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Simultaneous stochastic optimization of mining complexes: Integrating waste management and progressive reclamation with encapsulation

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Abstract : Effective waste rock management is a crucial aspect of long-term mine planning and production scheduling. When waste management is not considered during the life of mine production schedule optimization, it leads to an inaccurate assessment of the financial outcomes of the related mining complex. This oversight can be particularly problematic when dealing with waste rock that is potentially acid-generating (PAG), as it introduces the risk of significant treatment costs related to rehabilitation, primarily due to acid rock drainage (ARD). To prevent or mitigate ARD, proactive measures, such as encapsulating PAG material with non-acid-generating (NAG) material, are essential. Furthermore, stricter legislation reinforces the necessity to restore mining sites to an acceptable post-mining condition, using ongoing reclamation to ensure environmental stability and reduce long-term liabilities. This work integrates waste management and progressive rehabilitation into the simultaneous stochastic optimization of mining complexes, employing gradual encapsulation of PAG material to promote progressive reclamation, thereby reducing long-term environmental and financial liabilities. Uncertainties in acid generation are addressed using geostatistical simulations of the rock's geochemical properties of the mine deposit considered. A case study at a copper-gold mining complex demonstrates that incorporating waste management by using progressive encapsulation leads to minimal financial impact.

Keywords : Waste management; reclamation; stochastic simultaneous optimization; encapsulation

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1 Introduction

A mining complex is an integrated system that includes facilities such as mines, stockpiles, waste dumps, tailings dams, processing plants, transportation infrastructure, and a metallurgical plant. These facilities define the flow and transformations that materials undergo from extraction to final delivery to customers and/or the spot market (Dimitrakopoulos and Lamghari 2022; Goodfellow and Dimitrakopoulos 2017, 2016; Montiel and Dimitrakopoulos 2015; Pimentel et al. 2010). When optimizing mining operations, geological uncertainty has proven to be a major source of risk that directly affects the accuracy of forecasted key performance indicators (Dimitrakopoulos 2011; Dimitrakopoulos et al. 2002; Dowd 1994; Godoy and Dimitrakopoulos 2011; Ravenscroft 1992). However, due to the scale and complexity of the optimization problem, conventional approaches to long-term mine planning rely on a series of simplifications to reduce it to a manageable size, thereby ignoring uncertainty and adopting separate and sequential optimization (Hustrulid et al. 2013; Whittle 2018; Whittle and Whittle 2007). In particular, waste management is traditionally addressed without accounting for uncertainty in the classification of potentially hazardous material and is only included after the production schedule has been determined. Neglecting this material classification uncertainty can lead to misrepresentations of the quantity and quality of hazardous waste, while addressing waste management only after scheduling can result in mine plans that struggle to comply with environmental legislation and the capacity limitations of dumping areas. This work addresses these limitations by extending the simultaneous stochastic optimization framework to include waste management to prevent or mitigate acid rock drainage (ARD), while also addressing the reclamation process of waste dump facilities.

Acid rock drainage can lead to acidification, salinization, mobilization of heavy metals, sedimentation, and both direct and indirect impacts on the organisms that comprise the local ecosystem (Akcil and Koldas 2006; Gray 1997; Zheng et al. 2023). In addition to these environmental risks, once ARD is initiated, the long-term costs associated with water treatment and the restoration of local biodiversity can far exceed the costs of implementing preventive and mitigative measures (Johnson and Hallberg 2005; Qin et al. 2019). Furthermore, progressive reclamation strategies can be combined with ARD mitigation or preventive measures. If performed progressively, reclamation enables the continuous monitoring and refinement of reclamation methods, supports the development of a realistic and adaptable closure plan, and enhances compliance with environmental and closure requirements defined by the local government (Straker et al. 2020). For these reasons, the International Network for Acid Prevention (2022) emphasizes the importance of integrating a risk-based approach into mine planning and design, to be implemented throughout the mine life cycle, with the objective of quantifying the long-term impacts of ARD and evaluating appropriate prevention and mitigation strategies.

Prior research has typically ignored uncertainty in geochemical properties used in the classification of hazardous waste and metal grades, addressing waste management only after long-term extraction sequences and destination policies have been determined in a previous optimization step. Li et al. (2013, 2014) designed a mixed integer program (MIP) to control the placement of the waste with the objective of minimizing haulage and re-handling costs, while also ensuring encapsulation of PAG material with non-acid generating (NAG) material given a predetermined production schedule. Vaziri et al. (2021, 2022) incorporated waste management considerations by formulating a MIP model aimed at minimizing the risk of ARD formation through strategic waste placement in dump cells to achieve geochemically stable material blends. More specifically, the objective function of the MIP model minimizes the difference in the potential of acid generation of dump cells in relation to the potential of acid generation set as a target. In all these approaches, uncertainty in the classification of potentially hazardous material is ignored, which may lead to inefficient waste management considerations in the presented models. In addition, these sequential approaches fail to account for the costs associated with mining potentially acid-generating material, which can lead to the misclassification of ore and waste, resulting in suboptimal extraction sequences.

New research approaches have introduced models that integrate waste management directly into long-term mine planning, allowing production schedules to adapt in response to waste disposal requirements. However, these approaches typically ignore the role of uncertainty in metal grades and the potential of acid generation to produce risk resilient plans. Fu et al. (2019) proposes a MIP formulation that simultaneously optimizes the production schedule, destination of materials, and waste dump placement to maximize the net present value (NPV) of the mine, while also considering haulage costs and the encapsulation of PAG material. Lin et al. (2024) subsequently expanded the scope of the model proposed by Fu et al. (2019), considering multiple mines simultaneously. In both cases, single estimated block models are used as input, leading to decisions that do not consider geological uncertainty. While the proposed formulations in the above work consider haulage costs in the destination decisions, they do not offer destination policies as guidelines needed for the operation, given the uncertainty in material properties. Furthermore, in both studies, encapsulation is ensured only at the end of the life-of-mine, as opposed to being performed yearly. This can potentially expose the waste to weathering conditions during operations and increase the risk of acid generation (Williams 2012; Williams et al. 2006).

Few studies have addressed the integration of waste management into the simultaneous stochastic optimization framework. Rimele et al. (2018) shift the focus of potentially hazardous material management by emphasizing direct in-pit dumping into mined-out areas during the operation, offering the potential for significant reductions in both environmental impact and haulage costs associated with waste materials. Their proposed stochastic integer programming (SIP) formulation aims to maximize the NPV of the mine and minimize deviations from production targets, while avoiding waste dumping that could result in part of the reserve being inaccessible in later periods. Levinson and Dimitrakopoulos (2019) also incorporate waste management considerations by constraining the waste dump capacity to reduce the overall footprint. Their study emphasizes the significant variability in material properties, which introduces uncertainty in the classification of PAG materials. The results from their case study demonstrate that orebody estimation methods substantially misrepresent the volume of PAG material in the deposit. Nevertheless, their work does not extend to the development or integration of mitigation strategies for the management of extracted PAG waste.

Subsequently, Levinson and Dimitrakopoulos (2024) integrate both waste management and progressive reclamation into a simultaneous and stochastic optimization framework, while considering handling strategies of the PAG material. In their approach, waste management is included in the simultaneous stochastic framework by considering decisions aimed at controlling waste placement to ensure the appropriate blending of NAG and PAG materials, thereby reducing the acid generation potential of dump cells. The proposed formulation combines ARD mitigation with progressive rehabilitation and reclamation strategies, including penalties over deviations from reclamation targets in the objective function. However, this framework has not been extended to other mitigation strategies, which only consider blending as source control measures and does not provide a solution for the management of ARD when different methods for prevention are applied, for example the encapsulation of PAG material.

This work presents an extension of the simultaneous stochastic optimization of mining complexes framework proposed by Goodfellow and Dimitrakopoulos (2017). The extended formulation overcomes the aforementioned limitations by integrating uncertainty in metal grades and the classification of potentially hazardous material, while simultaneously optimizing waste management and the production schedule, limiting the exposure of waste to weathering conditions through the use of yearly encapsulation, providing a reclamation plan, and integrating alternative source control measures, other than blending, to the simultaneous stochastic optimization framework.

2 Simultaneous stochastic optimization of mining complexes

The simultaneous stochastic optimization framework proposed by Goodfellow and Dimitrakopoulos (2016, 2017) is extended to integrate waste management and progressive reclamation. The extended formulation is a stochastic integer program that considers all components of the mine complex under a single formulation and the geological uncertainty related to metal grades and geochemical properties of the material that can be used for the prediction of acid generation.

The model describes the mining complex as a directed graph $G(N, A)$, where N represents the set of locations, which can be either sources or destinations, and A represents the set of arcs, defining the material flow between these locations. The set N can be partitioned into different subsets, including clusters of blocks C, processing destinations P, stockpiles S, waste facilities W, and other destinations D. Clusters are treated as sources and are defined as groupings of materials with similar attributes. For each mine and material type, a cluster's attribute boundaries are defined using a k-means algorithm utilizing the block's attribute data of all geological simulations considered. Since a mining block can have different attributes for different simulations, its cluster membership may vary between simulations. More specifically, the block membership to a cluster can be determined by pre-processed parameters $\theta_{b,c,s}$, which defines whether (1) or not (0) block $b \in \mathbb{B}_m$ belonging to mine m is a member of cluster $c \in C$ in scenario $s \in \mathbb{S}$. Processing destinations P are locations where materials are received, transformed, and sent to other destinations. Stockpiles S can receive materials from various sources or other locations and hold them until they are needed elsewhere. Waste facilities and other destinations can receive materials from multiple locations and track crucial data for the mine complex.

Simulated block attributes or material classifications are denoted by $\beta_{p,b,s}$, where $b \in \mathbb{B}_m$ is the block, $p \in \mathbb{P}$ the attribute, and $s \in \mathbb{S}$ the scenario. This notation can represent, for example, metal grades or classify blocks as PAG or NAG. In addition, relevant information about material properties in the different components of the mine complex can be divided into two types of attributes: primary attributes and hereditary attributes. Primary attributes are fundamental characteristics of interest that can be sent between two nodes in the mine complex in accordance with the set of arcs A and are linearly additive. In contrast, hereditary attributes denoted by $h \in H$ hold important information for the optimization model but are not necessarily passed from one location to another. Instead, they can be expressed as non-linear functions of the primary attributes. Therefore, the quantity of a primary attribute $p \in \mathbb{P}$ in a location i in period t and scenario s can be expressed as $v_{p,i,t,s}$ and can represent, for example, the material or metal content tonnage sent to a location in a given period and scenario. Similarly, $v_{h,i,t,s}$ can represent the metal recovery at a processing plant i in period t and scenario s calculated from the primary attributes of that location.

The behavior of the mine complex is completely described given three sets of decisions: extraction sequence decisions, destination policy decisions, and processing stream decisions. Given these decisions and the connections between locations modeled $G(N, A)$, it is possible to calculate $v_{p,i,t,s}$ and $v_{h,i,t,s}$, whichever might be the property, location, period, and scenario considered. Extraction sequence decision variables $x_{b,t} \in \{0, 1\}$ determine whether a mining block $b \in \mathbb{B}_m$ is extracted (1) or not (0) in period $t \in T$. Destination policy decision variables $z_{c,j,t} \in \{0, 1\}$ determine whether cluster c is sent to destination j in period t (1) or not (0). Finally, processing stream decisions $\gamma_{i,j,t,s}$ determines the proportion of material sent from location $i \in S \cup P$ to destination $j \in S \cup P \cup W \cup D$ in period $t \in T$ and scenario $s \in \mathbb{S}$.

Both extraction sequence and destination policy decisions are scenario independent. Therefore, these decisions impact all possible scenarios and must be made resilient to uncertainty in order to maximize the NPV and minimize deviations from environmental, operational, and other constraints relevant to the problem. On the other hand, processing stream decisions are allowed to vary according to the scenario and can adapt to uncertainty. It is understood that, once the material arrives at its initial destination, its properties are known, and the mine complex is able to adjust processing stream decisions accordingly.

2.1 Objective function

To evaluate the performance of the mining complex, an extension of the objective function presented in Goodfellow and Dimitrakopoulos (2016) is proposed and presented in Equation (1). Waste management and progressive encapsulation are integrated into the model through the use of encapsulation penalties. The objective function can be decomposed in three main components: the maximization of the NPV generated from the profit of marketable products, the minimization of deviations from production targets across the mining complex, and the management of ARD using progressive encapsulation.

$$\max \frac{1}{|S|} \sum_{i \in N \setminus C} \sum_{t \in T} \sum_{h \in H} \sum_{s \in \mathbb{S}} \underbrace{p_{h,i,t} v_{h,i,t,s}}_{\text{Discounted revenues and costs}} - \frac{1}{|S|} \sum_{i \in N \setminus C \cup W} \sum_{t \in T} \sum_{h \in H} \sum_{s \in \mathbb{S}} \underbrace{\left(c^{+}_{h,i,t} d^{+}_{h,i,t,s} + c^{-}_{h,i,t} d^{-}_{h,i,t,s}\right)}_{\text{Risk-discounted penalties for deviations}} - \frac{1}{|S|} \sum_{i \in W} \sum_{t \in T} \sum_{s \in \mathbb{S}} \underbrace{\left(ARD^{-}_{NAG\ required,i,t} NAG^{-}_{NAG\ required,i,t,s}\right)}_{\text{Encapsulation penalties}} \tag{1}$$

In the first component, relevant quantities related to revenues and expenditures incurred in the mine complex can be measured by hereditary attributes $v_{h,i,t,s}$. Their economic impact is appropriately accounted for by applying discounted values, given by $p_{h,i,t} = \frac{p_{h,i,1}}{(1+d)^t}$ where d is the economic discount rate. Deviation variables $d^{+}_{h,i,t,s}$ and $d^{-}_{h,i,t,s}$ quantify deviations from upper and lower limits, respectively, which are defined as production targets in the second term. These deviations are then penalized in the objective function thorough the use of penalty costs $c^{+}_{h,i,t}$ and $c^{-}_{h,i,t}$. Finally, in the third term, acid rock drainage prevention and progressive reclamation are included in the form of penalties for not having sufficient NAG material to properly accommodate PAG material in waste dump facilities designed for this end, in a certain period t, waste dump i, and scenario s. In the formulation, $NAG^{-}_{NAG\ required,i,t,s}$ represents the quantity of NAG material lacking to properly encapsulate the PAG material extracted in the same period t and scenario s. The penalty applied to each unit of missing NAG volume for appropriate encapsulation is denoted by $ARD^{-}_{NAG\ required,i,t}$.

The inclusion of the encapsulation penalties in the objective function guides the optimization toward creating more informed sequences of extraction and destination policies by accounting for: traditionally ignored long-term treatment costs involved in the rehabilitation of areas impacted by ARD, additional costs in managing PAG material, and the uncertainty involved in the prediction of acid generation. Consequently, material destinations are defined based on a more holistic evaluation of their value, and sequences are not determined exclusively by metal grades, but also by a measurement of environmental risk. This allows the management of PAG waste material, decreasing the chances of ARD formation and performing progressive encapsulation.

The priorities of the different targets set in the objective function are controlled by the magnitude of the cost parameters, which can be changed to adjust to the risk profile of the project. The discounting of these costs can be used to generate a balance between the extraction of valuable low risk material in earlier periods and the deferment of riskier materials to later periods when more information is available.

2.2 Constraints

Deviations from production targets can be measured using the constraints described by Equations (2) and (3). These deviations can be used to manage capacity constraints within the mining complex, such as those related to the processing plant, stockpile, and mining capacities.

$$v_{h,i,t,s} - d^{+}_{h,i,t,s} \leq U_{h,i,t} \qquad \forall h \in H, i \in N \setminus C, t \in T, s \in \mathbb{S} \tag{2}$$

$$v_{h,i,t,s} + d^-_{h,i,t,s} \geq L_{h,i,t} \qquad \forall h \in H, i \in N \backslash C, t \in T, s \in \mathbb{S} \qquad (3)$$

$$v_{NAG\,loose\,volume,w,t,s} + NAG^-_{NAG\,required,i,t,s} \geq v_{NAG\,loose\,volume\,required,w,t,s} \qquad \forall w \in W, t \in T, s \in \mathbb{S} \qquad (4)$$

Waste management considerations penalize for not encapsulating all the PAG material extracted in a certain period in a certain scenario. The quantity of NAG material required for the encapsulation of the PAG material depends on the waste dump design, as well as on the sequence of extraction and the destination policies applied, which are all defined simultaneously during the optimization. More specifically, the waste dump is divided into sections that must be fully encapsulated by the end of each period, with their size defined by the optimization process. To achieve this, decisions regarding the waste dump's form, number of lifts, and width of the encapsulation are made prior to optimization, while the task of determining the scale of the predefined shape is left as an output of the model. Given these parameters, quantities of PAG waste extracted are tracked and used to calculate the quantities of additional NAG waste that must be sent to the waste dump to ensure yearly encapsulation. These quantities of NAG can be zero in some periods for some scenarios indicating that enough NAG was sent for the encapsulation of the PAG in the waste dump facilities. But, in years where there is not enough NAG to encapsulate the PAG, the objective function is penalized in proportion to the quantity of NAG missing, as described in the third term of Equation (1). Equation (4) measures the deviation over the adaptive production target of NAG material in function of the quantity of the PAG sent to the waste dump. In the equation, $NAG^-_{NAG\,required,i,t,s}$ for a period t and scenario s is a function of the quantity of PAG waste sent to the waste dump facilities in the same period, the pre-defined waste dump design characteristics discussed earlier, and the quantity of NAG sent to the waste dump facilities in the same period and scenario.

The calculation of hereditary attributes, reserve and access constraints, mass conservation of downstream destinations, integrality, and other constraints included in the model are explained in detail in Goodfellow and Dimitrakopoulos (2016).

2.3 Solution method

The model for simultaneous stochastic optimization presented incorporates non-linear transformations to better describe the behavior of the mine complex, in this case providing a more accurate value for the products sold to the market and managing risk in the extraction of potentially hazardous materials. In addition to the non-linearities, the high number of decision variables, as well as the integration of geological uncertainty, render the problem impractical for the use of commercial solvers. Alternatively, the solution approach used is a combination of multi-neighborhood simulated annealing (Goodfellow and Dimitrakopoulos 2016) with adaptive neighborhood search (Yaakoubi and Dimitrakopoulos 2023). Adaptive neighborhood search guides the choice of heuristics during the optimization by collecting the previous performance information of the heuristics, predicting their future performance and biasing heuristic selection accordingly.

3 Application at a copper-gold mining complex

The simultaneous stochastic optimization model presented in the previous section is applied to a copper-gold mining complex, shown in Figure 1, which consists of three mines and two material types classified according to their potential for acid generation. PAG material can either be sent directly to the processing plant or to the waste dump, where it will be encapsulated in the same year it is extracted. NAG material, on the other hand, can be stockpiled for multiple periods, as it is assumed not to contribute to the generation of ARD, and can, therefore, be sent to the waste dump, stockpile, or processing plant. The model includes a dedicated NAG waste stockpile to ensure the availability of sufficient encapsulation material in years when NAG extraction is not enough for PAG waste management. The inclusion of the stockpile accounts for the possibility of the proportion of PAG material increasing as the mine progresses below the groundwater table. In this case, encapsulation of PAG material would be infeasible if it was not integrated in the production plan from the beginning. In addition, recovery curves are considered in the processing plant, allowing metal recoveries to vary according to the geological and metallurgical attributes of the material sent for processing.

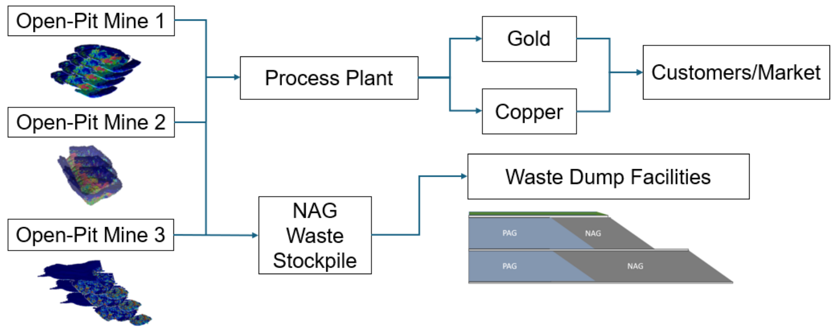

Figure 1: Mine complex with three open-pit mines, stockpile for NAG waste material, one processing plant and waste dump facilities designed for progressive encapsulation of PAG material.

Joint stochastic orebody simulations (Boucher and Dimitrakopoulos 2009) were used to quantify uncertainty and variability in copper and gold grades, as well as geochemical properties relevant to the classification of potentially acid-generating materials. More specifically, sulfur and calcium content were simulated to calculate acid potential (AP) and neutralization potential (NP). Sulfur grades are used to calculate the quantity of calcite required to neutralize all acid produced under the assumption that all sulfur is associated with pyrite, thereby providing a measure of AP. Similarly, calcium grades were used to approximate the quantities of carbonate minerals, which can be expressed in terms of calcite equivalence, to provide a measure of NP. These values are then used to compute the net producing ratio (NPR), defined as the ratio $NPR = \frac{NP}{AP}$, which serves as a criterion for classifying material such as PAG or NAG (Dold 2017). The threshold value for NPR used to distinguish PAG from NAG can vary depending on the environmental regulations, the methodologies used to calculate AP and NP, and the risk management strategy adopted by the mine (U.S. Environmental Protection Agency 1994). An NPR value of 1 indicates a balance between NP and AP, allowing for the classification of the material as NAG. However, neutralization reactions are pH-dependent, and acid generation may still occur at higher NPR values. For this reason, an $NPR = 2$ was adopted to classify material as PAG or NAG. Note that, since the classification of blocks as NAG or PAG varies across simulations, the optimization will control the production of PAG based on the availability of NAG and the potential rehandling costs associated with encapsulation, by prioritizing the mining of regions with a lower probability of encountering PAG material.

The waste dump design, combined with the extraction sequence and destination policy decisions, inform the model of the required quantities of NAG needed for the annual encapsulation of PAG. In this work, the waste dump design is predefined in terms of base layer thickness, number of lifts, cover layer thickness, horizontal encapsulation width, and overall dump geometry, in accordance with established guidelines for the construction of encapsulated waste dumps (Wetherelt and van der Wielen 2011; Williams 2012; Williams et al. 2006). The waste dump is subdivided into distinct sectors to be occupied progressively throughout the mine's life, with the size of each sector determined during the optimization process to accommodate the production of potentially acid-generating material.

3.1 Comparative case study

The optimization model presented in the previous section, which integrates waste management and progressive reclamation through encapsulation penalties, is applied to the copper-gold mine complex in Table 1 and will be, hereafter, referred to as integrated case. In parallel, the simultaneous stochastic optimization without waste management and reclamation is applied to the same mine complex, excluding a NAG waste stockpile, and will be referred to as base case. A comparative analysis of the base case and integrated case highlights the differences in key performance indicators and production planning decisions resulting from the inclusion of waste management and progressive reclamation considerations. Table 1 presents the economic parameters for the mine complex, followed by Table 2, which lists the penalty parameters applied during the optimization.

Table 1: Economic parameters

Parameter	Units	Value
Economic discount rate	%	10
Geological discount rate	%	10
Gold price	USD $/oz	2358
Copper price	USD $/lb	4.88
Stockpile rehandling cost	USD $/t stockpiled	0.84
Processing cost	USD $/t processed	9.24
G&A sustaining	USD $/t processed	3.61
Mining cost	USD $/t	2.30

Table 2: Penalties applied to deviations over constraints

Constraint	Unit	lower, upper bound	Penalty($/unit)
Mining capacity	Mt	−, 47	10
Processing capacity	Mt	−, 10	25
Stockpile capacity*	Mm^3	−, 3.7	10
Excess NAG*	Mm^3	0, −	10

* Not considered in the base case

− Non existing bound

Penalties constrain the optimization to ensure long-term plans that respect production targets and operational capacities. The relative magnitude of a penalty in relation to the other penalties defines if the associated production target has a higher or lower priority. Penalty values are controlled to create decisions that manage risk throughout the operation (Benndorf and Dimitrakopoulos 2013).

The mine complex consists of approximately 1.8 million blocks, each measuring 10×10×16 meters, distributed across three mines containing about 930,000, 455,000, and 500,000 blocks, respectively. A total of 10 orebody simulations were used to quantify uncertainty in metal grades and geochemical properties. Previous studies have shown that this number of simulations is sufficient to generate production schedules that are resilient to uncertainty (Albor Consuegra and Dimitrakopoulos 2009; Montiel and Dimitrakopoulos 2017). This is mainly due to the support-scale effect observed when relevant annual information of the mine complex is calculated based on the combined attributes of thousands of blocks making the problem less sensitive to variability of individual blocks.

3.2 Results

Figure 2a illustrates the effect of encapsulation constraints on mitigating ARD, with P10, P50, and P90 representing the 10th, 50th, and 90th percentiles, respectively. The figure shows the percentage of PAG production that can be encapsulated in the same period it is extracted, thereby avoiding exposure to weathering conditions during the mine's operational life. In the integrated case, almost all PAG material can be encapsulated in the same period it is mined throughout the entire life of the mine. In contrast, the base case shows three noticeable spikes in the percentage of encapsulated material in years 1, 6, and 10. Referring to Figure Figure 2d, this behavior appears to be associated with the extraction of large quantities of NAG during those years, possibly due to the mining of material located above the groundwater table, where most blocks are classified as NAG.

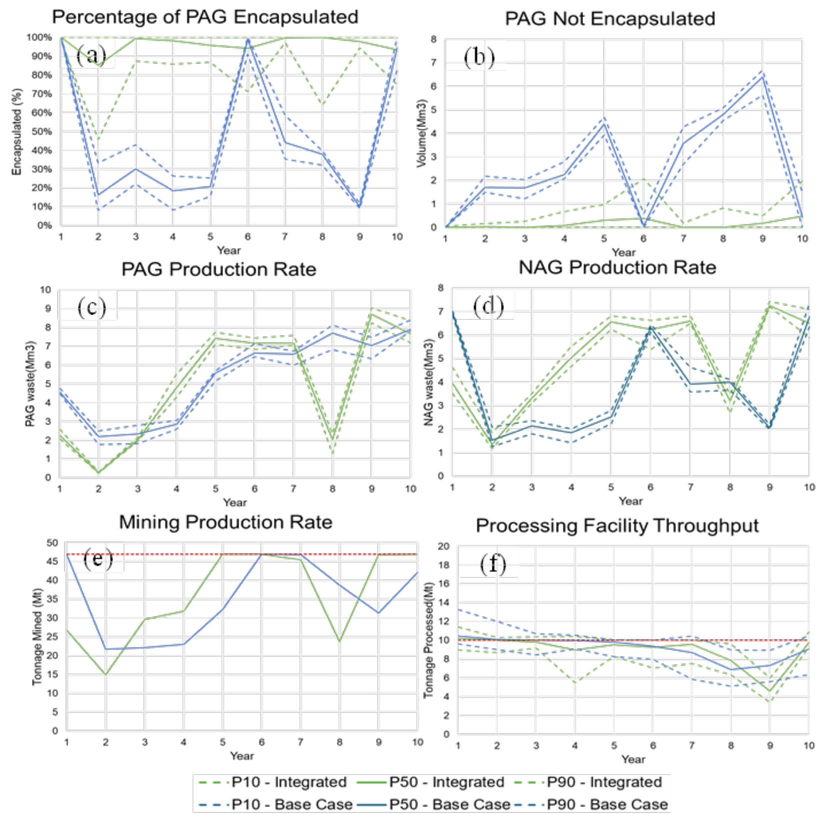

Figure 2: Results from the stochastic optimization in the integrated and base case (a) percentage of PAG encapsulated, (b) PAG not encapsulated, (c) PAG production rate, (d) NAG production rate, (e) Mining production rate, and (f) Processing facility throughput.

Figure 2b presents the quantity of PAG material not encapsulated in the same period of extraction in terms of cubic meters. When comparing Figure 2a and Figure 2b, it is observed that, even in years when a significant percentage of PAG was not encapsulated in the integrated case, this quantity is relatively small. An example of this is shown in the second year of operation under the integrated case, approximately 15% of PAG is not encapsulated at the P50 percentile; however, this percentage corresponds to approximately 0.08% of the total volume of PAG. Figure 2c and Figure 2d further clarify this behavior, showing that the NAG production of both cases are similar in the second year, however much less PAG material is extracted in the integrated case. This indicates that the integrated optimization framework effectively delays or avoids the extraction of potentially hazardous material when sufficient NAG is not available for encapsulation.

Figure 2c and Figure 2d show the risk profiles of the loose volume of PAG and NAG material extracted over the life of the mine. In all operating years, the extraction of PAG material in the integrated case is followed by the extraction of NAG material to minimize encapsulation penalties. This allows the operation to delay the mining of areas with high concentrations of NAG material to periods of increased PAG extraction, thereby avoiding the rehandling costs that would, otherwise, result from stockpiling NAG material in earlier periods. The base case, on the other hand, is not informed by the environmental costs associated with mining PAG materials. As a result, it fails to take advantage of encapsulation opportunities by not controlling the extraction sequence, which leads to the previously discussed spikes in Figure 2a and Figure 2b.

Figure 2e and Figure 2f demonstrate that the inclusion of encapsulation penalties did not significantly impact the overall mining production rate or the processing facility's throughput, thereby contributing to the financial performance of the integrated case, which will be discussed later. In total, the integrated case mined 2.4% more material than the base case, with this difference being mostly attributable to the greater quantity of NAG waste extracted. More specifically, the integrated case sent approximately 30% more NAG material to the waste dump and reduced the quantity of PAG material deposited in the dump by about 7.5%.

Figure 3a shows the risk profile of the volume of NAG material sent to the stockpile. The base case is not included in the figure, as the NAG waste stockpile was not considered in that scenario. The wider range of variation observed is attributed to the fact that downstream decisions are scenario-dependent and, therefore, adapt once uncertainty is revealed. Additionally, the stockpile was constrained to be emptied by the end of the mine life.

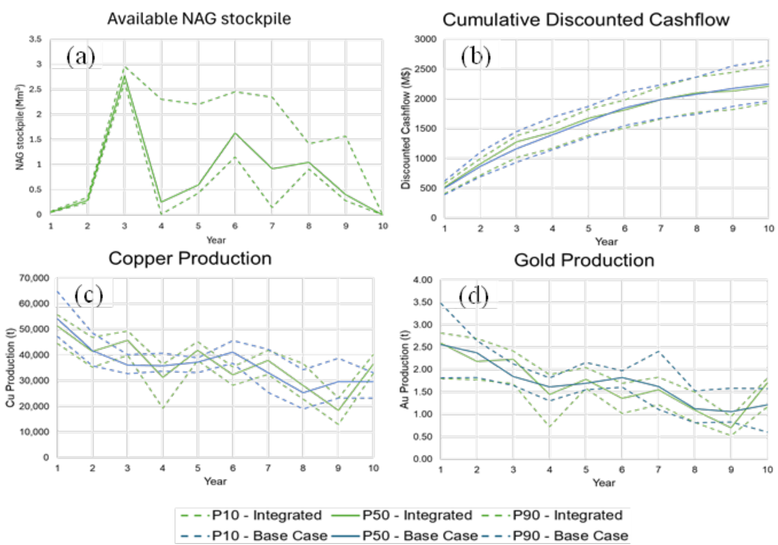

Figure 3: Results from the stochastic optimization in the integrated and base case (a) available NAG stockpile, (b) cumulative discounted cash flow, (c) copper production, (d) gold production.

As shown in Figure 3b, the rehandling costs associated with stockpiling NAG material for later use in the encapsulation of PAG material do not have a significant financial impact on the NPV of the mine complex. In fact, the NPV of the base case is approximately 1.6% higher than the NPV of the integrated case. However, the base case ignores the potential long-term environmental liabilities arising from the lack of ARD mitigations or prevention measures. As such, the NPV comparison may underestimate the long-term benefits of the integrated strategy. Similarly, the inclusion of yearly encapsulation constraints in the model does not appear to significantly affect the risk profiles of metal production. As shown in Figure 3c and Figure 3d, the risk profile curves for both the base case and the integrated case largely overlap throughout the mine life.

Lastly, Figure 4 shows a cross-section of the extraction sequence for both the integrated and base cases. As observed, the inclusion of waste management considerations in the model leads to distinct decisions regarding the extraction sequence. In other words, the mine plan resulting from the integration of waste management differs considerably from that of the base case, and ignoring these considerations can lead to significantly different operational decisions.

4 Conclusions

This paper presents an extension of the simultaneous stochastic optimization framework to integrate waste management and progressive reclamation through the use of yearly encapsulation. Unlike previous applications that incorporate encapsulation strategies (Fu et al. 2019; Li et al. 2013; Lin et al.

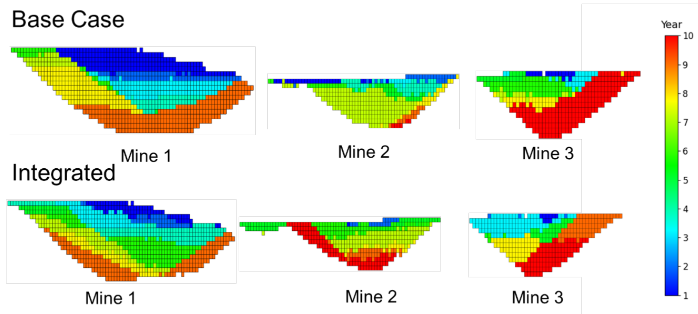

Figure 4: Comparison of the extraction sequences obtained in the base case and the integrated case.

2024b; Yu Li and Williams 2013), the proposed approach explicitly accounts for the progressive closure of waste dump covers throughout the mine's operational life, thereby minimizing the duration that PAG material remains exposed to weathering conditions. The performance of the proposed approach is explored in a case study at a copper-gold mine complex composed of three mines and around 1.8 million blocks in total. The mining complex is optimized simultaneously and accounts for geological uncertainties in metal grades and geochemical properties relevant for the classification of potentially acid generating materials. The effectiveness of the proposed model was compared with the case where no ARD mitigation measures were included. The results show that the integrated case was able to adapt extraction sequence, destination policy, and downstream decisions to accommodate the yearly encapsulation of almost all PAG material sent to the waste dump throughout the entire life of the mine, decreasing the risk of future liabilities. In addition, both the base case and integrated case presented a NPV difference of approximately 1.6%, showing that the proposed approach was able to manage the risk of acid generation without causing major financial differences, especially considering that no deduction was made in the NPV of the base case to handle the implementation of different mitigation strategies or treatment costs.

In this study quantities of PAG and NAG were controlled to ensure yearly encapsulation of potentially hazardous materials. However, this approach does not provide a dumping schedule that ensures encapsulation in the short term. Future research could focus on integrating long- and short-term planning to ensure an operational plan that is capable of performing a yearly encapsulation of PAG materials. In addition, the movement of waste can constitute a major source of cost and can have a significant effect on the financial performance of open pit operations. This could be explored in future studies by the simultaneous optimization of the production schedule and waste placement in order to effectively minimize haulage costs, while performing progressive encapsulation.

Disclosure statement

The authors report there are no competing interests to declare.

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