compare the economic and operational impacts of the SMILP model. Among these, the SMILP model with stockpile management (Case 4) achieved the highest NPV, demonstrating its superior performance and practical applicability in real-world mining operations.

Soroush conducted a comprehensive comparative analysis of mathematical and industrial approaches to long-term production scheduling in sublevel caving (SLC) mining. In **Paper 102**, he utilized an MILP model alongside the GEMS/PCSLC software. The MILP model integrated various operational constraints, such as active level limits, continuous mining, capacities, precedencies, and grade blending, to accurately represent the SLC method. The primary goal was to maximize the NPV of the mining project. Soroush developed and verified the model in a Jupyter Notebook environment, solving it with the CPLEX Python API. He compared the MILP model's performance with the Production Control System for Sublevel Caving (PCSLC) software, applying different mining strategies to assess project income over the mine's life. His analysis demonstrated the mathematical model's efficiency in optimizing production scheduling and highlighted its potential to improve decision-making and enhance economic outcomes in SLC mining.

Samaneh has focused on strategic mine planning, a crucial area in mining that aims to tackle long-term challenges while maximizing value within operational and financial limits. There are two main approaches to modeling mining problems: deterministic and stochastic optimization. Deterministic models, the traditional approach, use fixed input parameters but often overlook the uncertainties present in geological, economic, and operational factors. In real-world scenarios, addressing these uncertainties is vital, making stochastic optimization a preferred method. Unlike deterministic models, stochastic optimization accounts for uncertainties by considering multiple scenarios or probabilistic distributions for the parameters. In **Paper 103**, her study explores and compares these two approaches, highlighting that while stochastic optimization offers better solutions and enhances the sustainability of mining operations under uncertainty, it also introduces greater computational complexity. In **Paper 104**, she has focused on optimizing the economic value of a mining project through open-pit mine planning. Her work involves two key operations: ultimate pit and push-back design. She developed a method that integrates a maximum flow network problem while considering the precedence relationships between blocks in a block model. Using GEOVIA SURPAC, she created a block model with 26,162 blocks, each defined by various characteristics like volume and gold grade. The data was then processed in Python to solve a Mixed-Integer Model for optimizing the ultimate pit and push-back design. For the push-back design, the model constrained the capacity of each push-back, assigning blocks accordingly. The block model was then used to generate pushbacks and implement a production schedule using Whittle software, with the Milawa Balanced algorithm providing a robust schedule. A comparative analysis showed that her proposed Mixed-Integer Programming approach achieved a higher NPV than the traditional Whittle implementation.

The second group of papers investigated the implementation of In-pit Crushing and Conveying (IPCC) systems in open pit mining. The following five students and researchers have been the main contributors under this topic:

Nasib explored the growing potential of IPCC system as an alternative to traditional truck-shovel methods in open-pit mines, motivated by rising fuel costs and environmental concerns. Recognizing that effective short-term planning in these mines must address operational and equipment uncertainties, he focuses on the under-researched area of integrating IPCC into short-term planning. To bridge this gap, in **Paper 201** he developed a simulation-optimization framework combining an MILP model and Monte Carlo simulation. The MILP model minimizes haulage costs while meeting long-term production goals, optimally allocating shovels to mining cuts to generate schedules. These schedules are then fed into the Monte Carlo simulation, which evaluates operational uncertainties and estimates key performance metrics, such as tonnes per gross operating hour (TPGOH), under scenarios with and without IPCC. Validated through a twelve-month case study in an iron ore mine, his model demonstrates the potential advantages of adopting semi-mobile IPCC systems over conventional truck-shovel operations.

Sandra reviewed state-of-the-art open pit mine planning methods involving IPCC systems, considering various time scales in **Paper 202**. She provided an overview of methods for both long and short-term mine planning through an extensive literature review, elaborating on the gaps and shortcomings in current research. Consequently, Sandra outlined a specific research agenda focused on long and short-term mine planning with IPCC. She proposed a research project aimed at addressing the identified research problems. She also discussed and evaluated the results and observations from the literature review, offering suggestions for further research along with a comprehensive summary of the findings.

Hongshuo's research demonstrated that conveyor operations had shown significant cost advantages over truck systems for long-distance transportation, which led to the adoption of the IPCC method as a superior alternative, especially at greater mining depths. Recently, the In-Pit Crushing and Stockpiling (IPCS) method, or near-face stockpile (NFS) mining, had emerged, separating the process into truck-to-stockpile and stockpile-to-crusher stages. This separation reduced the impact of mining rate fluctuations on milling and enhanced system resilience. Studies indicated that IPCS improved equipment utilization, stabilized the mining system, and increased production compared to traditional methods, though its specific advantages over IPCC in risk resistance had not been quantified. To address this gap, in **Paper 203** he developed an optimization model for IPCC using mixed integer linear programming and conducted a discrete event simulation with Arena to simulate operations and incorporate uncertainties. Comparative analysis with real mine data showed that IPCS increased equipment utilization, boosted annual output, and reduced truck utilization, highlighting its efficiency in managing operational uncertainties. In conclusion, he found that IPCS enhanced mining system efficiency and resilience compared to IPCC, particularly in managing uncertainty, warranting further research to refine and apply this framework across different mining environments.

Alireza integrated IPCC systems directly from the pit, reducing the need for extensive truck fleets and haulage infrastructure typically associated with Truck Shovel systems (TS). This approach minimized truck-related costs and environmental impacts while improving operational efficiency. In **Paper 204**, he optimized long-term scheduling in open-pit mining operations by comparing IPCC with traditional TS systems. He employed a two-step mathematical optimization model to determine the optimal locations for crushers or crusher panels and to establish a practical long-term extraction sequence. Through a comprehensive case study involving pushbacks with roads and conveyor ramps, and by analyzing different road and conveyor network configurations, he examined the capital and operational costs across four scenarios for the in-pit crusher: without a crusher, with an ore crusher, with a waste crusher, and with both ore and waste crushers. His results included comparisons of NPV, tonne-kilometers traveled, total kilometers traveled, and the number of trucks required. Significant improvements in NPV were observed in scenarios with both ore and waste crushers, reflecting reduced hauling distances and operational costs. The waste crusher scenario also demonstrated substantial savings, while the ore crusher scenario showed moderate improvements compared to the base case without a crusher.

Vahid examined the cost-effectiveness and production efficiency of IPCC systems in mature open-pit mines. By integrating crushing with conveyor systems within the pit, these systems replaced part of the traditional Truck-Shovel haulage cycle, leading to significant haulage cost savings and improved operational efficiency. In **Paper 205**, he employed a robust methodology, including statistical analysis, data wrangling, and the development of a full-scale Discrete Event Simulation model using Simpy, which was validated against actual operational data. The simulation assessed various scenarios—pure Truck-Shovel, IPCC, and Out-Pit Crushing and Conveying (OPCC)—to evaluate their impacts on operational costs, production rates, and overall efficiency, providing valuable insights into the practical transition to IPCC systems.

The third group of papers consider elements of sustainable mining, specifically with a focus on quantifying and minimizing the Greenhouse Gas (GHG) emissions within the framework of mine planning optimization in different time horizons. The following students have contributed under this topic:

Bahar designed and coordinated mineral extraction systematically through mine planning, integrating exploration, production, and engineering considerations. Faced with growing pressure to incorporate environmental responsibility, her study addressed the precedence-constrained production scheduling problem (PCPSP) within green long-term mining planning. To optimize extraction processes while limiting carbon emissions, in **Paper 301** she introduced an adaptive large neighborhood search (ALNS) algorithm specifically tailored for long-term mine planning. This study involved parameter tuning for the ALNS algorithm, comparisons with an exact solver, and analysis of destroy-repair operators to identify key elements. The developed ALNS, evaluated through various benchmarks, showed optimality gaps of about 0.08, demonstrating the approach's effectiveness in enhancing mining operations while considering environmental impacts.

Cristina conducted a systematic review in **Paper 302**, addressing the critical challenge faced by the mining industry in reducing GHG emissions from mobile equipment. Her review examined recent technological advancements and techniques applied to mining mobile equipment aimed at mitigating GHG emissions. Through a thorough analysis of objectives, methodologies, results, production impacts, gaps, and limitations in various studies, she identified effective strategies for GHG reduction. The urgency of meeting the industry's commitments under the Paris Agreement for net-zero emissions by 2050 highlighted the significance of these advancements. Additionally, her review explored potential modifications and challenges in implementing these technologies to foster sustainable mining practices. Her study contributed valuable insights to the ongoing efforts of aligning mining operations with global climate goals, underlining the crucial role of mobile equipment in achieving a sustainable, low-carbon future for the mining sector.

Mohammad addressed the growing environmental impact of the mining industry amid rising global demand for mineral resources. He focused on the need for sustainable mining practices by integrating environmental considerations into planning and operations. In **Paper 303** he proposed an integrated framework, termed LCA-MILP, which combined life cycle assessment (LCA) data with an MILP model to optimize mine planning processes. The framework aimed to reduce GHG and dust emissions while evaluating various economic scenarios. He validated the framework through a case study on an open-pit iron ore mine, demonstrating that GHG emissions could be reduced while achieving nearly the same original NPV. His findings underscored the importance of aligning environmental impact reduction with long-term mine planning to promote a more sustainable and socially responsible mining industry. In **Paper 304**, he presented an innovative framework for long-term open-pit mine planning that integrated economic and environmental considerations. By incorporating carbon pricing into the decision-making process, the framework addressed financial risks and explored two scenarios: one focused on minimizing environmental costs and the other on maximizing adjusted NPV. Applied to an open-pit iron ore mine, the framework evaluated its impact on block sequencing, greenhouse gas emissions, and financial outcomes. Sensitivity analyses showed the framework's adaptability to different carbon pricing scenarios. In **Paper 305**, he introduced a transformative multi-objective optimization (MOO) framework aimed at balancing economic and environmental aspects of open-pit mining, particularly focusing on GHG emissions. The same case study validated the framework's effectiveness. The results revealed that significant GHG emission reductions could be achieved with minimal impact on economic returns. Through detailed scenario analysis, he illustrated the trade-offs and synergies between maximizing NPV and minimizing ecological costs, emphasizing the need for integrating environmental considerations into mine planning to ensure a sustainable and economically viable mining industry. His research provided a sustainable approach to mine planning, balancing economic returns with ecological responsibility, and offered valuable insights for decision-makers in the mining industry.

Amir Abbas presented an integrated stochastic discrete-continuous simulation-based optimization framework in **Paper 306**, designed to address GHG mitigation in operational decision-making for open-pit mines. This framework aimed to minimize transportation costs while simultaneously reducing carbon dioxide emissions. A case study on a copper mine was conducted to determine the optimal size of the transportation fleet, balancing cost reduction with minimizing CO2-equivalent emissions. He also introduced a novel truck allocation method that improved cost efficiency, emission reduction, and performance indicators like tonnage hauled and cycle time. Sensitivity analysis was performed to evaluate the impact of various parameters on the objectives and performance, offering valuable insights for advancing GHG mitigation and sustainable mining practices.

Milad introduced a novel MILP model for short-term open-pit mine planning in **Paper 307**, which integrated GHG emissions, with economic objectives. The model addressed complex operational challenges such as block sequencing, multiple transport destinations, and stockpile management. It also evaluated the potential of IPCC systems as an innovative transport method to reduce haulage-related emissions, which account for over 35% of GHG emissions in open-pit mining. Applied to a case study at an iron ore mine, the model highlighted significant reductions in GHG emissions, haulage costs, and carbon tax liabilities, demonstrating that fixed IPCC systems offer substantial benefits and making a strong case for their broader adoption in the industry.

The fourth group of works this year investigated some aspects of operational mine planning, such as fleet allocation and dispatch optimization using simulation and Artificial Intelligence techniques. The following students have contributed under this group:

Khaleeq examined the substantial impact of material handling and transportation costs, which could constitute up to 50% of operating expenses in open-pit mining operations. The challenge of efficiently transporting extracted material to various destinations such as processing plants, dumps, or stockpiles highlighted the importance of optimizing truck dispatching and shovel allocation. Simulation-based optimization and mixed integer programming models had been used to improve dispatching efficiency. Despite the success of Reinforcement Learning (RL) in various industrial processes over the past decade, deep Reinforcement Learning (DRL) had been relatively underutilized in mining. In **Paper 401**, he investigated the potential of DRL-based approaches for enhancing fleet management in mining operations, aiming to better understand current applications and future possibilities, as well as identifying any potential field constraints.

Yaa investigated the role of Discrete Event Simulation (DES) in optimizing mining operations and enhancing production. The review in **Paper 402** highlighted how DES addressed the complexities and variability inherent in mining systems, emphasizing its importance in improving operational efficiency, reducing costs, and supporting informed decision-making. Specific applications of DES in equipment usage were examined, demonstrating its capability to simulate mining processes, identify bottlenecks, evaluate alternate scenarios without disrupting real-world operations, and optimize resource allocation. Key benefits included the ability to forecast the impacts of operational and strategic changes, as well as predict environmental factors such as energy prices and resource depletion. The integration of DES with optimization methods, like mixed integer programming, was noted for creating comprehensive decision support systems that merge strategic, operational, and environmental considerations. Despite its advantages, challenges such as modeling complexity, data collection issues, and integration with existing management systems remained. This review aimed to provide a deeper understanding of DES's potential to improve mining operations and productivity. In **Paper 403**, she presented a structured guideline for designing, implementing, and validating a simulation model for optimizing mining operations using HaulSim. The study began by defining the conceptual framework, system boundaries, and key performance criteria, followed by thorough data collection and preprocessing to ensure reliable input parameters. HaulSim was employed to simulate various aspects of mining operations, including resource allocation, equipment utilization, and process flow. The research demonstrated HaulSim's effectiveness in predicting and enhancing mining operations, offering valuable insights for strategic planning and decision-making.

Ehsan developed a hybrid Discrete Event Simulation-Genetic Algorithm (DES-GA) approach to create an AI-driven Decision Support System (DSS) for optimal fleet assignment in open-pit mining operations. As presented in **Paper 404**, this approach utilized Graph Neural Networks (GNNs) to improve resource assignment decisions, addressing complexities such as fleet diversity, multiple dig and dump points, and process uncertainties. The DES-GA model generated a dataset for GNN training, incorporating key features like road networks, fleet availability, and shovel-to-dig point and truck-to-shovel allocations. The study demonstrated that this method significantly enhanced real-time dispatching, reduced costs, and minimized environmental impacts in mining operations.

Finally, the last group of works this year includes the following three papers about floating plant, blast analysis and rock excavation process.

In **Paper 501**, ***Khaleeq*** explored the application of machine learning models in mining processes, focusing on predicting output quality in flotation plants. He utilized the Extreme Gradient Boost Regressor (XGBR) and Long Short-Term Memory (LSTM) networks to predict the concentration purities of iron and waste silica. To achieve this, data from 23 variables reflecting a flotation plant were monitored every two minutes over six months, processed, and restructured for model use. The results demonstrated that while both XGBR and LSTM were effective, XGBR outperformed LSTM in predicting iron and silica concentrations. This research laid the groundwork for automating flotation plant control and highlighted the potential of both traditional and deep learning models in mineral processing engineering.

Magreth conducted a study on rock blasting, as reported in **Paper 502**, examining how the intact rock properties and the presence of structures influenced the intensity and distribution of fractures in the rock mass. Through field blasts and numerical simulations using the Riedel–Hiermaier–Thoma (RHT) material model in LS-DYNA, she found that structures did not necessarily stop the fracturing of the rock mass. Depending on their geometry and mechanical properties, the extent of damage could either develop or be halted by these structures. She also discovered that the material properties and location of the structures relative to the blasthole, free face, and pit wall significantly affected the size and distribution of fractures on the bench and the formation of the pit wall. When comparing the results to field measurements, she observed a general consistency in stress wave pressure, peak particle velocity attenuations, fracture distribution, and pit wall formation.

Pedro demonstrated how the production rate in mining operations was significantly influenced by the physical properties of the rock, such as density, compressive strength, and abrasiveness. These properties directly impacted the extent of fracturing and extraction, which in turn affected the overall production rate. To highlight the importance of measuring these rock features, he used neural network models in **Paper 503** to estimate two key properties: density and point load strength. He collected experimental data from rock samples with varying compositions, dividing them into training and testing sets. After data preparation, he built and trained neural network models with several dense layers and non-linear functions, incorporating techniques to prevent overfitting. The models performed well in predicting density and point load strength, achieving low error rates on the test sets. By integrating these predictions into production rate models, he quantified how factors like density and strength influenced excavation productivity, allowing for optimization by relating controllable parameters to the target production rate while considering site-specific rock characteristics. His study demonstrated how machine learning techniques, such as neural networks, could improve predictive models used in rock excavation operations.

We extend our gratitude to all the contributors who played a crucial role in preparing the 2024 MOL Report. This includes the dedicated faculty members from four universities, the graduate students, postdoctoral fellows, and alumni from nine universities, and two industrial/consultant affiliates. Special thanks to Dr. ***Hongshuo Gong*** for his review of the submitted papers and to ***Liane Tse Tse*** for her tireless efforts as the administrative assistant in proofreading and editorial revisions, ensuring the highest quality of this report. Your collective contributions have been invaluable.

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Mining Optimization Laboratory (MOL) Researchers / Graduate Students

Following are researchers and students affiliated with Mining Optimization Laboratory in September 2024.

1.	**Hooman Askari-Nasab**	Professor - Director of MOL
2.	**Eugene Ben-Awuah**	Professor, Laurentian University
3.	**Yashar Pourrahimian**	Associate Professor, University of Alberta
4.	**Ali Moradi Afrapoli**	Assistant Professor, University of Kentucky

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5.	**M. Mahdi Badiozamani**	PhD, Research Assistant - 2018/03
6.	**Shahrokh Paravarzar**	PhD, Post Doctoral Fellow - 2022/10
7.	**Hongshuo Gong**	PhD, Post Doctoral Fellow - 2024/01
8.	**Magreth Dotto**	PhD Student – 2018/01
9.	**Emmanuel Appianing**	PhD Student – 2018/05
10.	**Nasib Al-Habib**	PhD Student – 2018/09
11.	**Alireza Kamrani**	PhD Student – 2018/09
12.	**Soroush Khazaei**	PhD Student – 2019/09
13.	**Pedro P. Vasquez Coronado**	PhD Student – 2019/09
14.	**Mojtaba Yeganejou**	PhD Student – 2020/05
15.	**Sandra Fahl**	PhD Student – 2022/09
16.	**Samaneh Moradi Pirbalouti**	PhD Student – 2022/09
17.	**Khaleeq Ahmed**	PhD Student – 2023/01
18.	**Mohammad Al-Masri**	PhD Student – 2024/09
19.	**Milad Rahnema**	MSc Student – 2022/05
20.	**Bahar Amirmoeini**	MSc Student – 2022/09
21.	**Yaa Karikari**	MSc Student – 2023/01
22.	**Joshua Azorliade**	MSc Student – 2023/09

23.	**Eyram Agozie**	MSc Student – 2023/09
24.	**Kwaku Konadu Akuffo**	MSc Student – 2023/09
25.	**Emmanuel Donea**	MSc Student – 2023/09
26.	**Cristina Miranda Bermudez**	MSc Student – 2024/01
27.	**Obed Appiah**	MEng Student – 2023/09