MONDAY, JUNE 26, 2023

Autonomy and Electrification

Dakota Ballroom  ABCE
Chair: Dr. Winfred Assubey-Bonsu

1:00 pm
Open-Pit Load & Haul Simulator: Exploring the Effects of Haul Truck Electrification on Mining Productivity
K. Everly, J. Pohl, C. Utter, A. Chowdu; Komatsu, Tucson, Arizona, US

Battery Electric Vehicles offer increased energy efficiency for open-pit load & haul operations at a potentially lower overall carbon cost. Electrifying a mine’s fleet, however, presents a unique set of operational challenges. In this study, we explore the effects of electrification on productivity at real operations using a Discrete Event Simulator. The model can simulate multiple shifts, a mixed fleet of diesel and electric trucks, charging and refueling stations, trolley systems, and accurate shovel-truck loading cycles. This study helps determine the trade-offs of adopting electric fleets and how they interact with the layout of today’s mines.

1:20 pm
Mixed Traffic Autonomy and Functional Safety - A Contradiction?
G. Biro and C. Mueller; MobileTronics GmbH, Ladeberg, North Rhine-Westphalia, Germany

A number autonomous operations is in place in several, mainly in fenced areas, where safety is assured by locking off the entire area for other traffic. However autonomy can be brought much further if functional safety is assured and a real mixed traffic of autonomous and manually operated vehicles is possible. MobileTronics has created a modular software and control framework for autonomous machines. The paper covers application examples in which the deterministic object recognition in combination with probabilistic algorithms and sensors is used as a basis for functional safe certification of mixed traffic autonomy.

1:40 pm
Autonomous Mining – From Current Implementations to the Zero Entry Mine
D. Larsen, ASI Mining on behalf of H. Ednie; Global Mining Guidelines Group - GMG

This presentation will discuss: a pathway for the industry, from the necessities for surface, underground and deep mining, through safety and productivity, to what we want the future of mining to be; how zero entry mining can enable us to achieve a zero emissions footprint, combining autonomous technologies, next generation mine design opportunities, and leveraging future fuels and Battery Electric Vehicles (BEVs); and the strategic requirements for getting to the Triple Zero Mine such as rethinking how we mine, taking a system safety approach, the skills shift and future needs, and more.

2:00 pm
Electric Vehicle Fleet Optimization Software (EV-FOS) for Planning and Optimizing BEV Fleets in Any Mining Environment
A. Rafi, T. Davies, R. Rennie; MEDATech Engineering Services Ltd., Collingwood, ON, Canada

In 2017, MEDATech began developing Electric Vehicle Fleet Optimization Software (EV-FOS) in collaboration with McMaster University’s Bauman Lab for Electrified Powertrain Research. Based on in depth knowledge of electric and diesel vehicle performance characteristics and many years of experience in designing vehicles for underground mining and other heavy equipment applications, EV-FOS optimizes battery-electric vehicles (BEV) to the duty cycle and the energy usage for new and existing mines. It’s useful for mine development and production, clearly showing the effectiveness of BEVs compared to diesel vehicles in all mines, as well as optimal BEV type, battery size and charging infrastructure.

2:20 pm
Electric Transport in Underground Operations - Technology and Operational Experience
G. Tabak and C. Mueller; MobileTronics GmbH, Ladeberg, North Rhine-Westphalia, Germany

Basing on five years of experience, this paper discusses modern e-drive systems used in underground transport. This covers Energy distribution and cabling principles, inverters and motors as well as auxiliary aggregates. Also an overview of different regimes for battery charging and the energy management and the method of control of the traction are lined out: This means that throttle and brake are not handled separately, but integrated into "lateral control" algorithms which assure that a commanded speed is maintained while synchronizing the multi motor systems and taking into account the constraints imposed by e.g. slope grade and battery parameters.
1:00 pm
**Using Precedence Constraints to Model the Geometry of Optimal Mining Envelopes**

N. Morales Varela; Polytechnique Montreal, Quebec, Canada, G. Nelis; Universidad Técnica Federico Santa María, Santiago, Chile, F. Saavedra; Universidad de Atacama, Copiapó, Chile, J. Amaya; CMM, Universidad de Chile, Santiago, Chile, R. Gómez; Universidad de Concepción, Concepción, Chile

Precedence constraints are broadly used in mathematical models and algorithms for mine planning to model, for example, slope angles in open pit operations or connectivity in underground mines. Unfortunately, these constraints do not capture relevant geometrical aspects for the design of the mine like minimum bottom space of pits or smoothness of the economic envelope. In this work, we present different approaches that utilize precedence constraints generating economic envelops that are more suitable for design purposes. The numerical experiences show that the proposed techniques produce high value envelops with better geometrical properties and that the methods that can be computed efficiently.

1:20 pm
**Mineral Resource and Mineral Reserve Reporting for AngloGold Ashanti Under S-K 1300**

M. Godoy, T. Flitton, and A. Eliot; AngloGold Ashanti, Johannesburg, South Africa

AngloGold Ashanti (AGA) is listed on multiple stock exchanges and is required to adhere to South Africa’s SAMREC code and the SEC Regulation S-K 1300 when reporting Resources and Reserves. To streamline efforts and minimize workload, AGA aligned SAMREC with S-K 1300 requirements. This allowed for the storage of all pertinent property information into a single data repository. Reporting from the data repository was then done according to the applicable code and regulatory body. This study presents and overview of AGA’s reporting processes and level of detail involved, while exploring the key differences between SAMREC and S-K 1300.

1:40 pm
**Evaluation of Heterogeneous Real Estate Portfolios in Portfolio Theory and the Potential for the Valuation of Diversified Mining Portfolios**

K. Boede; HOCHTIEF Poland, Warszawa, Poland, A. Bendiek; HOCHTIEF PPP Solutions GmbH, Essen, North Rhine-Westphalia, Germany, J. Grunow; Engel & Völkers Investment Consulting GmbH, Frankfurt, Frankfurt, Hesse, Germany

According to the Markowitz portfolio theory the value of a diversified portfolio is higher than the sum of the parts of a portfolio, which is an important consideration for the correct valuation. This is valid for real estate portfolios as well as for mining assets (or enterprises). This paper analyses the application of the portfolio theory to a diversified portfolio of assets in the real estate industry and draws conclusions on further research work to be done in the minerals industry.

The volume of real estate transactions is increasing over recent years. As such, the nature of those transactions is constantly changing and in some cases portfolios become more heterogeneous as they are composed of different property categories, e.g. locations and types of use. This makes their economic evaluation more difficult. This paper focuses on the acquisition of a fairly heterogeneous real estate property portfolio purchased by “Commerz Real” in Germany in Q4 2019. For economic evaluation the widely used Markowitz portfolio theory (Markowitz, 1952) was applied. It was investigated whether diversification effects could achieve added value in the form of a reduction in risk compared to the sum of their individual components. As a result the findings of this research could be applied to other heterogeneous real estate transactions and even to mine property portfolio or PPP1 project portfolio transactions.

2:00 pm
**A Comparative Study of the Application of Machine Learning Techniques to Analysis and Prediction of the Market Prices for Precious Group Metals**

M. Madahana and J. Ekoru; University of the Witwatersrand, Johannesburg, Gauteng, South Africa

For efficient management of operations, mining companies are required to be able to predict potential scenarios for main market factors. There is a need for accurate analysis of data and prediction of future market trends for Precious Group Metals (PGM). This research work applies machine learning methods to identify, analyze and predict patterns and trends for PGMs. Artificial Neural Networks, Linear Regression, and Hidden Markov models are applied to a dataset consisting of 15 years of daily prices for PGMs. Accurate Prediction of Market prices for PGMs will result in unlocking untapped sources of value in the mining industry.
2:20 pm

An Ad Hoc Solution to the Transition Mine Problem

W. Medina and G. Angulo; Pontificia Universidad Católica de Chile, Rancagua, Libertador General Bernardo O’Higgins, Chile; A. Anani; The University of Arizona, Tucson, Arizona, US,

A current challenge faced by the mining industry is solving the integrated transition mine problem (TMP) that maximizes the net present value (NPV). This study aims to develop an optimization framework capable of solving the TMP. The problem is NP-hard and therefore computationally intractable. Three ad hoc approaches – Exact solution, Benders’ decomposition, and Benders’ decomposition with Bienstock-Zuckerberg (BZ) algorithm – are compared for different scheduling periods. The TMP is formulated as a mixed integer linear programming model, implemented in Python, and solved with the Gurobi optimizer. The results showed that Benders’ decomposition with the BZ algorithm outperforms the other approaches in execution time, computational cost, and feasibility to address large problems in exchange for a marginal cost in the quality of the NPV obtained. In addition, the probability of finding the optimal point of transition is higher regardless of the number of feasible crown pillar locations evaluated. This is achieved through the optimality cuts proposed in the algorithm.

Mine Safety

Dakota Ballroom ABCD

Chair: Dr. Vaibhav Raj

3:00 pm

Camera-Aided Technology for Underground Mine Safety (CAT-UMS)

C. Olmos de Aguilera, N. Risso, A. Anani; University of Arizona, Tucson, Arizona, United States

The traditional approach to safety clearance monitoring and proper PPE usage in underground mines is time-consuming, costly, and susceptible to negligence. However, automated real-time monitoring can be implemented using computer vision-based approaches. This study aims to develop a system that provides timely information based on the automatic detection of proper PPE use and safety clearance in underground mines. Deep learning and a decentralized computing structure between the cloud and sensing devices (fog technology) are used. We hypothesize that a camera-based system can provide near real-time assessment of proper PPE use and verified clearance to access restricted areas in underground mines.

3:20 pm

Natural Language Processing for Classification of Narratives from MSHA Data

M. Shahsavar, J. Gomez, J. Sattarvand; University of Nevada Reno, Reno, Nevada, United States

Mining can be categorized as a hazardous activity, considering some factors such as environmental conditions with a considerable presence of humidity, suspended particles, or falling rocks have affected the severity and number of accidents compared with other economic sectors. The industry analyzes incident reports to narrow the rate of severe injuries and fatalities, conducting root cause analysis and identifying leading indicators. As the International Council on Mining and Metals noted, the vast trove of incident data is not analyzed as much as possible due to a lack of analytics expertise at mine sites. However, machine learning could solve the problem of analyzing all the incident data in a no-time-consuming way, considering the abundant data, and without using expert personnel in data science. Thus, a Convolutional Neural Network and a Naïve Bayes model were introduced to perform classification in the MSHA database. The database from 2020 consists of 60 fields to describe safety incidents; these fields include mine I.D., accident date, subunit (mill, surface), material extracted, and other metadata.

3:40 pm

Usability of Collaborative “VR Mine Rescue Training” Platform


National Institute for Occupational Safety and Health (NIOSH) in partnership with the Mine Safety and Health Administration (MSHA) developed VR Mine Rescue Training. It is a training platform that allows mine rescue team members to explore virtual emergency scenarios collaboratively. Team members use a head-mounted display to visualize and interact with equipment, hazards, and dynamic ventilation. All player actions are recorded and displayed in a debrief. Researchers at NIOSH demonstrated the training at various mine rescue competitions including the International Mine Rescue Competition and collected feedback. Participants were overwhelmingly positive. This paper describes the development of the software and the results of the usability surveys and interviews.
4:00 pm
Developing a Smart Evacuation System for Underground Mines Considering Human Factors
P. Augustine and J. Sattarvand; University Nevada Reno, Reno, Nevada, United States
Despite significant safety improvements, the mining industry remains one of the most hazardous occupations globally and the evacuation of Miners, when an uncontrollable incident occurs in the mine, is the best bet to saving lives. However, Human factors/behaviors during an emergency are likely to influence the evacuation performance. Other industries have made a significant effort to determine these human factors that can impede evacuation performance, however, the current state-of-the-art in mine evacuation or self-rescue is that the evacuation route is predetermined, and a static sign is used to direct miners to the predetermined safe location. This method is limited in representing actual conditions that arise in a real emergency, neglecting the different behaviors displayed by humans. As optimization of the evacuation of a mine plays a fundamental role in emergencies and modeling evacuation behavior and movement of miners is a complex task, this research utilized Agent-Based simulations to simulate the evacuation behavior and performance. It was observed that people with the smart evacuation device made fewer mistakes and arrived at the safe place in less time compared to those have no access to the device. The Mathematical model used in optimizing the shortest path to a safe place is also explained in this paper.

4:20 pm
Application of Mixed-Integer Programming for Mine Evacuation Modeling With Vehicle
F. Kwaku Asare and J. Sattarvand; University Nevada Reno, Reno, Nevada, United States
The safe evacuation of miners during an emergency in the shortest amount of time is one of the most essential features of a mining operation. Despite advancements in mine evacuation research, the usage of mine vehicles during evacuation has not been considered. The majority of recent studies have been done on miners’ evacuation on foot. Mathematical formulations including Minimum Cost Network Flow (MCNF) models, Dijkstra’s algorithm, Floyd-Warshall algorithm, and Ant Colony Optimization models have been used to solve mine evacuation problems. These models, which concentrate on determining the shortest escape routes during the evacuation, have been found to be computationally expensive and may not offer the best solutions in some cases.
The goal of this paper is to incorporate light vehicles in the evacuation process using a mixed-integer programming approach. The methodology aims to minimize the total time required to evacuate the mine, ensuring minimal exposure of the miners to the adverse conditions that triggered the evacuation.

3:00 pm
Orebody and Mine Planning Assessment Based on Alternative Recoverable Resource Model Techniques and Options
A case study based on two recoverable resource modelling techniques (indirect and direct or localised methods) have been derived using typical feasibility study or new mine drilling data configurations from the extensions of an existing mine’s massive production database. The database is from the Gold Fields Tarkwa Gold mine (~6Moz Mineral Reserves and 13-year Life-of mine). The corresponding recoverable resources from the various techniques are then analysed using the open pit Whittle optimisation process. The results were then compared based on the Whittle optimisation results to determine the efficiencies of the approaches and the validity of the recoverable mineral resource estimates for mine planning and financial forecasts (including Cash Flows etc). Based on historical production metal recovery, the paper also assesses the corresponding orebody and mine planning as well as financial risks with regards to the modelling techniques. The study shows that the localised direct and somewhat more straight forward approach if applied efficiently can provide an equally useful tool for computing recoverable resources for mine planning and financial forecasts, as compared to the indirect approach as presently in use.
**3:20 pm**

**Machine Learning Driven Domain Modeling for Stratigraphic Deposits**

R. Mentzingen Rolo and G. Moreira; Geovariances, Belo Horizonte, Minas Gerais, Brazil, O. Guimarães; Alcoa, Juruti, Pará, Brazil, C. Fonseca; Alcoa, Juruti, Pará, Brazil, G. Usero; Geovariances, Belo Horizonte, Minas Gerais, Brazil

Geological domain modeling is an important step in mineral resources evaluation. The procedure can be laborious and time-consuming, especially in multivariate settings. However, estimates are significantly improved when carefully limited by geological variables. This paper proposes a workflow for geological domain modeling suited for stratigraphic deposits. The workflow consists in automatically defining the domains by using clustering algorithms, generating the surfaces that represent the contacts by interpolation and subsequent triangulation, and simulating the surfaces. The proposed workflow produces consistent and realistic results and allows the user to test different domain configurations and assess volumetric uncertainty automatically and quickly.

**3:40 pm**

**Integrating Machine Learning and Geostatistics for Grade Control Models**

G. Moreira, R. Rolo, A. Endlein; Geovariances, Belo Horizonte, Minas Gerais, Brazil, V. Silva, L. Pereira, A. Lopes, M. Feitosa, and H. Silva; Vale S.A., Itabira, Minas Gerais, Brazil, G. Usero and J. Lague; Geovariances, Belo Horizonte, Minas Gerais, Brazil

Grade control models are supposed to provide a higher resolution than long-term or interim models. However, available grids from diamond or reverse circulation drilling do not provide that required resolution. In this study, a geostatistical workflow is proposed to integrate available grade data from production blastholes with its operational parameters taken when drilling downhole. The step of geological logging is replaced by machine learning models for classifying blastholes into lithologies and hardness classes. Next, indicator and ordinary kriging use the classified blastholes and previous data for estimating the model domains and the grades within each one. The workflow is applied in a world class iron ore mine in Brazil.

**4:00 pm**

**Use of Non-Linear Estimates and Local Anisotropy in Mineral Resource Modeling**

S. Misk; Geovariances, NOVA LIMA, Minas Gerais, Brazil, J. Felipe Costa; UFRGS, Porto Alegre, Rio Grande do Sul, Brazil, C. Araújo and R. Rolo; Geovariances, Belo Horizonte, Minas Gerais, Brazil, M. Sabori; Cobre del Mayo, Nova Lima, Sonora, Mexico

Linear estimation methods are widely used for resource evaluation. among the existing linear estimation methods, ordinary Kriging (OK) was accepted as the best estimator to determine the average ore grade of each block. However, OK is inadequate for modeling small blocks in relation to data spacing, resulting in over-smoothed models. In this study, the results of the recoverable resource from the short-term model are compared to estimated models generated by the traditional method, i.e., OK, and non-linear methods. The conclusion is that non-linear methods improve the accuracy and precision of the long-term model when compared to the model generated by OK.

**TUESDAY, JUNE 27, 2023**

Sponsored by Freeport-McMorRan

**Mineral Processing and Extraction**

Dakota Ballroom ABCD

Chair: Dr. Akshay Chowdu

**8:00 am**

**Schedule Optimization Considering Ore Blending and Nonlinear Geometallurgical Variables**

P. Henrique Alves Campos, J. Felipe Costa, V. Koppe, and M. Bassani; Universidade Federal do Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil, C. Deutsch; University of Alberta, Edmonton, Alberta, Canada

Blending inevitably occurs to some degree during mining and mineral processing operations. Traditional mine scheduling assumes that all variables average linearly, which allows the calculation of the blended material properties as a linear weighted average. However, metallurgical properties such as metal recovery and Bond Work Index (BWI) are known to average nonlinearly. The nonlinear properties of the blended material can be calculated using nonlinear blending models. A simulated annealing algorithm is developed and applied to a short-term mining face optimization problem to maximize the total metal recovered considering nonlinear blending. Compared to a standard schedule plan, the optimized one shows relevant improvements in synergistic and antagonistic blending behaviors.
**8:20 am**

**Stochastic Optimization for Long-term Planning of a Mining Complex with In-pit Crushing and Conveyance Systems**  
L. Finday and R. Dimitrakopoulos; McGill University, Montreal, Quebec, Canada

Optimizing a production schedule with semi-mobile in-pit crushing & conveyance (IPCC) requires integrating extraction sequence, destination policy, crusher relocation, conveyor layout, and truck fleet investment decisions. An integrated stochastic optimization framework is proposed to produce long-term schedules for mining complexes using multiple semi-mobile IPCC systems. The optimizer selects the crusher locations and designs the conveyor routes from anywhere in the mines. The stochastic framework considers simulated multi-element orebody realizations and manages associated risk. A hybrid metaheuristic based on simulated annealing and evolutionary algorithm is implemented for the optimization. The method is demonstrated using an iron ore mining complex.

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**8:40 am**

**Ore Control Data Driven Method for Estimating the Bulk Ore Sorting Value at Base Metal Open Pit Mines**  
F. Faraj; MineSense Technologies Limited, J. Ortiz; Queen’s University, Robert M. Buchan Department of Mining Engineering, J. Arnal, University of Toronto - Institute for Aerospace Studies, M. Carrera and M. Haest; MineSense Technologies Limited

ShovelSense is a complete solution for bulk ore sorting at the mine face that combines robust shovel bucket mounted X-ray fluorescence sensors, with real-time material classification, fleet management integration and supporting cloud-based data infrastructure, to ensure each truck always goes to the right destination. Correct truck destinations are a challenge in many current mining settings because the material classification of a truck, which is the key input into the truck destination, is often based on estimates at block resolution (~20x20x15m), with limited adjustment for blast movement and mixing.

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**9:00 am**

**A Two-step Model to Optimize the Semi-mobile In-pit Crusher Locations and the Mine Schedule**  
A. Kamrani and H. Askari-Nasab; University of Alberta, Edmonton, Alberta, Canada

In-pit crushing and conveying (IPCC) is an option to decrease the enormous operating costs that a truck shovel can introduce in an open-pit mine. Finding the best locations for the IPCC over the mine life will impose a new set of requirements for the mine planning. Through a two-step mathematical programming model alongside the road network, this method finds the optimal in-pit crusher locations and relocation times first and then optimizes the long-term mine schedule. The model is verified by a real mine. The results show that the truck travel time could be reduced by 500% and the discounted cash flow increased by 8% with an optimized schedule considering the crusher placement.

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**9:20 am**

**The Influence of Working Parameters on Ball Mill Performance and Charge Behavior**  
B. Doroszuk; Wrocław University of Science and Technology, Wrocław, Dolny Śląsk, Poland, R. Król; Wrocław, Dolny Śląsk, Poland

Mill drums are essential equipment in various industries for the comminution of materials. To optimize their design and operation for efficient and cost-effective processing, it is necessary to understand the behavior of the mill drum under various operating conditions. This study investigates the behavior of a mill drum using a combination of experimental and numerical methods. The factors that can influence the behavior of the mill drum, such as the size and shape of the mill, grinding media, rotational speed, filling level, and material properties, are discussed. Experimental methods can be limited in obtaining measurements of internal processes, so numerical methods such as the Discrete Element Method (DEM) are also used to simulate the behavior of the mill drum. In this study, the experimental measurements of the motion of the grinding media are obtained using computer vision methods, and the numerical simulations are calibrated using the experimental results. A designed experiment approach is used to evaluate the performance of the mill drum under various operating conditions. The results of this study can be useful for the design and optimization of mill drums to achieve better performance and energy efficiency.
Risk and Uncertainty

8:00 am
Modern Visualization to Aid in Communication of Mine Planning Uncertainty
C. Roos; Montana Technological University, Butte, Montana, United States

The mining industry has made strides in planning for operations to be safe for the workforce and public, to protect the natural environment, and to maximize value for shareholders. However, many of the techniques used to accomplish these goals are based on estimated models of mineral content, production efficiency, and economic performance. The industry has begun to recognize the need for understanding the uncertainty in these models, how it affects their decisions, and what the potential impacts are for each project. The challenge has become how technical professionals can effectively communicate the impact of this uncertainty and its importance to both technical and non-technical audiences. This paper presents mining engineers (and other technical professionals) with traditional and modern principles of data visualization and technical communication that can assist with communicating the effects of uncertainty in the mine planning process.

8:20 am
Optimum Open-Pit Mine Scheduling Considering Multivariate Grade Uncertainty Using Deep Q-Learning
S. Avalos; Advanced Predictive Modeling Technology, Kingston, Ontario, Canada; J. Ortiz; The Robert M. Buchan Department of Mining, Queen’s University, Kingston, Ontario, Canada

The long-term mine scheduling is the optimal decision on how to extract and process the mining reserves. The resulting plan is mainly driven by economic, metallurgical, and geological factors. Accounting for their uncertainties leads to a robust solution and the feasibility for economic-risk quantification. In this work, we model the spatial uncertainty of grade distributions of multiple correlated elements, by using a multivariate morphing transformation. The result is a set of multivariate geostatistical realizations of the grades, which honor the conditioning data, the direct and cross variograms and the multivariate statistical distribution, inferred from a set of samples. These models are the input in a reinforcement learning framework, adopted to train a deep neural network that considers the grade uncertainty and leads to an optimum mine plan after training using deep Q-Learning. Mining and processing capacities, as well as economic parameters and metallurgical constraints, are incorporated as the reinforcement learning environment rules. The method is validated on a real deposit, providing insights for future applications.

8:40 am
A Novel SIP Formulation for Long-Term Production Scheduling Optimization Problem in Open-Pit Mines Under Uncertainty
K. Toluoei and E. Moosavi; Department of Petroleum and Mining Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran

In open-pit mines, the long-term production scheduling optimization problem (LTPSOP) is a complicated problem that contains constraints, large datasets and uncertainties. Due to its dimensions and NP-hard nature, it is usually difficult to find an ideal solution to the LTPSOP. The optimal schedule generally restricts the ore, metal and waste tonnages, average grades, and cash flows of each period. In this paper, to synthesize grade uncertainty into the strategic schedule, a stochastic integer programming (SIP) framework is presented to LTPSOP. The objective function of the SIP model is to maximize the net present value and minimize the risk of deviation from the production targets considering grade uncertainty simultaneously while satisfying all technical constraints and operational requirements. Instead of applying one estimated orebody model as input to optimize the production schedule, a set of equally probable orebody realizations is applied to synthesize grade uncertainty in the strategic schedule and produce a more profitable and risk-based production schedule. To solve the LTPSOP, the hybrid approach with the augmented Lagrangian relaxation method, the Harris Hawks optimization, the Random Forest method and Monte Carlo method was proposed. To indicate the applicability of the model, a case study on a gold mine was implemented. The framework displays the capability to minimize risk and improvement in the expected net present value and financial profitability.

9:00 am
Uncertainty Estimates for Geomtallurgical Models
M. Rossi; GeoSystems International, Boca Raton, Florida, United States

Often geometallurgical models are prepared at various project stages from very few data and are assumed to be representative of very large tonnages. These may include recovery models; crushing and grinding parameters and models; models of concentrate grades; models of acid consumption; etc. These models commonly do not carry a measure of uncertainty or variability, and are taken at face value at the time of design and planning. This paper proposes a proactive approach to modelling variability, providing uncertainty estimates and thus allowing for risk analysis and mitigation of geometallurgical models. The variability model is built up by understanding the limitations of the pillars of a geometallurgical model: data uncertainty, geologic model uncertainty, domain definition uncertainty, and parameter estimation uncertainty. Of these factors, typically domain definition is probably the most significant conditioning to geometallurgical model variability. First, the fundamental supports for these models are discussed, with domain definition emphasized. Second, two methods for uncertainty
modelling are proposed. The first, more applicable to conceptual or early-stage projects, is a simpler and more expedient alternative that provides initial assessments of variability. This is intended to aid management in decision-making related to budgeting, including further sampling and testing. The second, a block-by-block approach that allows a detailed assessment of risk for specific designs and mine plans, thus providing further opportunities for mitigation. In the example provided, emphasis is placed in communicating this variability to both management and technical personnel in the form of “measured-indicated-inferred” indicators and also block by block confidence intervals.

9:20 am
Incorporating Geological Uncertainty to Define Weathering Contacts and Grades in Medium- and Short-Term Scheduling
V. Euler; Universidade Federal do Rio Grande do Sul, Belo Horizonte, Minas Gerais, Brazil, R. Peroni; Porto Alegre, Rio Grande do Sul, Brazil

Knowing the depth of contacts between weathering zones in phosphate mines is determinant to define the stripping ratios and the mineralized zones. Contacts are gradational and difficult to define even in the drillhole samples, so the combination with geostatistical simulation techniques helps to define the contact zone and the grade distribution, providing a way to assess the probability of the occurrence and the positioning of contacts between the barren waste and the ore zones. These inputs are used in the scheduling, anticipating risks associated with mine planning scenarios. The results from an application to a case study showed a good improvement when compared to traditional techniques.

Simulation
Dakota Ballroom ABCD
Chair: Prof. Joao Felipe Coimbra Leite Costa

10:00 am
Using Simulation and Optimization to Support the Mining Execution Plan
C. Eustace; Polymathian, Paddington, Queensland, Australia and K. Hynard; Polymathian, South Brisbane, Queensland, Australia

Development quarterly mine plans is generally time-consuming and requires consideration for many operational constraints and competing objectives. With lengthy turnaround times, there is often limited opportunity to adjust the quarterly plan details to account for differences between actual state of the mine operation at the time of execution and expected state at the time that the plan was developed. Actual mining task completion times can vary significantly from the expected task completion times, due to many factors. In the absence of revision to account for differences between the planned and actual state, resource allocations and mining sequences, embodied in the quarterly mine plan may no longer be the best approach at the time of execution to achieve an efficient mining operation. Simulation and optimisation tools can be used to support rapid refinements for development and execution of weekly mine plans. When initialized with an operations data feed to establish the actual state of the mine operation, optimisation models can be used to facilitate both automation and revision of the quarterly plan to produce a weekly or daily plan for execution. This approach can remove much of the manual burden of revision if the existing quarterly plan no longer represents the best approach to meeting production objectives. Following initialisation with mining actuals, simulation models can provide a representation of the range of likely mine operations outcomes. The models can be used to accelerate the planning process by providing visibility of future performance and identifying likely operational issues. They can also be used to test the robustness of the plan with respect to performance variability and response to disturbances. Following identification of issues, simulation models can also be used for evaluating mitigation measures, through automated testing of alternative plans. Integration of mine data feeds with simulation and optimisation tools enables automated optimal responses to variations between the quarterly mine plan and actuals to be tested prior to release of execution plan and implementation. The use of simulation and optimisation in weekly mine planning will be discussed in this paper with reference to surface mining examples.

10:20 am
Discrete-Event Simulation for Predicting Equipment Fleet Failure Behavior
J. Sattarvand and A. Moniri-Morad; University of Nevada Reno, Reno, Nevada, United States

Predicting equipment failure behavior plays a critical role in providing a safe operation. Although various reliability evaluation methods are available for estimating failure behavior profiles, these approaches are based on mathematical formulation, leading to actual operation simplification and improper estimation of failure trends. This study proposes a discrete-event simulation (DES) approach to model fleet failure behavior. This approach can model the maintenance strategies in multi-component systems with minimum simplifications. In this regard, the first step was to collect a historical failure time dataset (e.g., the time between failures). Then, the DES model is established to predict the severity of failure events and design maintenance strategy considering actual operation circumstances. Afterward, the maintainability analysis was performed to estimate equipment downtime and availability. The achieved results showed that the system availability was about 85%. Also, the findings demonstrated that the DES could efficiently predict the equipment failure behavior using various stochastic events.
10:40 am
Mining Data Collection, Storage, and Interpretation Method Advancements
M. Minnick, C. Johnson, E. Walega, and J. Nopola; RESPEC, Rapid City, South Dakota, United States, E. Hemstad; RESPEC, Grand Junction, Colorado, United States

Mining data collection, storage, and interpretation methods have progressively changed over time. Data collection, for the most part, has transitioned from handwritten notes and logs based on manual gauge readings to real-time data streaming through instrumentation capable of directly communicating with site-based data historians or cloud storage. Data collection and storage have had to adjust commensurately with the volume of data, leading to more complex database architecture. Geoscience interpretation methods have also changed; however, the first goals of modeling and understandings from first principles remain the same and are typically deeply rooted in historical academic work. Machine learning methods are becoming more common, available, and implemented by industry and practitioners. Despite the wide accessibility of machine learning methods, the population of geoscience subject matter experts in the underlying theory of this analysis type is limited. This form of analysis, therefore, must be conducted carefully and in conjunction with subject matter experts, on both machine learning theory and the field it is being applied to. This paper aims to provide background history on data analytics and machine learning, current methods and practices, and high-level geoscience case study examples, as well as takeaways regarding the mining industry, potential pitfalls specific to geosciences, and possible perspectives on the direction of artificial intelligence in the future.

11:00 am
Truck Fleet Dispatching Control in Open-Pit Mining Based on Reinforcement Learning and Discrete Event Simulation
R. Noriega and Y. Pourrahimian; University of Alberta, Edmonton, Alberta, Canada

Truck fleet dispatching plays a crucial role in reducing operational costs and fulfilling operational targets in open-pit mining operations and is subject to large uncertainty arising from the operating cycles of trucks and loading equipment. This paper proposes a reinforcement learning-based truck dispatching system. Reinforcement learning is a machine learning area that deals with learning an optimal sequential decision-making strategy in an uncertain environment. An open-pit load-and-haul simulation is developed that also captures the truck movements and interactions in the shared road network, and a Neural Network is successfully trained to suggest truck dispatching decisions in a real-time manner.

11:20 am
Multiple-Criteria Cut-Off Grade Optimisation Utilising Excel Solver
C. Birch; The University of the Witwatersrand, Johannesburg, Gauteng, South Africa

The multiple-criteria decision analysis is a technique that helps to find an optimal solution by evaluating conflicting criteria. In this study, an approach to perform multiple-criteria decision analysis for cut-off grade optimization, which considers the diverse stakeholder groups prevalent in the mining industry, is presented. The optimization model developed in this approach links the resource block model to the financial model, enabling the process to either maximize profit, net present value, revenue to the State, or extend the mine’s life. To identify the optimal cut-off grade in each case, the Excel Solver function is utilised. Although it has limitations, the Solver function can still be modified to handle models with thousands of block values for determining input variables based on the target value. Following stakeholder engagement and dialogue, a single weighted average cut-off grade can then be determined. This approach is demonstrated for nine South African Witwatersrand gold mines.

Tailings & Waste Management

10:00 am
A Model for Minimizing Water Losses Due To Evaporation in Copper Tailings
N. Morales Varela; Polytechnique Montreal, Montreal, Quebec, Canada, J. Silva, E. Jelvez, and C. Ihle; University of Chile, Santiago, Chile

All mineral beneficiation processes require water for its execution. Therefore, the availability and adequate management or water are key to the existence of any mine operation. However, many mines operations are affected by water scarcity and risk an increase of operational costs or even production in some cases. This paper proposes a model to minimize the losses of water due to evaporation and infiltration by adjusting the active and inactive periods of the discharge in different points of the tailing. When applied, the model determines optimal or nearly optimal discharge operation in all the scenarios that were evaluated.
10:20 am
Drone-Based Applications for Tailings Dam Monitoring
J. Gomez Llerena and J. Sattarvand; University of Nevada Reno, Reno, Nevada, United States

Failures of tailings dams have been happening lately. Due to the lack of laws on particular design criteria and stability requirements related monitoring during construction and maintenance, they are thought to be more fragile than hydraulic dams. Monitoring the dam is therefore necessary to understand its current condition and guarantee its safety. The physical condition of the dam could be evaluated with the early identification of seepage. Additionally, due to their adaptability and capacity for high-resolution data collecting, UAVs are an excellent choice for efficiently covering the tailings dam site. UAVs may capture high-quality photos when equipped with a high-resolution RGB camera, thermal sensors, or multispectral sensors. When these sensors are paired with image processing and machine learning algorithms, the result is a reliable estimate of the dam condition.

10:40 am
Decision Support System for Monitoring and Stability Assessment of the Tailings Storage Facility
S. Anufriiev, M. Stachowiak, S. Anufriiev; KGHM Cuprum Research and Development Centre, Wrocław, Dolnośląskie, Poland, B. Bursa; GEOTEKO Serwis Ltd., Warsaw, Mazowieckie, Poland, P. Stefaniak and P. Stefanek; KGHM Polish Copper, Rudna, Dolnośląskie, Poland

The article presents the main functionality of the DSS class system for monitoring and stability assessment of tailings storage facilities. The presented demonstrator was deployed on the example of the Żelazny Most reservoir - the largest active facility of this type in Europe and second one in the world. Considered as a high-risk structure demands a system capable of online analysis of big data from various sources using machine learning, 3D modeling or GIS mapping with the functions of interactive spatial-spatial analysis. In this paper we present a complex calculation module with integrated user interface.

11:00 am
Computer Vision on Soft Soils Waste Dump Areas
P. Mochamad Rizki, A. Satya, and Sukrisno; PT. Pamapersada Nusantara, Jakarta, Indonesia

High-risk area in open-pit mining should always be monitored by the operational supervisor because of its nature. One of this type is the soft soil dump area. Due to the unstable bearing capacity of the soil, its highly possible for us to find cracks in the area. This paper aims to build computer vision which able to detect truck’s distance from safe limit allowed during dumping activity. The system will warn the truck’s driver if the truck has crossed that predetermined safe limit.

11:20 am
Artificial Intelligence Algorithm for Tailings Storage Facility Soil Classification Based on CPT Measurements
S. Anufriiev, P. Stefaniak, N. Duda-Mróz, W. Koperska, and P. Stefanek; KGHM Polish Copper, Rudna, Dolnośląskie, Poland

Due to the high environmental risks and negative impact of a failure, tailings storage facilities (TSFs) need constant monitoring. Advanced mathematical models have been developed in the past to predict the behavior of TSFs and raise alerts if needed. To be precise and reliable, such models need a spatial distribution of soil types within the dam as an input. Getting this data from laboratory measurements is time and cost-consuming. In this article, we propose an ANN-powered algorithm, which allows us to accurately estimate the soil distribution based on a cone penetration test (CPT).

Surface Mine Planning I

Dakota Ballroom ABCD
Chair: Prof. Marcos Goycoolea

1:00 pm
A Dynamic Programming Algorithm for Selecting Evenly Spaced Pushbacks from Nested Pits
M. Deutsch, K. Dagdelen and T. Johnson; Colorado School of Mines, Golden, Colorado, United States

Nested pit analysis in open-pit long range mine planning is used to define approximate ultimate pit limits and an initial high-level schedule in the early stages of a project. Modern ultimate pit optimizers can solve for dozens, or even hundreds, of nested pits however often a smaller subset of pits which are evenly spaced with respect to contained tonnage are desired for downstream analysis. In situations where that pushback selection process must be automated, such as when performing sensitivity analysis, or when the best subset of pushbacks is required; an optimization procedure is warranted. This paper describes a dynamic programming based algorithm for selecting pushbacks following nested pit analysis which is performant and addresses a long standing inconvenience faced by long range open-pit mine planners.
Developing and Testing an Optimisation Algorithm for Practical Open-Pit Pushback Design

J. Yarmuch Guzman; Departamento de Ingenieria de Minas, Universidad de Chile Santiago, Santiago, Chile, H. Rubinstein; The University of Melbourne, Melbourne, Victoria, Australia

Open-pit mine planning is a key process in the definition of mineral reserves and their efficient extraction. Open-pit mines are extracted by the mining of sequential pits called pushbacks. Pushbacks need to satisfy complex geometrical constraints to ensure the efficient usage of equipment. To date, no algorithms that account for those constraints are commercially available. Therefore, pushback design is done by engineers relying on their expertise. In this article, we present the process of developing a new algorithm that produces close to optimal practical pushbacks and we illustrate its performance in real mines.

Reinforcement Learning Applied to Shovel Allocation and Grade-Control for Short-Term Production Planning of Industrial Mining Complexes

J. De Carvalho and R. Dimitrakopoulos; COSMO Lab - McGill University, Montreal, Quebec, Canada

An actor-critic reinforcement learning approach is presented to improve the production of an industrial mining complex by defining shovel allocation and adapting the short-term plan given grade-control decisions. Blasthole data updates the simulated orebody models, which are input into a stochastic grade-control method based on a spatially constrained clustering approach that minimizes the profit-loss function. These aspects are embedded in a discrete-event simulator that defines the material flow from faces to processors. A case study at a copper mining complex shows the methods’ ability to adapt to new information, improving the quality of the material feed and increasing cash flow by 23% compared to a baseline case.

Pushback Design in Open-Pit Mines by Considering Geometric Requirements under a Mathematical Programming Approach

E. Jelvez and P. Nancel-Penard; amTC - Universidad de Chile Santiago, Santiago, Chile

The traditional way of generating open-pit mine production schedules has several limitations. In this work, we address the design and production scheduling problem by considering minimum operational space requirements. Two approaches based on the Lerchs & Grossmann methodology and Direct Block Scheduling are addressed and combined to generate extraction sequences that satisfy the operational space required. For this, we extend traditional formulations by including a new set of constraints that generate operating spaces for mining equipment to move and extract material. This proposal was applied to a case study to show its ability in generating practical production schedules maximizing NPV and the results were compared with those obtained using the traditional approach.

Comparative Analysis on the Effect of Mining Parameters on Open-Pit Optimisation

J. Muchiri Githiria and K. Omar; Taita Taveta University, Voi, Taita Taveta County, Kenya

Mineable material is defined using either geological or economic cut-off grade. Both geological and economic cut-off grade affects the output generated in an open-pit mining operation. It distinguishes the amount of ore sent to the mill for processing and waste to the dump consequently affecting the overall profits generated from mine operation. There are several mining parameters that are considered in a typical cut-off grade model. The modified Lane’s model is developed into a stochastic computer-aided application code-named: NPVMining. Using NPVMining, selected stochastic parameters are considered in this exercise to show the effect on the output (net present value). The selected parameters (price, operating costs, discount rate, grade-tonnage, recovery and capacity) are varied by ± 10%. This paper analyses the effect of each of the mining parameters on cut-off grade using NPVMining to show the significance of monitoring their variance.
Underground Mine Planning

Dakota Ballroom
Chair: Prof. Alexandra Newman

1:00 pm
Multidimensional Data Analysis for Drilling Process in Underground Mines
A. Skoczylas, P. Stefaniak, S. Anufriiev, W. Koperska, and M. Stachowiak; KGHM Cuprum Research and Development Centre Ltd., Wroclaw, Lower Silesia, Poland, A. Fhager; Epiroc Rock Drills AB, Örebro, Sweden, Sweden

In many underground mines the excavated ore is produced during the blasting process. Drilling machines that are used to drill the blastholes, where later the explosives will be mounted, are crucial for this task. In order to optimize the currently used techniques, great emphasis is placed on increasing the efficiency and safety of blasthole drilling operations. The natural consequence is the development of monitoring systems and algorithms for processing operational and historical data. In this article, we present the result of the analysis of drilling data carried out as part of the IlluMINEation project. The paper proposes an algorithm for work cycle detection for drilling machines, together with the estimation of general operating parameters and diagnosing the drilling process on the basis of long-term data. Based on the available data, selected components of the drilling cycles have been indicated. Several approaches based on the parameters of the defined cycles are proposed. These approaches can be used in the future to create a full-fledged system for examining the effectiveness and safety of mining drilling rigs.

1:20 pm
Using a Dual Interchange Algorithm to Evaluate the Effect of Stope Size on Economic Value in Planning an Underground Sublevel Open-Stopping Layout
C. Musingwini and M. Mabala; University of the Witwatersrand, Johannesburg, Gauteng, South Africa

Optimisation of a three-dimensional (3D) underground stope layout is complex given the number of variables and constraints to consider, such as the stope size. Determination of the appropriate stope size in stope layout optimisation problems is a complex process that must consider several factors including placement of infrastructure and development, production scheduling, and equipment selection. An inappropriate stope layout can result in unrealistic expectations for a production schedule, consequently negatively affecting the derived economic value. Therefore, this paper used a dual interchange algorithm (DIA) to evaluate the effect of stope size on the stope layout economic value (SLEV) for a synthetic Platreef mineral deposit planned for extraction using sublevel open-stopping. The results showed that generally as the stope size increases, the SLEV decreases. This aligns with practical mining because larger stope sizes have a higher chance of incurring more dilution which reduces economic value, while smaller stope sizes enable more flexible extraction where unprofitable blocks can be left unmined as waste, thus increasing the derived SLEV.

1:40 pm
A Binary Integer Linear Programming Model for Optimizing Underground Sublevel Stope Layout
T. Mensah and K. Awuah-Offei; Missouri University of Science and Technology, Rolla, Missouri, United States

Engineers face significant challenges when determining what geometry provides the most profitable and safe stope for extraction. Several techniques and optimization algorithms have been developed in recent years, but most fail to find optimal solutions because they are heuristic or LP-based without efficient geometric constraints. This paper presents a two-dimensional binary linear programming (BLP) model for determining the optimal combination of blocks in a stope that maximizes the economic value of the layout of stopes for a sublevel deposit. The work draws from Queyranne and Wolsey’s (2017 & 2018) formulations of tight constraints for bounded up/down times in production planning problems to formulate novel and efficient geometric constraints along with geotechnical and grade constraints for the BLP stope layout optimization problem. Results from the model indicate that it is possible to formulate efficient shape constraints in LP-based approaches. The model used for the numerical example contained 144 valuable blocks out of 774 blocks which translates into an economic value of $53.21M. The BLP model selected 60 valuable blocks and 13 waste blocks that met all constraints translating into a maximum economic value of $34.4M in 1.83 hours within a gap tolerance of 0.00%.
### 2:00 pm
**Data & Analytics Supporting Longwall Automation Everyday**

*W. Fourie, Komatsu, Warrendale, Pennsylvania, United States*

Komatsu’s business focus is to provide surface and underground mining operations with superior equipment, solutions and direct service. Komatsu’s Smart Solutions has been at the technology forefront in the mining industry using big data and operational technology for aiding mines to improve operator performance and mechanical reliability. Smart Solutions is the combination of three key components which are smart and automated machinery, analytics and people. The product has been developed to suit the needs of longwall coordinators and other stakeholders at mines in daily operations. This method is key because the product matches the need of management personnel every day. The goal is to deliver the lowest cost per unit of production over the life cycle of the equipment while prioritizing safety. To achieve these results, Komatsu utilizes data, prognostics and analytics in applications throughout Smart Solutions centers around the globe to improve production, refine operations, detect premature failures and implement preventative strategies. The smart connected products of a Joy longwall system include a shearing machine, armored face conveyor (AFC), roof supports, stage loader, crusher, and mobile belt tail-piece. While monitoring longwall operations, the ongoing aim is to detect patterns and systematic relationships amongst the operator inputs, control system parameters, sensor data and alarm/event information. Statistical techniques, such as regression analysis, and single and multi-variables analysis are utilized to optimize cutting speed, detect roof cavities and improve roof support cycle times. Predictive diagnostics and analytic rules are implemented to analyze real-time data and provide notifications and alerts of changing longwall characteristics.

### 2:20 pm
**An Integrated Approach for Long-term Production Scheduling Optimization of Sublevel Caving Mines Using Mixed-Integer-Linear-Programming Model**

*S. Khazaei and Y. Pourrahimian; University of Alberta, Edmonton, Alberta, Canada, A. Mousavi Noghol; Tarbiat Modares University, Tehran, and F. Khodayari; Dassault Sysems*

As a factory-like method, sublevel caving consists of development and production activities that are carried out on separate levels independently. Therefore, considering the operation from the development phase to the plant will lead to more reliable production scheduling. This paper presents a mixed-integer linear programming framework for the long-term production scheduling of sublevel caving that maximizes the net present value while satisfying development activities, mining, and processing capacities, continuous mining, the allowable number of active mining units, grade blending, and vertical and horizontal sequencing. The model is coded in Jupyter Notebook and is solved using the CPLEX solver.
into consideration time periods as variables and integrating them as part of the analysis, providing a better overview of the forecast plan completion with respect to past experiences and evaluating best alternative to handle future events to minimize losses or maximize profits, resulting in better truck assignments, minimum shovel idle times and overall improved Net Present Value of the operation at the end of the time horizon.

8:20 am
Training/testing Mining Truck Drivers for Proximity Awareness Through Multiplayer Virtual Reality Game

A. Kamran Pishhesari, J. Dahl, E. Marsh, J. Sattarvand, F. Harris Jr.; University of Nevada Reno, Reno, NV, United States

Based on the mine safety and health administration (MSHA) reports, mining truck accidents are among the significant causes of fatalities in the mining industry. The major causes of haulage accidents can be divided into non-driving and driving factors, such as truck-related sudden failures and operator performance. Numerous parameters affect trucks’ safe operation, but situational awareness plays a significant role. Due to the distinct structure of mining trucks, making them efficient for mining purposes, the operator has a very limited field of view (FOV), making them prone to accidents resulting in losing lives. The cabin’s position blocks the truck’s right and rear sides, creating several blind points around it. Aiming to test/train the operator’s awareness of the surrounding, a proximity detection system is developed through a multiplayer virtual reality (VR) application to investigate the human factor in equipment collisions. The operators were examined and monitored when asked to conduct what exactly happened in the Marigold mine truck accident without being aware of the scenario. After receiving sound, vibration, and visual alarm warnings, their reaction and performance were analyzed. The platform is developed using the Unity game engine for HTC VIVE virtual reality goggles. An Omni-direction treadmill and a motion simulator platform are utilized for the player and dump truck operators. Fifteen students were monitored when driving the dump truck receiving/not receiving proximity detection alarms. None of them repeated the accident when receiving proximity alarms. Also, they found the visual alarm the most comfortable while driving the truck.

8:40 am
Evaluation of Models for Interaction Probability in Autonomous Monitor and Control Environments

R. Bissonette and S. Sbai; NIOSH, Spokane, Washington, United States

A critical component of implementing autonomous control and/or monitoring systems is realistic, human-like perception of the operational environment. This means that any such system would need to gather robust and accurate data about its environment, evaluate what objects of interest exit in that environment (with relevant data about identity, trajectory, characteristics, etc.), project a future continuum of those objects (including considerations for variabilities), and make control choices to minimize risk cost due to exposures in the present operational area. The components of such system are a) sensors and fusion b) probability projection of future states of objects and the environment, c) generation of alternate futures and d) determination of best action to reduce risk cost. The system needs to take data with different time stamps with variability parameters and create probability clouds into the near future, evaluate how those clouds interact and identify areas of risk. This paper focuses on using information from the sensor fusion engine to generate a continuous projection of future state incorporating the factors of confidence, accuracy, tolerance, and other variabilities.

9:00 am
Applications of Digital Twin Technology in Productivity Optimization of Mining Operations

J. Sattarvand and M. Ghahramaniesalou; University of Nevada Reno, Reno, Nevada, United States

As new technologies are introduced to the mining industry, the challenges related to their safe assimilation and the potential changes they bring to mining techniques necessitate adjustments to the current operations. Predictive simulations are critical to understanding unforeseen scenarios and shifting costly changes from the operational stage to the design. The Digital Twin methodology has gained a lot of attention in recent years. Many industries, from manufacturing to engineering and even social sciences, are adopting this approach to understand better the complex systems they are working with. By considering the enormous expenses and risks related to a pilot project, DT could replace that by acting as a prototype in which realistic tests and simulations are carried out with close to zero cost. DT includes a data hub, simulation and analysis tools, and visualization platforms to enable appropriate designs and monitoring plans focusing on unknown areas. A few examples of DT’s application in mining include fleet management, Mine-to-Mill optimization (especially D&B), geotechnical digital twin (gDT), etc. When developing regulations, testing the efficiency of the mine layout, design, and magnitude of the restricted area and its access points, human-machine interactions, risk identification, and management processes, examining the efficacy of control systems, and monitoring, DT could help speed up (or completely replace) the process in the physical world.
**Blasting**

Dakota Ballroom  
Chair: Dr. Amy McBrayer  
8:00 am

**Comparative Data Analysis Using Machine Learning Based Approach for Estimation of Particulate Matter Concentration in the Mines and the Vicinities**

M. Madahana and J. Ekoru; University of the Witwatersrand, Johannesburg, Gauteng, South Africa

Particulate matter is one of the leading pollutants in the mines and in the communities in the areas near or surrounding the mines. The availability of large Clinical and environmental data sets obtained from the mines has brought about the need to use better approaches to analyse the collected data. Prediction and control of particulate matter concentration in the mining environment is essential in minimizing air pollution and protecting the respiratory health of mine workers. The main objective of this research work is to analyse datasets obtained from a mining area using machine learning techniques which will then be followed by the real-time estimation of dust particulate in the mines. Datasets collected over 8 years in an hourly sampling rate from an open cast mine is cleaned and analysed for trends and patterns. Artificial Neural Networks (ANNs), Support Vector Machines and decision trees techniques are applied to analyse and predict the particulate concentrate. The estimation of particulate concentration using Artificial Intelligence will significantly contribute toward the development of quantitative tools to be used in correlating of cause and effect of dust concentration in mines. The results obtained in this work will form a sub-unit of a respiratory health monitoring system for mine workers. From the existing theory, we expect the Artificial Neural Network will perform much better than previously used classical models.

8:20 am

**The Effects of Rock Mass Properties on Explosive Energy in Rock Blasting**

M. Dotto and Y. Pourrahimian; University of Alberta, Edmonton, Alberta, Canada

Fragmentation by blasting is a critical process in hard rock mining. The blasting process and outcomes are highly influenced by rock mass properties and their response to higher stresses and loading rates. Each rock mass is unique, but some features affect the blast energy similarly, leading to similar outcomes. Having analyzed these features and their influence on blast results, they can be incorporated into the blast design to achieve better outcomes. This paper presents a numerical model validated by a case study from the actual mine blasts that studied the effect of rock mass properties on explosive energy production, attenuations, and overall blast outcomes. The results show that when the model parameters are calibrated based on real data, they can be used to simulate the fragmentation process and therefore be used to aid blast design.

8:40 am

**Leveraging Air Quality Sensing for Carbon Monoxide Transport Modeling in Underground Coal Mines**

K. Brown, E. Lutz, and M. Momayez; University of Arizona, Tucson, Arizona, United States

As air quality sensor networks become increasingly popular in underground coal mines, it is important to generate paradigms for the application of the collected data. To date, air quality sensing has been primarily used as an early warning system for hazardous air conditions. Using data collected from a network of sensors in a US underground coal mine, we have created multiple visualization methods to show the interactions of carbon monoxide evolution with ventilation airflow. These visualization methods can allow for further analysis of the source of contaminant, as well as better data resolution across the area of concern within the mine. By utilizing univariate spatial interpolations, we present methods for identifying the movement of carbon monoxide at one-minute intervals. The resulting visualizations display the evolution of carbon monoxide concentration across a sizeable study area over a period of 14 minutes.

9:00 am

**Machine-Learning Model for Predicting Shock Loss due to Buntons in a Shaft**

A. Adhikari, P. Tukkaraja, and S. Sridharan; South Dakota School of Mines and Technology, Rapid City, South Dakota, United States

Shafts are critical components of the mine ventilation systems and contribute significantly to the mine ventilation pressure. Estimation of shaft pressure losses is an important aspect of mine ventilation planning and shaft frictional pressure losses are extensively studies. Shock losses contributed by shaft buntons are estimated using the interference factor model developed half a century ago. This study aims to develop a better performing prediction model for shaft buntons using state of the art experiment and numerical data, and machine learning techniques. Results show that the present prediction model is performing poorly, and the prediction performance can be improved by incorporating additional predictor variables. The Artificial Neural Network standardized Machine Learning model developed in this study is able to predict the shaft bunton shock loss with high accuracy (R2 = 0.956).
Surface Mine Planning II

Dakota Ballroom
Chair: Mr. Matthew Deutsch

10:00 am
Planning Open Pit Mines Using Direct Block Scheduling Technology
J. Camus and M. Brücher; InnovaMine, Santiago, Metropolitan Region, Chile

This article deals with open pit mine planning and a computer technology known as Direct Block Scheduling, or "DBS". This is an emerging technology for modeling mine exploitation strategies using mixed-integer linear programming. This technique has proved to yield stronger economic results compared to the Lerchs-Grossmann ("LG") algorithm currently used at the beginning of the mine planning process. The article briefly describes the shortcomings of current practice; then, this delves into the superior results obtained by DBS technology compared to current practice. Finally, the article argues that results achieve so far by DBS could be enhanced even further. To do this, the framework to apply this emerging technology, which is also used in current practice, should be modified to better exploit the capabilities of DBS technology. To better understand this change, an illustrated case study is presented at the end of the article.

10:20 am
Incorporating Value to Waste Rock in the Ultimate Pit Optimization for Haul Road and Mining Pads Construction and Maintenance Purposes
V. Campos; VALE, Belo Horizonte, Minas Gerais, Brazil and R. Peroni; Universidade Federal do Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil

Carajás is one of the largest open pit mines in the world. The mine is comprised by a haul road network with more than 100 km long, where the necessity to have good roads is paramount, determining the truck performances. This work integrates in the ultimate pit design an approach to consider an economic value to an originally barren material assuming it has the appropriate characteristics for haul road construction and sometimes it lies over economic iron ore. This measure demonstrated to improve the resources utilization and guaranteeing the necessary material to the haul road design and Mining Pads maintenance.

10:40 am
Developing a Production Scheduling Model for Large Area Mines
A. McBrayer and A. Brickey; South Dakota School of Mines and Technology, Rapid City, South Dakota, United States

Limited research has been conducted related to the development of mathematical optimization models for production scheduling at large surface coal mines using the area, i.e., strip, mining method. Increased economic and technical challenges have led to a new interest in production schedule optimization models for these type of mining operations like those currently applied to model underground and open pit mines. While area mines share similar characteristics to both open pit and underground metal operations, neither an open pit nor underground production scheduling model adequately depicts an area mine mathematically. We present an integer programming model with blending constraints and discuss the challenges and opportunities related to the implementation for area mines as well as future research in area mine production scheduling.

11:00 am
A General Short-Term Planning Model of Open Pit Mines with Semi-Mobile In-Pit Crusher or Traditional Truck-Shovel Haulage
N. Habib and H. Askari-Nasab; University of Alberta, Edmonton, Alberta, Canada and E. Ben-Awuah; Laurentian University, Sudbury, Ontario, Canada

In-pit crushing and conveying (IPCC) is getting popular in deeper open pit mines as a suitable alternative to truck haulage because it offers a lower operating cost due to shorter haulage distance and less truck requirement. Semi-mobile in-pit crusher, currently the most popular IPCC system, is relocated every two to five years, and the short-term plan needs to be updated accordingly. To the best of our knowledge, short-term planning with IPCC is an area of research that has yet to be explored extensively, and hardly any model can generate a short-term extraction sequence considering an IPCC. This research work proposes a mixed integer programming model to develop a short-term production plan within a time horizon of 12 months. The model’s objective is to optimally allocate shovels to minimize the cost of material handling and maximize revenue subject to meeting plant requirements, maximum allowable tonnage variation and IPCC location constraints to achieve production and NPV targets set by the strategic plan. The proposed model will be implemented in an iron ore mine case study for verification. The model is developed and solved using MATLAB. The comparison of results between scenarios with and without IPCC justifies the use of IPCC in large open pit mines from a short-term perspective.
The Open Pit Mine Production Scheduling Problem (OPMSP) is a complex optimization problem that seeks to determine the best sequence for extracting mineralized material from the ground in order to maximize the Net Present Value (NPV). This process must take into account various capacity constraints, such as mining rates, processing limits, stockpiling capacities, blending requirements, and precedence constraints, which dictate the order in which blocks can be extracted. Traditionally, the OPMSP has been formulated as a mixed integer programming problem, employing binary and continuous variables to represent the extraction of each block. However, this approach has limitations, particularly when it comes to addressing the stockpiling issue. In response, some researchers have proposed mathematical models, which offer a more accurate representation of the problem but come with their own set of challenges. In this study, an alternative approach to tackle the OPMSP with stockpiling by employing constraint programming (CP) is explored. The method was carefully tested on the Newman dataset from the well-known Minelib library. The results show that the CP-based model obtained a production schedule having about 2.69% higher NPV than the NPV of the solution, which is recorded in the Minelib Library.

Incorporating Operational Modes into Open-Pit Stochastic Mine Planning: An Optimization Using VND and LP

A. Quelopana and A. Navarra; McGill University, Montreal, Quebec, Canada

For decades, open-pit mine planning algorithms have incorporated geological uncertainty and other elements or characteristics for increasingly realistic representations. Among these complexities is the detailing of downstream processes that occur inside processing plants. Previous studies have demonstrated that the strategic mine plan and mineral concentrator design are coupled, and should therefore be optimized simultaneously within the same quantitative framework. However, existing frameworks offer limited representation of operational modes. This work demonstrates an approach to resolving this gap, in an optimization based on a parallelized Variable Neighborhood Descent (VND). The resulting algorithm embeds mass-balancing linear programming (LP) using a Dantzig-Wolfe decomposition. A case study of a Zn-Pb deposit is presented to show the performance reached.
10:40 am
Multivariate Stochastic Mine Scheduling Targeting Stationary Grades
A. Andres Toledo, J. Costa, and D. Marques; UFRGS, Porto Alegre, Rio Grande do Sul, Brazil, L. Capponi; Mosaic Fertilizantes, Araxa, Minas Gerais, Brazil

Short-term mine planning requires defining diglines to orient the excavation geometry. In deposits with multiple chemical variables, it is necessary to have more rigorous control over the feeding of the processing plant. This study analyzes the impact of incorporating multiple chemical variables, the risks generated by geological uncertainty, and the number and starting point locations of shovels in the sequential design of diglines. The objective is to maintain and preserve the low-grade variability, necessary tonnage, and continuity to sequentially select blocks. To achieve this, the probability distribution function of each chemical variable is used, attempting to maintain the ore grades as constant as possible simultaneously. As it is difficult to maintain multiple elements with low variability simultaneously, the relevance of each chemical variable in the economic benefit is identified. Weights are assigned to signal the importance of each element based on its significance in the recovery process. Several sequential diglines were generated to meet the ore demand for a weekly timeframe, optimizing the stationarity of multiple chemical variables, geological uncertainty performed through geostatistical simulation of grades, and the number and location of shovels, while meeting the operational restrictions of the selected blocks. The optimized digline with the multiple grades as stationary as possible is retained. The process is illustrated in a phosphate mine. The results show that the proposed method is viable and allows for a quick solution.

11:00 am
Maximum Estimation Error Correlation Between Short and Long-Term Production Volumes
A. Amaral; Federal University of Rio Grande do Sul, Belo Horizonte, Minas Gerais, Brazil, J. Costa, V.C. Koppe, and D.M. Marques; UFRGS, Porto Alegre, Rio Grande do Sul, Brazil

Errors associated with estimating the grade of an attribute of interest in a deposit can compromise planning, sequencing, and mineral beneficiation decisions. Several factors are associated with estimation errors. Among them, we can highlight the factors associated with sample spacing, the size of production volumes, and the variability of the attribute considered in the estimation. The access to estimation error can be obtained by some geostatistical methods, for example, by stochastic simulation. However, this is a process that in some situations is computer intensive and takes time. Previous works have proposed a simplified method to access the Maximum Estimation Error (MEE) associated with different types of grade variables, depending on the sample spacing, at small production volumes and considering specific coefficients of variation ranges. This paper presents an approach to assess the MEE associated with long-term volumes. Considering the methodology proposed, it is possible to approximate if a specific drilling pattern used in a deposit provides an acceptable pre-determined estimation error for Resource Classification. Results and considerations on the impact of the geometry of larger production volumes on the MEE calculation are also presented.
11:20 am  
**Application of Multiple-Point Statistics (MPS) For Stochastic Gold Grade Estimation in Areas With Sparsely Spaced Drillhole Data**  

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The application of multiple point statistics (MPS) in oil studies has gained traction over the years, however, the use of MPS in mineral resource estimation and classification is still limited. This is despite MPS' ability to deal with complex and heterogeneous geology better than the commonly applied two-point based methods. The availability and choice of a representative training (TI) is often cited as the main challenge that is holding back MPS' application in mining geostatistical studies. On the other hand, the general approach used in mining whereby high-grade areas are extracted first and lower grades are planned to be mined later presents a massive opportunity for the development of representative TIs. Mined-out areas (usually high-grade) provide large amounts of historical data that can be used to develop training images or training datasets that can be used to estimate in mining extension areas (which are usually low grade). This approach will enable more robust estimates in mine/pit extension areas (wherein the sampling density is usually low) than can be achieved with traditional two-point geostatistical methods.

The paper provides a proof of concept about the applicability of MPS’ direct sampling simulation (DeeSse) in grade estimation studies in areas with sparsely spaced drill holes. The area with scarce data at the mine is in the pit extension area (EA) where diamond drill holes are at 200 m x 100 m x 3 m spacing. However, there is sufficient closely spaced grade control data in the nearby pit at a grid spacing of 25 m x 25 m x 3 m. These closely spaced samples were used to create a training image (TI) on a 10 m x 10 m x 3 m grid using simple kriging. All subsequent simulations were run on the same support. To validate the applicability of DeeSse, firstly, 50 gold (Au) grade realizations were simulated using Sequential Gaussian Simulations (SGSIM) by using the same conditioning data as the data used to develop the TI. Subsequently, 50 gold grade realizations were also simulated using DeeSse by conditioning it to the same data as the TI but a lower 50 m x 50 m x 3 m resolution. DeeSse was found to be generally comparable with SGSIM and the TI with some minor bias. Following the validation of the applicability of DeeSse within the well understood TI area, it was then implemented and compared with SGSIM in the EA. DeeSse was found to provide a robust approach that offered more confidence in the estimates in areas with sparse data. Lastly, several recommendations for further research including suggestions about possible training images that can be integrated into the application of DeeSse in mining environments are made.
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