Strategic and tactical mine planning considering value chain performance for maximised profitability

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ABSTRACT

In the minerals industry, 'value' is the difference between the expected revenue derived from saleable minerals and the costs required to liberate them from gangue. In the early 1990s, it was found that the interconnected nature of mining and minerals processing provides an opportunity to unlock additional value by breaking from the established practice of silo-based cost minimisation to focusing on maximising profit across the value chain. The approach of 'Mine-to-Mill' was thus formalised as an operating strategy aiming to improve profitability through leveraging blast intensity for increased milling throughput. However, today the mining sector not only has to deal with more complex orebodies at lower grades, but there is also an accelerating need to develop sustainable capabilities and continuously upgrade its practice for addressing other challenges; of the intensified global demand for commodities, limited resources, market volatility and also new environmental and social regulations/responsibilities. Therefore, this level of sophistication necessitates innovative solutions for effective response to changed situations, hence setting real-time optimising strategies towards risk mitigation and value maximisation.

The constant challenge for any mining operation whichs to align strategic and tactical objectives. Strategic Mine Planning is a long-range production planning which aims at maximising the value from the exploitation of an ore deposit, while Tactical Mine Planning focuses on short-range plans to maintain operational viability. With recent advances in technology and data analytics, there is an opportunity to integrate key mining and processing stages. That is, integrating existing isolated mine production planning and optimisation strategies with the downstream KPIs, assessing performance through scenario-based simulations, and then dynamically re-optimising production plans for maximised profitability across the value chain over the mine lifespan.

This paper offers a methodological framework for integrating mine production planning and downstream process performance. A 'Holistic Model of Mine Optimisation' is conceptualised, which relies on GEOVIA's capabilities ranging from mineral resources modelling, design and planning to simulating process plants through evaluation of 'what-if' scenarios. A case was exemplified for a Cu-Ag-Ag deposit, and the potential impact of implementing Mine-to-Mill improvement strategies was quantified at a strategic level through simulating several scenarios. Improvement ranges of three key variables of mining rate, milling rate and Cu recovery were considered for analyses which were based on several reported Mine-to-Mill projects. The results implied the potential to improve the Net Present Value (NPV) by 15 per cent without deploying Capex only through maintaining Mine-to-Mill optimisation strategies. This approach offers sustainable solutions for unlocking the potential for improving the NPV over life-of-mine for green – and brownfield projects through practicing Mine-to-Mill basics, which essentially would assist with better decision-making by aligning optimisation objectives across the value chain. The developed approach is proposed, case examples presented, and implications discussed.

INTRODUCTION

From the early 1900s, mining and processing have been operated as separate silos. The former was focused on producing ore at a required rate and cut-off grade. The latter's objective was to process ore as provided by the upstream. However, the realities of mining and processing confirm a series of interconnected and sequential stages aiming at removal, transportation and size reduction of ores for liberating valuable minerals from the gangue. This interconnected nature of the minerals industry motivated a paradigm shift from silo-oriented optimisation strategies to value-based, integrated approaches. The new paradigm demands optimal contribution of each stage towards maximising overall value across the value chain rather than realising silos' distinct objectives – widely known as 'Mine-to-Mill' since the the early 1990s. Recognition of the importance of drill-and-blast as the first step in comminution, let to the approach aiming at manipulation of blast designs to produce more appropriate mill feed size distributions for improved grinding capacity. The Mine-to-Mill approach is now widely implemented in the mining industry across the globe, with documented productivity gains in the range of 5–20 per cent (Burger *et al*, 2006; Hart *et al*, 2001; Kanchibotla *et al*, 1999; Scott *et al*, 2002; Valery *et al*, 2019). From the mining perspective, drill-and-blast is an excavation method for exploiting an ore deposit rather than tailoring feed size distribution for increased milling throughput. The mining stage is mainly concerned with '*in time* extraction and transportation' of certain volumes of material within a time frame, which has to be executed in sequence following a 'mining plan'. The time frame defines the nature and hence key objectives of mine planning strategies, commonly known as 'Strategic' for long-range and 'Tactical' for short- and medium-range planning.

Today, the mining sector is confronting new challenges in dealing with more complex ore deposits at lower grades and the elaboration of social and environmental concerns, limiting the effectiveness of conventional strategies if not nullify. Therefore, the next generation of Mine-to-Mill should adapt the emerging techniques and technologies in field measurement, ore characterisation, data analytics, advanced control systems, ore pre-concentration, blending strategies, valourisation of low-grade dumps, waste management, modelling and simulation in a more sophisticated and inclusive manner. This offers new opportunities to further improve downstream gains by leveraging more variables and allows for effective integration of mining and processing stages. With this proviso in mind, application of Mine-to-Mill should not be limited to downstream gains, but also could be deterministic in Strategic and Tactical Mine Planning. That is, the development of stochastic analysis to quantify Mine-to-Mill impacts at strategic and tactical levels, which are deterministic in achieving economic and strategic targets of mining companies.

Optimisation is a continuous and data-driven endeavour for mining projects, which materialises when maximum profitability is achieved across the value chain. The measures for an optimised operation frequently change with an update of information on resource properties and market initiatives, which ultimately determine the expansion or contraction of mining projects. Therefore, in the presence of large uncertainties, integrated modelling solutions would accelerate the real-time alignment of upstream and downstream objectives more interactively. Simulation is an established approach for exploring the feasibility and impact of 'change(s)' on Key Performance Indicators (KPIs) through analysis of 'what if' scenarios. Scenario-based analysis has been widely used in mining and processing with exemplified applications in optimising upstream (Godoy, 2018; Morales *et al*, 2019; Poblete *et al*, 2016b; Rimélé *et al*, 2020; Smith *et al*, 2021) and downstream (Carrasco *et al*, 2016; Faramarzi *et al*, 2018, 2019; Grundstrom *et al*, 2001; Kanchibotla *et al*, 1999; Scott *et al*, 2002) KPIs. Accordingly, this study reviews several Mine-to-Mill case studies in the Asia Pacific region with the aim to establish linkages between KPIs of mining and processing disciplines at a strategic level and improve our understanding of their interdependence through analysis of scenarios. A few published works have highlighted the interdependence of mine planning and processing, but without quantifying the impacts on strategic and tactical measures. In this respect, a well-structured study was conducted at the Mount Isa lead-zinc to explore the flotation performance of ore sourced from key mining domains (Munro, 1986; Young *et al*, 1997). This resulted in adopting a pre-concentration strategy to reject some ore from the mine plan, which lowered the tonnage of ore being mined and processed. Moreover, Bye (2011) documented case studies mainly centred on spatially modelling and applying geo-metallurgical/geo-technical attributes and discussed potential benefits to mine planning and economic optimisation. He pointed out the significance of ore variability on mine valuation, production schedule and economic gains. In an example, Bye (2011) employed a geo-metallurgical model to gain further value from geo-metallurgical initiatives by incorporating them into block models to show the impact of ore variability on the mine plan and identified high-risk periods to optimise the mine schedule.

In this paper, we document proof of concept of an outcome-based solution developed at GEOVIA Dassault Systèmes, which expectedly assists the minerals industry with improved operational viability and sustainability. The proposed solution extends the application of conventional 'Mine-to-

Mill' to the mine planning space. A scenario-based example is developed in the context of Mine-to-Mill based on considered case studies, demonstrating the potential for unlocking additional value for the whole mine lifespan by using the most-trusted software package in Strategic Mine Planning GEOVIA Whittle™.

STRATEGIC VERSUS TACTICAL

In mine planning, Strategic and Tactical encapsulate objectives to be achieved at certain timespans over the life-of-mine (LOM).

Strategic Mine Planning aims at capturing maximum potential value from the exploitation of an ore deposit on an annual time scale, generally expressible in Net Present Value (NPV).

Tactical Mine Planning aims at ensuring viability and sustainability of the strategic planning at an operational level on monthly or even weekly scales. Therefore, it tracks and measures operational performance regarding its alignment with strategy, and corrective action is taken when required to minimise the gap between planned versus actual practice.

In the context of Mine-to-Mill optimisation, with extending its application to the realm of mine planning, we propose approaches as follows:

- Strategic Mine-to-Mill
- Tactical Mine-to-Mill

Strategic Mine-to-Mill aims at considering and quantifying potential gains from applying Mine-to-Mill optimisation strategies in long-term, for capturing maximum economic potential of ore reserves. The key objective would be to establish linkages between strategic KPIs of a mining project (eg NPV, IRR, and LOM) and performance improvement possibilities in the downstream. This level of integration allows for a more realistic assessment of overall value by harmonising upstream and downstream activities at a strategic level.

Tactical Mine-to-Mill centres on the realisation of Strategic Mine-to-Mill by implementing Mine-to-Mill optimisation strategies in a sustainable manner. In general, Tactical Mine-to-Mill applies conventional Mine-to-Mill strategies to maximise profitability across the value chain by improving process performance (eg throughput, target product size, recovery) and to ensure objectives of the Strategic Mine-to-Mill are fulfilled.

Overall, the conceptualised Strategic and Tactical Mine-to-Mill approaches aim to integrate key stages exploration, mining and processing and interrogate their interdependence through simulating 'what-if' scenarios. To further explain, achieving objectives of Strategic Mine-to-Mill depends on downstream gains and accounts for reliability the '*block model*' used for development of a strategic mine plan. Therefore, the extent of exploration activities, resource modelling and estimation and mine design considerations are respected. The representativeness of the block model improves during the LOM through continuous accumulation of orebody knowledge, which assists with fine-tuning adopted strategies for optimal outcomes. The Tactical Mine-to-Mill uses the block model for delivering short- and medium-range schedules. It engages drill-and-blast progress, haulage system, blending strategies, destination and flow of materials of different types. The Tactical Mine-to-Mill takes place at an operational level, not only accounts for blasting outcomes (ie muck pile fragmentation and ore loss/dilution) but also it engages timing and characteristics of material flow across the value chain – which should assist with *ore/waste tracking* most useful for ore feed quality and waste management.

WHERE ARE OPPORTUNITIES?

Mine-to-Mill optimisation is a well-established technique with a range of applications for improvement and optimisation of process performance. It effectively leverages the drill-and-blast practice to influence downstream stages' performance by implementing blast-induced changes to ore feed size distribution (Morrell and Valery, 2001), breakage, and physical properties (Michaux and Djordjevic, 2005). These then translate into changes in crushing and screening performance (Kojovic *et al*, 1995), AG/SAG mill throughput (Hart *et al*, 2001; Nielsen and Kristiansen, 1995), and flotation. Several examples are but are not limited to the influence of blast fragmentation on crushing and screening performance (Kojovic *et al*, 1995), and AG/SAG mill throughput (Dance, 2001; Michaux and Djordjevic, 2005; Morrell and Valery, 2001; Nielsen and Kristiansen, 1995) and flotation (Valery *et al*, 2019). However, as exemplified in this paper, the Strategic and Tactical Mine-to-Mill aims at real-time re-scale of mining and processing activities for optimal outcomes in response to large uncertainties introducible to most operations.

A more advanced Mine-to-Mill strategy should incorporate key processing parameters into the mine planning for improved '*productivity*' of the whole value chain (mineral reserve-to-metal) over LOM rather than boosted '*production*' (ie mill throughput) gains maximised value, ie NPV. This approach would further support the sustainability of green- and brownfield mining projects via operational leverages, as further explained below.

- Project risk mitigation options at strategic and tactical levels:

  To de-risk mining projects, it is necessary that the interaction between key stages across the value chain being captured in a quantitative manner. This allows for the short and long-term development of tailored strategies for scaling mining and processing activities which most reflects on orebody characteristics, hence mitigates 'unknown' risks associated with CAPEX and OPEX. Embedding Mine-to-Mill possibilities into Strategic and Tactical Mine Planning procedures is a dynamic approach which aims at estimating value over LOM in real-time, so corrective actions are taken when required for minimising the gap between planned versus actual practice or improvement strategies implemented when the opportunity is recognised.

- Improving sustainability at the operational level:

  As aforementioned, Strategic and Tactical Mine Planning leaves the door open to improvement opportunities which is critical to the sustainability of current and future mining operations. There is no limit to confronting challenges to the mining sector, which can limit the effectiveness of conventional strategies if not nullify. Strategic and Tactical Mine-to-Mill has to account for the integration of emerging technologies towards risk mitigation and value maximisation. As mining operations adapt the emerging techniques and technologies in practice, surveying and data analytics, automation and control systems in a more sophisticated manner; then the influence of such changes/improvements has to be reflected at a strategic and tactical level over LOM. That is, expressing value as a dynamic measure *'in practice'*, so it requires re-evaluation for best representing the economic status of a project.

- Harmonising upstream and downstream activities:

  The upstream activities are mainly concerned with removal of *in-situ* rock volumes in sequence, and then depending on transferring them to different destinations based on their value (ie grade/metal content). The key objective of downstream activities is to extract value from the material provided by the upstream, which may not necessarily result in maximum profitability. However, the question is:

  - What if, we tailor/scale the upstream activities eg planning, blasting, loading and haulage to provide the downstream with the material, which gains optimal *productivity* across the value chain?

  This obviously requires tuning conventional mine plans to account for new considerations and establish harmony between the mining and processing stages in short, medium and long-terms. It is important to note that the heterogeneous nature of orebodies introduces large uncertainties into all quantitative evaluations, design, and predictions (Faramarzi *et al*, 2020). The extent of the variability of ore changes across the value chain, and hence its impact. A better understanding of the flow of material of different types from the pit to the process plant should assist with better 'waste/ore tracking' for ore feed quality and variability management. More importantly, it helps quantify the impact of ore-induced operational variations (ie production bottlenecks or poor productivity) on the viability of mining projects in different timespans.

- Waste management and valourisation:

  Commodity price volatility is an ever-present and influential factor in decision-making at both strategic and tactical (or operational) levels, which ultimately determine expansion or contraction of mining projects. Strategic Mine-to-Mill might provide a better understanding of 'value volatility' over LOM. The development of stochastic analysis for price changes and accordingly estimating contingencies for difficult periods, or potential gains from the valourisation of 'low-grade' material. This area requires further investigation and development of robust techniques in future because appropriate management of waste/low-grade materials is critical to the sustainability of green- and brownfield mining projects.

MINE-TO-MILL CASE STUDIES IN ASIA PACIFIC REGION

Review of selected case studies

The Mine-to-Mill approach has been implemented at many mining operations worldwide, showing that the capacity and efficiency of crushing and grinding processes are significantly influenced by run-of-mine (ROM) size distribution, which is driven by the blasting. Through modelling and simulation, McKee *et al* (1995) indicated the potential for 20 per cent higher grinding capacity achievable by tailoring the blast-induced PSD. The practice has resulted in billions of dollars of additional value to the minerals industry since 1990s, mainly achieved through increased throughput. Many of these are documented, and operational improvements gained are reported. In this section, we review several Mine-to-Mill optimisation projects commissioned in the Asia Pacific region across gold, copper, lead and zinc commodities. Each project offers exclusive lessons to learn depending on their considerations and characteristics, providing a better understanding of possibilities if embedded in the mine planning context.

Case Study #1 – Cadia Hill Gold Mine, Australia

The Cadia Hill concentrator was commissioned in July 1998, aiming at processing 2065 t/h of monzonite ore, giving an annual processing rate of 17 Mtpa. Hart *et al* (2001) reported a range of strategies for SAG mill capacity debottlenecking and improving overall performance of Cadia Hill comminution circuit – one of which strategies was Mine-to-Mill optimisation. A reduction in SAG mill feed size F80 to 70 mm increased throughput between 10–15 per cent. Accordingly, the powder factor increased from the standard 0.8 to 1.2 kg/m^3 for improved fragmentation, which resulted in a 10 per cent higher throughput by improving the SAG feed rate from 2270 to 2505 t/h. More intense blasting by tightening the drill pattern (Burden × Spacing) produced more 'fines', visually evident during the trial and confirmed by lower pebble recycle rates. A finer PSD from intense blasting increased SAG mill power draw but resulted in overall lower specific power consumption.

Case Study #2 – Porgera Gold Mine, Papua New Guinea

Progeria Joint Venture and Dyno Nobel identified the SAG mill as a production bottleneck, in particular when milling hornblende diorite (Lam *et al*, 2001). The Mine-to-Mill project centred on optimising blast design for improving the milling rate by altering the feed size distribution. For this purpose, the blasting powder factor was increased from the standard 0.24 to 0.38 kg/t, which reduced SAG feed P50 from 75 to 35 mm. Thus, the finer feed boosted the SAG milling rate from 673 to 774 t/h, which equals a 15 per cent increase in SAG milling throughput.

Case Study #3 – Ernest Henry Copper-Gold Mine, Australia

The Ernest Henry Mine concentrator, commissioned in August 1997, with a nominal throughput rate of 1200 t/h. Strohmayr and Valery (2001) conducted an extensive optimisation program which included filed surveys, ore characterisation, blast fragmentation modelling, comminution modelling and simulations. In this Mine-to-Mill project, alternative blast designs in conjunction with a closer crusher gap (from 130 to 115 mm) improved SAG mill throughput. More intense blasting provided more favourable feed size distributions as the amount of fines (below 10 mm) in the feed increased from 18.6 per cent (standard blast practice) to 21.4 per cent in blast designs with higher powder factors. The study confirmed the potential to increase mill throughput to 12 per cent by altering the blast designs and primary crusher gap (Strohmayr and Valery, 2001).

Case Study #4 – KC Gold Mine, Australia

The KC Gold Mine (KCGM) treats ore from the Super Pit at Kalgoorlie. Kanchibotla *et al* (1998) explored the interdependence between fragmentation size distribution from blasting and SAG mill throughput. Standard blast design with powder factor of 0.58 kg/m^3 compared to modified designs with powder factors of 0.66 (Design 1) and 0.96 kg/m^3 (Design 2). The simulations indicated that the SAG mill feed rate of 1250 t/h from standard blasting could be improved up to 1480 t/h, which equals 18.4 per cent higher milling capacity. This study argued possible pitfalls of intense blasting from the dilution viewpoint and more importantly highlighted the need for the energy balance between the SAG and ball milling circuits as well as loss of recovery for a changed final grind size.

Case Study #5 – Batu Hijau Copper-Gold Mine, Indonesia

The key objective of commencing Mine-to-Mill at the Batu Hijau Copper-Gold operation was to modify blasts for improved SAG mill throughput (Burger *et al*, 2006; McCaffery, 2006). For different zones of the orebody, regression models were developed to predict throughput separately for 16 domains. In addition to grinding capacity, it was recognised that a domain-based blasting strategy should also improve loading rates through fragmentation top size reduction. Between 2006 and 2011, extensive orebody characterisation allowed for improvement of blasting and mill throughput predictive models and coding mill throughput predictive equations into the mine block model, which was used for short and long-term production planning based on mill throughput prediction to ±2.0 per cent accuracy.

Productivity gains of 10 per cent for loading rates in the pit and 10–15 per cent increases in SAG mill throughput for individual ore domains were reported. The Sandsloot mine is another example where a modified blasting strategy was deployed for improving operational performance (Bye, 2006). Loading rate and milling performance were monitored at this mine between 2001 and 2003, which demonstrated a significant impact of powder factor on these KPIs by 18 per cent improvement in average milling rate, and 13 per cent increase in average instantaneous load rate (ore and waste).

Case Study #6 – Mount Isa Lead and Zinc Mine, Australia

The case study of Mount Isa Lead and Zinc Mine demonstrates benefits from applying integrated mining and processing strategies in a different space through cut-off grade control for improved flotation performance (Young *et al*, 1997). It was noticed that determination of ore cut-off grade without accounting for flotation performance of ore from different sources in the mine results in poor prediction. Recognising the interconnected nature of mining stages, a new strategy was adopted to establish the link between head grades of each ore type, concentrate grades, recovery as well as capital and operating costs for each mined ore resource. Because of alignment of the mining practice with downstream objectives, 30 per cent of the 'low-value' ore was removed from the mine schedule, which reduced operating costs, while improved recovery of silver, lead and zinc by 5.0 per cent, 5.0 per cent and 2.0 per cent, respectively.

Implications from the case studies

Numerous Mine-to-Mill case studies at mining operations across the globe provide a reliable base from which to integrate and harmonise the upstream and downstream stages for maximised controllability and, therefore value. The literature does not reflect long-term outcomes of implementing Mine-to-Mill at the operations – if the changes were sustained for a while. However, the authors believe that Mine-to-Mill strategies determined at a specific time frame, need continuous re-visit because of the thin line between profit and loss in mining industry.

The review of selected case studies commissioned in the Asia Pacific region, provides a base for the proof of concept by indicating improvement potentials. The conventional Mine-to-Mill studies imply the potential to improve milling capacity by 20 per cent (from intense blasting), productivity gains of 10 per cent for loading rates in the pit (from intense blasting) and metal recovery up to 5 per cent (from ore feed quality management). These values vary by site; however, in this paper, we use the values to quantify the impact of such improvements over LOM at strategic and tactical levels. The authors acknowledge that there are other improving techniques such as coarse flotation and Grade Engineering®, application of novel explosives etc, which can significantly enhance profitability and sustainability of mining operations. In this paper, we mainly focused on conventional

Mine-to-Mill leverages; however, there is no limit for applying other technologies to improve the overall practice, all of which are well-settled within the Mine-to-Mill optimisation context developed in the early 1990s.

METHODOLOGY

The Strategic Mine-to-Mill optimisation comprises several strategic steps required for unlocking maximum potential economic gains from an ore reserve. The term 'strategic' in this concept aims at aligning the steps with the strategic objectives of the project (Figure 1).

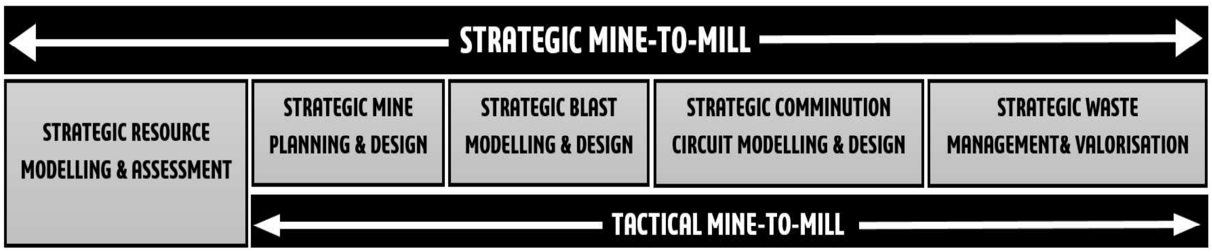


FIG 1 – Strategic Mine-to-Mill and involved stages.

Key requirements of applying any Mine-to-Mill optimisation are as follows:

- Data acquisition across the value chain:

  Data collection, curation, analysis, and interpretation are important parts of any quantitative evaluation, and Mine-to-Mill has been no exception. For the diverse nature of mining stages in practice, a wide range of information has to be analysed in order to quantify the interaction between them, which also necessitates effective communication between people of different disciplines/specialisations across the value chain.

- Access to reliable software packages for modelling and evaluation:

  There are numerous technologies available in the industry ranging from simple to sophisticated, which assist specialists in their everyday decision-makings. GEOVIA Dassault Systèmes software capabilities (with over 17 000 active users) covers geology modelling, resource estimation and mine design (GEOVIA Surpac™), Strategic Mine Planning (GEOVIA Whittle™), Tactical Mine Planning and scheduling (GEOVIA MineSched™). For simulation purposes, simulation process automation and design optimisation solutions (SIMULIA and CATIA Products) provide a reliable base for integrating and optimising all mining stages through the development of 'what-if' scenarios. In blasting and processing fields, the JKSimBlast® and JKSimMet® software packages developed by Julius Kruttschnitt Mineral Research Centre, The University of Queensland, are among the most widely-used products in the field, which have been used for decades in Mine-to-Mill projects worldwide. It is evident that applying Mine-to-Mill at strategic and tactical levels requires suitable tools and technologies critical to each stage. In this paper, an outcome-based solution is proposed based on some of the most industry-trusted software packages available in the minerals industry. Today with the fast progress of technology in computation, measurement, data analytics and simulation areas, it is expected that more sophisticated technologies are being developed for modelling, simulating and controlling all stages of ore resource exploitation on platforms in a real-time manner.

Data requirement

To develop a holistic model of a mining operation, representative data has to be collected sufficiently across the value chain. Availability and representativeness of data is critical to modelling and process design. A detailed data-related discussion is beyond the scope of this paper, and could be found elsewhere (Hustrulid and Kuchta, 1995; Napier-Munn, 2014; Napier-Munn *et al*, 1996). However, the nature of data requirements is briefly addressed here. In general, the data required for Strategic Mine-to-Mill can be categorised depending on its applicability:

- *The data required for Strategic Resource Modelling and Assessment*:

  Resource estimations underpin multi-million-dollar investment decisions made by mining companies, strategic decisions along with financial, social and environmental considerations. Geological databases acquired from drill holes are the most common set of data used for Strategic Resource Modelling and Assessment. The information from drill holes describes the location of the drill hole collar, the maximum depth of the hole and whether a linear or curved hole trace will be calculated when retrieving the hole. This information combined with data acquired from topographic surveys and characterisation test works conducted on retrieved cores (eg assays, geological, geotechnical and chemical properties of deposit at different subsurface spatial coordinates) are used to describe an orebody. An outcome of this stage is a block model, which describes orebodies properties, eg shape, volume and characteristics through size cubes or cuboids. A block model is critical to all quantitative evaluations in most mining operations, where upstream and downstream data such as mining, blasting and metallurgical data can be coded into it to describe impact of mined blocks on operational performances. GEOVIA Surpac™ is one of the world's most popular software, supporting open pit and underground operations and exploration projects.

- *The data required for Strategic Mine Planning and Design*:

  The resource block model is the data library, which is used for mine planning and design at strategic and tactical levels. A wide-range of information is utilised at this stage, which covers topographic surveys, rock mass and ore geological, mechanical, metallurgical characterisations, mining and processing capacity, elements prices, and costs imposed across the value chain over LOM.

- *The data required for Strategic Blast Modelling and Design*:

  The essential task to break rock down into a specific size fraction starts at the very beginning by drilling and blasting operations and continues by subjecting ore to a series of breakage processes through comminution machines. This proceeds to the point where particles meet appropriate size criteria for being treated in a beneficiation process. Strategic Blast Modelling and Design aims at optimal overall productivity, which is reachable if design criteria are aligned with a project's strategic objectives. The key data required for this practice could be described as pre-blast and post-blast. Key pre-blast information required is rock mass properties, explosives properties, operational and safety considerations. Post-blast data are but not limited to fragmentation size distribution, backbreak, ground vibration, noise, flyrock, movement and ore dilution, dust and Nox emissions.

- *The data required for Strategic Comminution Circuit Modelling and Design*:

  To model a process plant is to configure a flow sheet, which illustrates units and their interaction. An initiative of a flow sheet is to model the state of the process. Irrespective of simulation structures, to develop a 'base-case' model, consistent data has to be collected sufficiently, which can be sourced from site and plant surveys, laboratory experiments, value chain instrumentation, technical reports etc. Today, some industry-trusted examples of simulating packages are JKSimMet® (Morrison and Richardson, 2002), MODSIM (King, 1990), SysCAD (Stepto *et al*, 1990) and MolyCop Tools (Silva *et al*, 2015) with a range of useable unit models incorporated in them. Reliable comminution circuit modelling and design is a strategic step towards harmonising upstream and downstream activities and is critical to project economics. The data should be sourced from plant surveys; nonetheless, an alternative might be considering the operational history of the plant, namely 'historic or operational data'. Common data is a requirement of this stage but not limited to the units/equipment design and operational characteristics, ore properties (eg A, b, ta, SPI, BWi, density, grade, mineralogy), flow characteristics through streams (eg mass flow, percent solids, size distributions), operational considerations (eg power draws, mill fractional speed, screen sizes, hydrocylones pressure, target size), and KPIs (eg throughput, recovery).

- *The data required for Strategic Waste Management and Valourisation*:

  Developing a plan for managing current and future waste/low-grade material should be part of any strategic decision-making. In addition to ore physical, mechanical, metallurgical and chemical properties, it would be worth creating a data set including the location of dumped materials of different kinds by deploying GPS-based and survey techniques, or even track of material by implanting RFIDs. Such information should assist with generating new block models of waste dumps for future modelling and assessment practices.

- *The data required for continuously improving accuracy and precision of strategic stages*:

  Finally models of mining and processing activities developed based on operational data represent a narrow time frame and will lose their fidelity over time due to frequent variations introducible within a mine life cycle. The fidelity of a model can be assessed by comparing the degree of agreement between actual and predicted values where an error is given as a quantitative measure of the discrepancy. For the models representing operational stages a 'mean absolute error' within ±10 per cent is desirable. As a measure of precision, the Relative Error (RE) expresses magnitude of error relative to the measured/actual value, which reads:

$$Relative\ Error(\%) = 100 \times \frac{(Measured\ Value - Predicted\ Value)}{Measured\ Value} \quad (1)$$

  Upon collecting more descriptive data by integrating and using more accurate measurement systems and sensors into mining and processing stages, a more detailed description of an orebody can be generated. This should assist decision-makers with considering unseen aspects of their plans, refine, improve or even re-define their strategic and tactical objectives.

It is important to note that not all the information collected is useful. The key objective of data curation and analysis is preparing 'relevant' and 'reliable' data. For this purpose, useful data should be discriminated from the redundant and presented in an appropriate number, format, size and units. In this process, it is also important to account for misinformation as well as disinformation. The former considers vital data missed or unavailable, and the latter refers to 'unexpected' information, ie unreliable instrument readouts. Analysis of data is an essential step, which also engages technical and analytical knowledge of individuals, eg engineers, data analytics specialists. This includes running several basic tests to ensure 'consistency' of the data by establishing relevant correlations between different values eg ore properties and KPIs. Additionally, when developing a base-case model, specifically a 'process plant' if using a software package eg JKSimMet®, it is vital to check if the data available aligns with the unit models requirements. For example, the common breakage test in most South American operations is SAG Power Index, namely SPI (Starkey *et al*, 1994), however, this index is not useable in the JKMRC AG/SAG mill model (Morrell and Morrison, 1989) as the model requires A, b (ore competence indices) and ta (ore abrasion index) values from the JK Drop Weight Test (JKDWT) (Napier-Munn *et al*, 1996). Therefore, relevant test works should be conducted, or the values should be estimated based on available indices using established correlations. As these breakage tests are extensively used, it has been a common practice for metallurgists developing correlations between the SPI and JKDWT breakage indices.

In summary, because of the very diverse nature of data generated across the mining value chain, data preparation for modelling such activities would engage multiple disciplines of geologists, geotechnical, exploration specialists, mining, blasting and process engineers, and well as data scientists. Within the context of mine planning, Couzens (1979) advised that it is 'vital to keep our objectives clearly defined while realising that we are dealing with estimates of grade, projections of geology, and guesses about economics – *we must be open to change and communicate'*.

Software packages

Strategic resource modelling, assessment and mine design – GEOVIA Surpac™

The software supports to open pit and underground operations and exploration projects in more than 120 countries. Key capabilities of GEOVIA Surpac™ are drill hole data management, geological and block modelling, resource estimation; geo-statistics, drill-and-blast and mine design.

Strategic mine planning – GEOVIA Whittle™

The software is used to evaluate the financial viability and the optimal open pit mining strategy for a deposit. It is a commercially trusted tool applied in scoping, feasibility, life-of-mine scheduling, and ongoing re-evaluation of mine plans throughout the production phase. GEOVIA Whittle™ aims at optimal scenarios through provides the capability to consider key mining, processing, geological, geotechnical and financial considerations into any analysis at an annual timescale over LOM.

Tactical mine planning – GEOVIA MineSched™

The software provides scheduling to improve productivity for surface and underground mines of all sizes and types. GEOVIA MineSched™ aims at realisation of a strategic mine plan by taking into account operational details at monthly and weekly timescales over LOM. Tactical Mine Planning is the chain loop that facilitates harmonising the upstream and downstream stages through integration. The tool provides seamless capabilities in short- and medium-term mine scheduling by accounting for the strategic mine plan considerations, grade control, blasting sequence, haulage system, mining and processing capacities, and tracking different types of materials. It allows for the development of constraint-based scenario analysis to reach optimal and feasible alternatives, which de-risk realisation of strategic objectives.

Blasting and mineral processing – JKSimBlast®, JKSimMet® and MolyCop Tools®

JKSimBlast® is a user-friendly tool for drill-and-blast design and predicting muck pile PSD based on blast fragmentation models such as the original Kuz-Ram (Cunningham, 2005) and Crushed Zone Model (CZM). It is proven that the Kuz-Ram model underestimates the amount of fines (-25 mm) in the ROM PSD (Comeau, 2018), which significantly affects the downstream processes of crushing, grinding and flotation. Therefore, the CZM developed by JKMRC is a suitable alternative when estimating the contribution of smaller size fractions is of prime importance, specifically for Mine-to-Mill optimisation purposes because the model provides a more realistic estimation of blast-induced fines (Kanchibotla *et al*, 1999). In mineral processing, software packages such as eg JKSimMet® and MolyCop Tools® might be used for developing reliable base-case flow sheets of process plant. For example, JKSimMet® is software for comminution circuit mass balancing, modelling and simulating, which benefits from a wide range of validated comminution and separation models developed by the JKMRC (Napier-Munn *et al*, 1996).

Design of experiment

Design of experiments consists of carrying out a set of tests that allow the generation of results, which, when analysed, provide objective evidence to study the behaviour of a process, in this case Mine-to-Mill optimisation process.

The objective is quantify and analyse the influence of applying Mine-to-Mill optimisation at strategic and tactical levels – so it centres on overall value maximisation, ie Net Present Value, 'NPV'. The Net present value is the present value of the cash flows at the required rate of return of a project compared to your initial investment. In other words, it considers the 'Time Value of Money' in the assessment of an investment opportunity. Thus, near future cash flows are worth more today than distant future cash flows. The equation for NPV reads as follows (Fisher, 1930):

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+k)^t} - C \tag{2}$$

Where C is initial capital investment, R is cash flow per period, k is the discount rate and t represents time. Another economic indicator is the Internal Rate of Return, 'IRR' which is used in financial analysis to estimate the profitability of the potential investment. IRR is a discount rate that makes the NPV of all cash flows equal to zero in a discounted cash flow analysis. In general, the higher IRR is, the more desirable an investment is to make.

In this paper, we propose an example based on implications from conventional Mine-to-Mill projects, which demonstrates the potential application of the GEOVIA Surpac™, Whittle™ and MineSched™ in the implementation of 'Strategic Mine-to-Mill' and 'Tactical Mine-to-Mill' approaches, which are conceptualised at GEOVIA Dassault Systèmes in 2021, and introduced in this paper.

The considerations and assumptions of this study are:

- The JKSimBlast® and JKSimMet® software packages are not used for the modelling nor for the analyses given in this paper. However, base-case models of downstream processes are critical for linking and harmonising the upstream and downstream activities in an interactive manner. That is, GEOVIA Whittle™ (Strategic Mine Planning software package) is fed by downstream KPIs generated from a base-case model of a process plant, which assists with integrating the upstream and downstream KPIs, and quantify their interactions.

- This study does not consider ore loss and dilution in value quantification. However, intense blasting generally limits control over the outcomes. It increases the risk of undesirable side effects such as backbreak, ground vibration, air-blast and flyrock, and dilution, which imposes additional expenses for taking appropriate mitigation measures and control strategies. However, ore dilution is the phenomenon, which may result in a remarkable loss of value as reported before (Engmann *et al*, 2013; Esen *et al*, 2007; Eshun and Dzigbordi, 2016). It can directly affect the overall value through ore loss and disposal of waste or less valuable material to the mill. In this space, blast movement modelling and monitoring systems assist with tuning blast design parameters (ie timing, pattern, explosives properties and distribution of blast energy etc) for reduced ore loss.
- Review of several implemented Mine-to-Mill projects in Asia Pacific region implies performance improvement opportunity of up to 20 per cent in milling capacity, 10 per cent in loading rate, and 5.0 per cent in recovery. The values are used to quantitatively taking into account impact of such Mine-to-Mill induced results on strategic and tactical mine plans. Accordingly, What if scenarios will be considered in ±20 per cent, ±10 per cent and ±5 per cent for milling rate, mining rate and recovery, respectively.
- Pre-concentration in mining aims to manipulate ore feed quality by removing low value gangue material prior to the comminution process. Pre-concentration requires a suite of well-established techniques and technologies being utilised to exploit differences in physical and chemical properties of an ore to separate valuable minerals from gangue. Thus, depending on ore characteristics, a technique based on size, gravity, conductivity, competence, magnetic susceptibility, thermal reactivity etc, can assist with feed upgrade prior to energy-intensive size reduction stages – and should be used as an optimising leverage for next generation Mine-to-Mill projects. GEOVIA Whittle™ allows for grade control (improving ore feed quality) for both the pit and process plant. Accordingly, the impact of adopting an ore pre-concentration strategy on the strategic outcomes is quantified, and discussed.
- Metal (copper, gold and silver) price and selling costs are assumed constant over LOM.
- In this paper, a constant financial model is used for estimating mining and processing costs. Because of confidentiality considerations, details of financial models used cannot be shared. However, it is worth noting that implementing Mine-to-Mill practices generally results in more than doubled drill-and-blast costs, while saving money by improving loading and haulage efficiency and even safety. On the processing side, an intense blasting practice potentially could reduce the cost of processing for a given ore type by reducing the process time. To reflect such changes in cash flow across the value chain, it is required to develop *sophisticated financial models* by tracking changes over a significant timespan, which is an area of future investigation in Strategic Mine-to-Mill planning and optimisation.

Base-case development

A block model of copper-gold-silver deposit with two dominant rock types is used for developing a base-case model for quantifying the impact of downstream changes on overall value, NPV. For this purpose, GEOVIA Whittle™ was used to integrate mining throughput with downstream KPIs of mill throughput and recovery, which are the focus of this paper. It is also worth highlighting that this study specifically deals with mining production rate, process throughput and recovery as the three key KPIs that were frequently considered in previous Mine-to-Mill projects. However, these KPIs are significantly determined by geology, mineralogy and geo-mechanical properties of orebodies and quantifying the impact of such variables on mine plans is beyond the scope of this article. It is worth adding that it benefits from the 'Throughput Factor' as a useful leverage to account for the milling rate of different rock types (influenced by ore competence and feed PSD), which makes it most appropriate for Mine-to-Mill investigations. Operational constraints/considerations can be set to account for likely bottlenecks between mining and processing for any given period. Furthermore, GEOVIA Whittle™ allows for accounting variable values for different times for any given input eg mining and milling rates, recovery, financial variables and grade targets as business objectives and hence adopted strategies may require refining changes over time (See Figure 2).

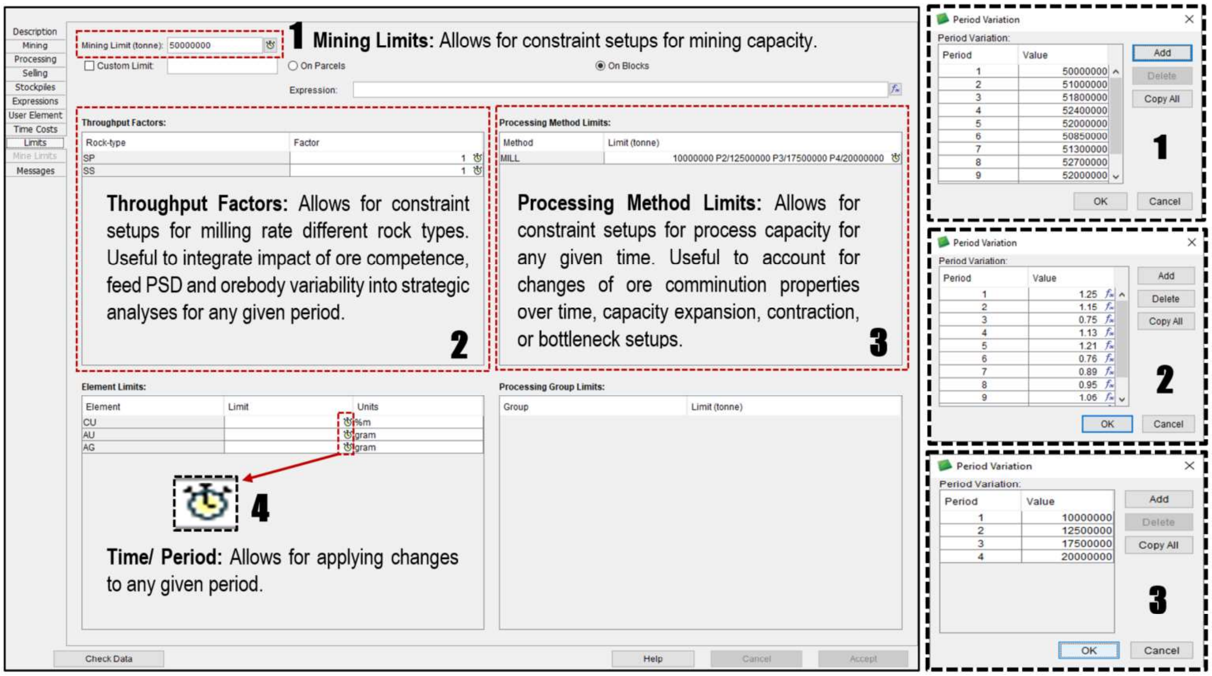


FIG 2 – Mining and processing constraints set-up interface – GEOVIA Whittle™.

The optimal pushbacks were selected through the 'directional mining' approach, which evaluates profitability through testing several mining starting points. That is, depending on orebody shape and distribution of grade within it, adopting an appropriate starting point will impact NPV as it controls 'metal yield' from any part of an orebody over time. Poblete (2016a) comprehensively describe the approach, and then estimated its influence on NPV.

In this study, we tested directions of North (0°), North-east (45°), East (90°), South-east (135°), South (180°), South-west (225°), West (270°) and North-west (315°), out of which the 'East' alternative resulted into the best outcome compared to the others.

The 3D Lerchs-Grossmann algorithm is used for pit optimisation, which accounts for block values, mining precedence and is capable of fining 3D outline with the highest possible value. For the Scheduling practice, GEOVIA Whittle™ benefits from Milawa algorithm, which combines feasible schedules into careful economic forecasting for improved NPV. Details on Lerchs-Grossmann and Milawa algorithms are beyond this paper's scope and is comprehended elsewhere (Lerchs, 1965). Figure 3 showing mining directional and phases (pushbacks) optimised for Cu-Au-Ag deposit.

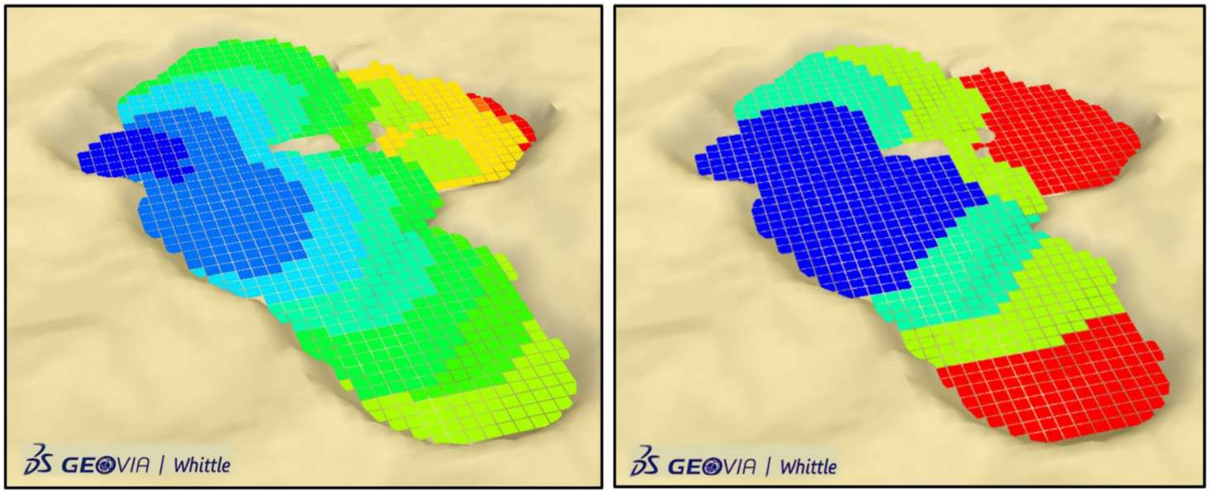


FIG 3 – Pit expansion towards East using directional mining approach (Left) and the four optimal mining phase (pushbacks) selected for scheduling purposes (right) – GEOVIA Whittle™

The pushbacks should satisfy mining and processing constraints, and produce the highest NPV from moving volumes of earth in sequence. Figure 4 shows the base-case schedule which illustrates the amount of material of different type and their destination over 17 years of mine life. Failure to provide enough ore feed results in decreased profitability, therefore strategies like having stockpiles for compensating ore feed shortage for difficult periods are helpful to maintain productivity over LOM and ensure production balance between the upstream and downstream stages.

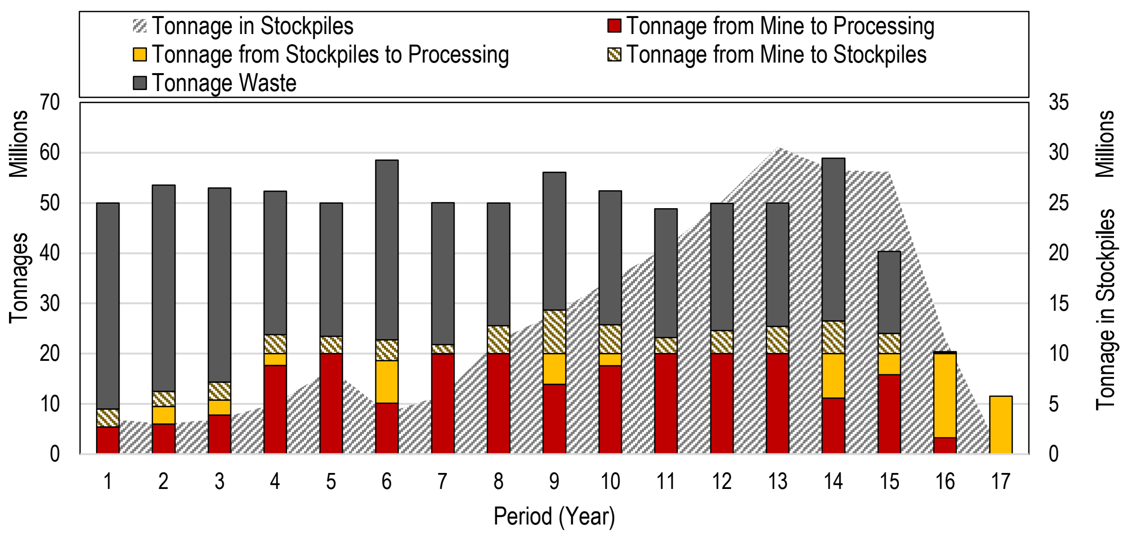


FIG 4 – Strategic scheduling: material movement over LOM, Base-Case

Figure 5 shows the scheduling for tonnage removal from each pushback. Obviously, in the 17th year of LOM, removed tonnages from the pit is zero, indicating that the ore reserve is fully exploited. The ore feed required by the process in the last two years of LOM (years 16th and 17th) is provided by the stockpiles.

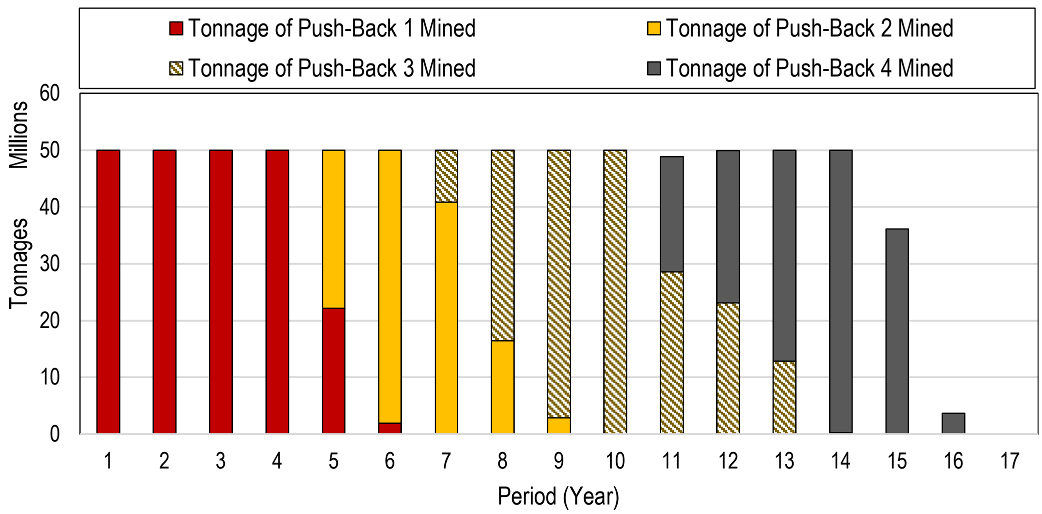


FIG 5 – Strategic scheduling: tonnage of pushbacks mined over LOM, Base-Case.

Scenario-based simulations

Three key areas of improvement by adopting a Mine-to-Mill approach are mining rate, milling rate and recovery. Based on documented values from reviewed case studies, the variation of values by 10 per cent, 20 per cent and 5 per cent were considered improvement opportunities compared to the base case. However, a poor drill-and-blast practice can be deleterious and limit value. Therefore, sensitivity analysis of individual key variables (26 scenarios) and combinations of them (8 scenarios) were conducted in the context of Mine-to-Mill.

Table 1 provides further details on development of scenario-based simulation runs for sensitivity analysis of individual key variables by using GEOVIA Whittle™.

TABLE 1

Ranges and levels of key variables used in GEOVIA Whittle™ (26 scenarios).

Description	Variation	Scenarios	Unit	Minimum	Base-case	Maximum
Mining Capacity/Rate	± 10.0% @ 2.5% Levels	8	t/h	5137	5708	6279
			t/d	123 288	136 986	150 685
Milling Capacity/Rate	± 20.0% @ 5.0% Levels	8	t/h	1826	2283	2740
			t/d	43 836	54 795	65 753
Cu Recovery	± 5.0% @ 1.0% Levels	10	%	78	83	88

Four scenarios were considered for evaluating potential losses and gains from optimising key variables of mining and milling rates as well as recovery in a Mine-to-Mill context:

- Scenario 27: Mining Rate = -10%, Milling Rate = -20%, Cu Recovery = -5%
- Scenario 28: Mining Rate = -5%, Milling Rate = -10%, Cu Recovery = -2.5%
- Scenario 29: Mining Rate = +5%, Milling Rate = +10%, Cu Recovery = +2.5%
- Scenario 30: Mining Rate = +10%, Milling Rate = +20%, Cu Recovery = +5%

Four additional scenarios were assessed with only accounting for the mining and milling rates, and assuming Cu recovery is constant:

- Scenario 31: Mining Rate = -10%, Milling Rate = -20%, Cu Recovery = 0.0%
- Scenario 32: Mining Rate = -5%, Milling Rate = -10%, Cu Recovery = 0.0%

- Scenario 33: Mining Rate = +5%, Milling Rate = +10%, Cu Recovery = 0.0%
- Scenario 34: Mining Rate = +10%, Milling Rate = +20%, Cu Recovery = 0.0%

RESULTS, ANALYSIS AND DISCUSSION

Three areas of potential gain from implementing changes in drill-and-blast practice were studied and their impact on NPV was quantified by simulating several scenarios using the Strategic Mine Planning and Optimisation software package, GEOVIA Whittle™. Accordingly, generated variations in overall value were recorded. This provides a quantitative figure of potential gains from Strategic Mine-to-Mill under several operational conditions, and how upstream and downstream processes may interact; hence NPV is impacted. This section centres on presenting such results and developing a discussion on the technical and economic aspects of the simulated scenarios.

For a given example of Cu-Au-Ag deposit, three key variables of mining rate, milling rate and recovery were analysed to quantify their impact at a strategic level. The range of variation for each variable was adopted from several Mine-to-Mill case studies in Asia Pacific region.

Figure 6 provides a brief summary of how implementing Mine-to-Mill optimisation strategies potentially changes the Net Present Value, NPV in the long-term without deploying CAPEX. In the context of Mine-to-Mill and its improvement potentials, the simulation outcomes suggest recovery and mining rate as the most effective leverages the overall value and then the milling rate. It is important to note how failure in maintain optimal mining and milling practices (here blast-induced impact on the downstream stages) may diminish profitability over life-of-mine.

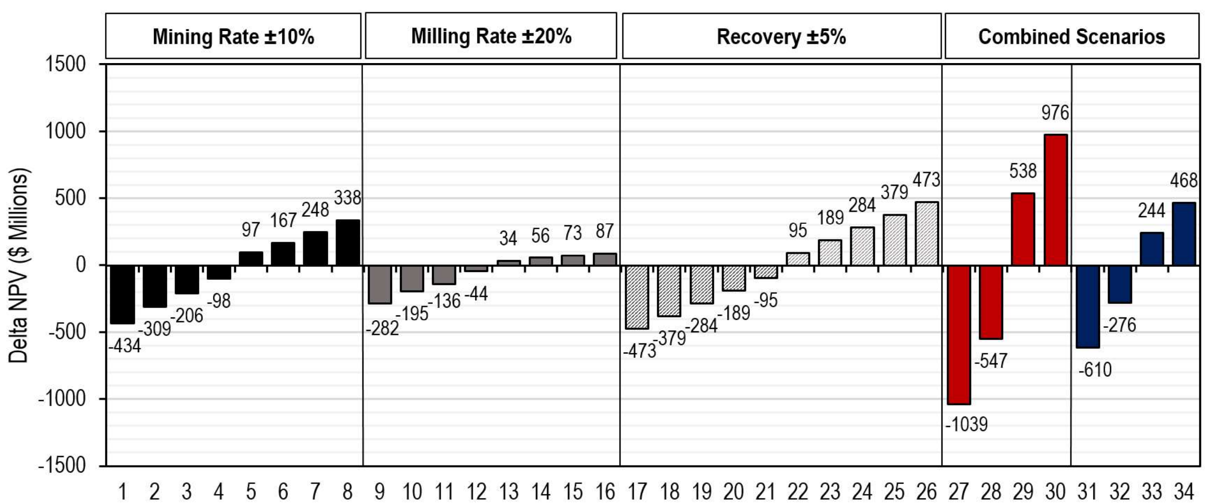
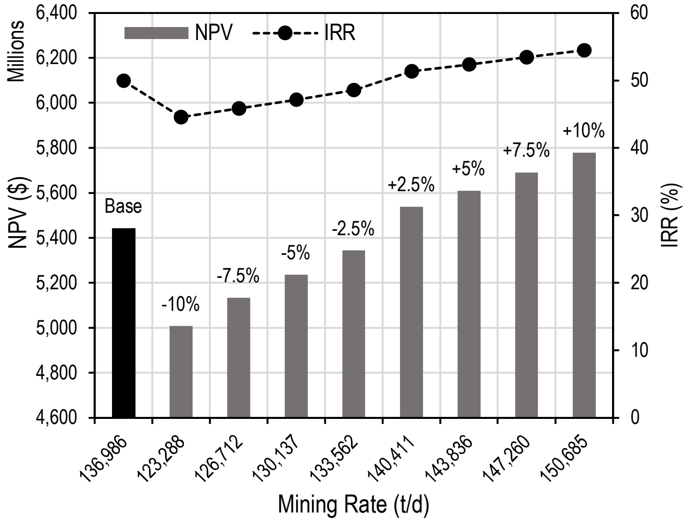


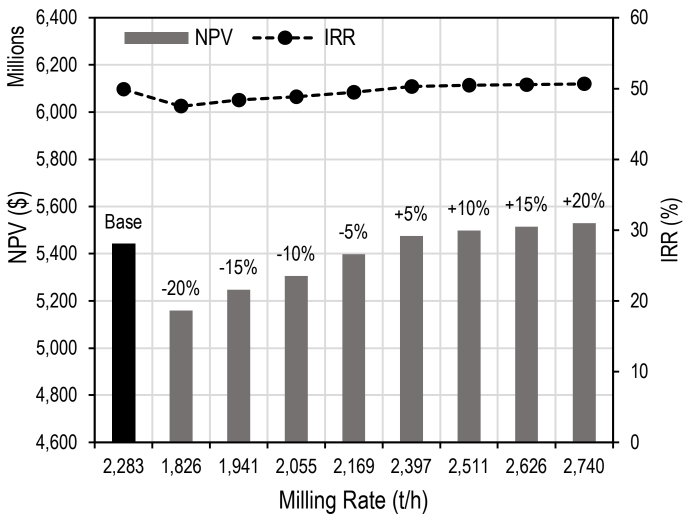
FIG 6 – NPV changes compared to the base-case NPV for all considered scenarios.

The results of simulated scenarios are given in Figure 7 for individual variables. Figure 8 and Table 2 summarise the results for the combined scenarios, which account for potential improvements or decrease of mining rate, milling rate and recovery at the same time, indicating extreme possibilities for potential gains and losses.

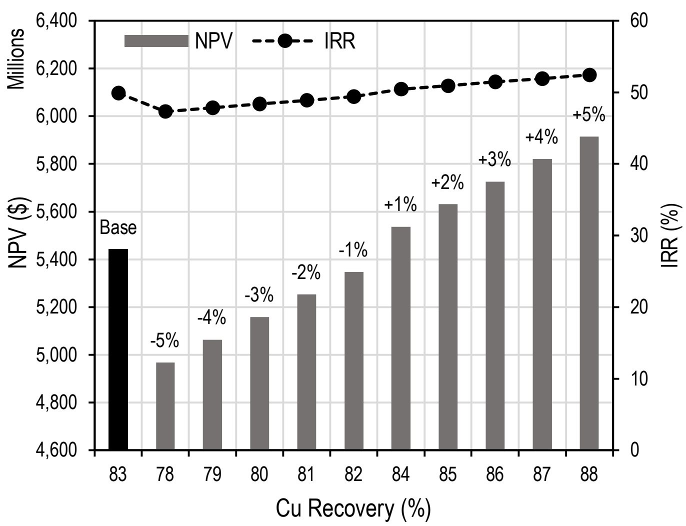
As it is implied in Figure 7, for the given example, 10 per cent improvement in *mining rate/capacity* through '*implementing and maintaining*' quality drill-and-blast practices over life-of-mine can translate into approximately 6.0 per cent increase in the NPV, while failure to move earth volumes in sequence may impose a loss of 9.0 per cent in NPV over LOM. Mining rate changes resulted in ±5.0 per cent.changes in IRR. Increases in mining capacity should generally be accompanied by a reduction in costs due to economy of scale. However, if the original fleet is maintained and this improvement is associated with improved performance of load-and-haul operation as a result of a finer muck pile fragmentation (eg if the shovels were the bottleneck for mining and any improvement in their performance results in shorter waiting times for trucks), it should imply an extra cost also associated with the mine cost, specifically associated with drill-and-blast costs – this additional cost should cushion the increase in value. On the other hand, the increase in this mining capacity offers the possibility of providing better quality ore available over time, to be sent to the process plant, and postponing the lower quality material by sending it to the stockpile, which would contemplate its re-handling costs.



Run #	Mining Rate (t/d)	NPV ($M)	IRR (%)	Mine Life (y)
Base	136 986	5442	49.92	16.58
1	123 288	5007	44.55	17.28
2	126 712	5133	45.83	17.00
3	130 137	5236	47.14	16.76
4	133 562	5344	48.55	16.69
5	140 411	5539	51.31	16.46
6	143 836	5609	52.37	16.40
7	147 260	5690	53.42	16.35
8	150 685	5779	54.46	16.30



Run #	Milling Rate (t/h)	NPV ($M)	IRR (%)	Mine Life (y)
Base	2283	5442	49.92	16.58
9	1826	5160	47.51	19.89
10	1941	5247	48.39	18.89
11	2055	5306	48.86	18.01
12	2169	5398	49.5	17.22
13	2397	5476	50.28	16.08
14	2511	5498	50.46	15.66
15	2626	5515	50.56	15.37
16	2740	5529	50.66	15.29



Run #	Recovery Cu (%)	NPV ($M)	IRR (%)	Mine Life (y)
Base	83	5442	49.92	16.58
17	78	4969	47.32	16.58
18	79	5063	47.85	16.58
19	80	5158	48.37	16.58
20	81	5253	48.89	16.58
21	82	5347	49.4	16.58
22	84	5537	50.43	16.58
23	85	5631	50.93	16.58
24	86	5726	51.44	16.58
25	87	5821	51.94	16.58
26	88	5915	52.44	16.58

FIG 7 – Results of sensitivity analysis of individual key variables by using GEOVIA Whittle™.

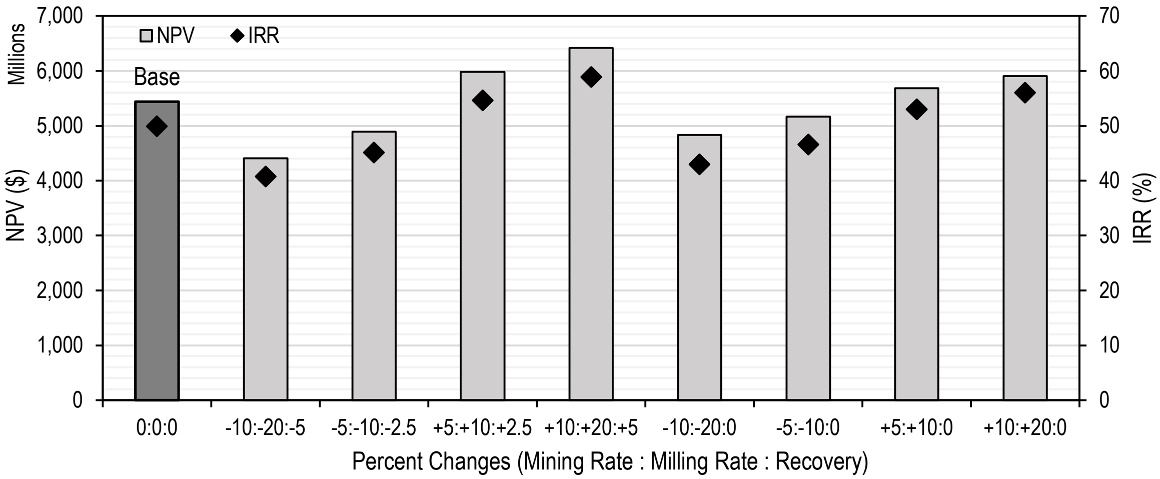


FIG 8 – Results of sensitivity analysis of combinations of key variables by using GEOVIA Whittle™.

TABLE 2

Details of simulated scenarios for combinations of key variables.

Run #	% Changes (M:M:R)	Mining Rate (t/d)	Milling Rate (t/h)	Recovery Cu (%)	NPV ($M)	ΔNPV ($M)	Relative NPV Changes (%)	IRR (%)	Mine Life (y)
Base	0:0:0	136 986	2283	83	5442	0	0.0	49.92	16.58
27	-10:-20:-5	123 288	1826	78	4403	-1039	-23.6	40.77	20.21
28	-5:-10:-2.5	130 137	2055	80	4894	-548	-11.2	45.17	18.14
29	+5:+10:+2.5	143 836	2511	86	5980	538	9.0	54.66	15.36
30	+10:+20:+5	150 685	2740	88	6418	976	15.2	58.91	14.30
31	-10:-20:0	123 288	1826	83	4832	-610	-12.6	43.00	20.20
32	-5:-10:0	130 137	2055	83	5166	-276	-5.3	46.61	18.14
33	+5:+10:0	143 836	2511	83	5686	244	4.3	53.04	15.36
34	+10:+20:0	150 685	2740	83	5910	468	7.9	56.06	14.30

NOTE: **M**ining Rate: **M**illing Rate: **R**ecovery = (M:M:R)

The *milling rate/capacity* suggests the potential to impact the NPV between -6.0 per cent and +2.0 per cent, which its dollar equivalence range would be -$282 M and +$87 M (See Figure 7). The process plant is generally the bottleneck of the value chain, so its limit determines the metal yield, and hence cash flow. It is worth noting that conventional Mine-to-Mill optimisation mainly aims to improve the milling throughput by performing high-energy blasts to tailor ore feed PSD in favour of SAG milling (generate more <10 mm fines). However, it is of prime importance to ensure power balance between the SAG and ball milling stages. The finer fragmentation feed may result in overloading the ball mill-cyclone circuit, and consequently impose pressure on circulating load – limiting throughput. For such operational scenarios, enlarging cyclone cut size (Product P80) might reduce circulating load – however, the impact on recovery should be evaluated. As expected, the milling rate is most effective on life-of-mine in longer term if milling rate improvements could be maintained.

The Cu *recovery* directly accounts for metal yield/saleable product, and the result suggest dramatic influence of recovery on NPV over life-of-mine. In this example, ±5.0 per cent changes in recovery resulted in NPV varying between -10 per cent and +8.0 per cent, equivalent to half a billion dollar in 17 years of operation (See Figure 7). The simulation scenario indicate 1.0 per cent change in recovery means $95 M over LOM, which is $5.6 M per annum for the given example – which highlights importance of applying grade control and ore loss reduction strategies across the value chain.

Applying a Mine-to-Mill optimisation approach at strategic level, should aim at delivering operational improvements. Not only limited to milling throughput, but also in mining rate as well as recovery. Figure 8 and Table 2 show the results of scenarios that account for Mine-to-Mill gains in three key areas of production with varying degrees/percentages. Compared to the conventional Strategic Mine Planning (Base-Case), the results suggest the potential to improve NPV up to $976 M over 14 year life-of-mine, by adopting a Mine-to-Mill at a strategic level without the need to deploy additional CAPEX. However, poor performance of mining, milling and beneficiation stages may be associated with risk of diminishing NPV by $1.039 B over an extended LOM of 20 years.

It is important to note that Strategic Mine-to-Mill optimisation can only be realised in the presence of tactical plans. The tactical plans are tailored to deliver improvements at an operational level. With respect to the significant influence of metal yield/recovery on NPV, proper grade control and ore loss reduction strategies should be considered across the value chain to manage grade variability and maintain recovery over time with the objective to maximise orebody utilisation. This requires several techniques, including measurement and analytics, Strategic Geological Modelling, blast movement monitoring and control for reduced ore dilution, ore pre-concentration and blending, comminution and classification. Exploring the results of all scenarios, highlights that maximised profitability is only achievable if the ore reserve is efficiently utilised in sequence and maintaining quality practices in mining, milling and flotation over LOM. With For this purpose, operational KPIs should be optimised and continuously improved over time, following development of new solutions, technologies and techniques (ie Mine-to-Mill approach) and their long-term impact being described quantitatively. At an operational level, Tactical Mine-to-Mill aim at realising strategic objectives through plans of implementation in medium- and short-term time frames.

An area of interest for future work should be integrating energy consumption estimates into strategic LOM evaluations, specifically the amount used at the downstream stage. To further discuss the matter of importance, Cohen (1983) estimates that 30–50 per cent of total plant power draw, and up to 70 per cent for hard ores is consumed by comminution. In minerals industry, energy is not consumed to best possible advantage in the comminution equipment and efficiency is only of the order of 0.1–2 per cent considering the energy required to generate new surface area relative to mechanical energy input (Fuerstenau and Abouzeid, 2002; Tromans, 2008). It has been identified that power efficiency for crushers varies between 70–80 per cent compared with single particle breakage in a drop weight tester (Morrell *et al*, 1992), while the value for ball mills and SAG mill is about 30 per cent and 40 per cent, respectively (Musa and Morrison, 2009). It was noted by Tromans (2008) that the limiting energy efficiency under compression varies between 5–10 per cent depending on the value of Poisson's ratio and under the uniaxial tension does not exceed 66 per cent. He argued that efficiencies of 5–10 per cent will not be achievable in practice, because the strain energy within a considerable region of a compressed particle makes no contribution to the fracture process and dissipates in forms of heat and kinetic. Thus, understanding fundamental limitations inherent in mechanical breakage of rock is the key to explore more efficient alternatives (Napier-Munn, 2015). Measuring the extent of competence variability within an ore domain should help to more accurately scale the size of quipment, estimate required energy and also better understand the nature of observed variation in the mill performance whether it is ore-induced or has an operational/technical origin. As an example, the Extended Drop Weight Testing (EXDWT) approach allows to consider particles pre-breakage physical properties, eg mass, density, dimension, orientation, colour, roundness, textural features etc, and investigate their possible link to particles competence based on the concept of 't_n-family per particle'. This capability offers the potential for the first time to account for more sources of variation, thus more closely estimate the true competence heterogeneity within a sample of ore (Faramarzi, 2020; Faramarzi *et al*, 2020). Overall, energy consumption is important to the mining industry and is likely to become more so because of increasing expense, as well as new regulatory and market interventions (Napier-Munn, 2015), therefore estimating energy usage at a strategic level should be beneficial in decision-making and establishing more sustainable alternatives for efficient utilisation ore reserves.

This study, specifically underlined the NPV improvement potential that could be achieved only by quality, value-driven drill-and-blast practices within Mine-to-Mill. Although blasting plays a deterministic, proven role in improving downstream performances; for best utilisation of an ore reserve, innovative techniques should be applied across the value chain, backed by more sophisticated financial models which could effectively reflect economic consequence of changes over life-of-mine.

CONCLUSIONS

The Strategic Mine-to-Mill optimisation as conceptualised in this paper, centres on long-term impact of adopting and maintaining optimisation strategies. Application of Mine-to-Mill at strategic and tactical levels would suggest opportunities for a step change improvement in the controllability of mining and processing performances, and substantially improved economics of operations.

In this paper, the potential impact of adopting Mine-to-Mill improvement strategies on the Net Present Value (NPV) was estimated for a Cu-Au-Ag deposit. Three key variables of mining, milling, and recovery rates were analysed within potential ranges for performance improvement, reported from Mine-to-Mill studies.

For the given case study, analysis of outcomes indicates that, maintaining value-driven strategies could result in up to +15 per cent higher NPV relative to the base-base. Although, recovery was found to be the most influential variable on NPV (by 8.0 per cent); however, based on the results, only mining and milling performance improvements through blasting could generate 7.9 per cent more value relative to the base-case. It is concluded that developing such analyses at a strategic level and integrating operational possibilities into calculations should assist with better understanding of potential gains and losses quantitatively. This would also be useful for establishing more robust risk management strategies in presence of uncertainties (ie commodity price, ore property) introducible over LOM. It is concluded that sustainable ore reserve utilisation is achievable if upstream and downstream activities becoming '*mutually informative*' and their KPIs shared in real-time for harmonising activities for maximised overall value. Future study should focus on addition of more levels of sophistication, some would be as follows:

- S*tochastic analysis of the impact of ore variability at a strategic level*: Although, ore variability is frequently debated as a major source of uncertainty in process performance, most of the current ore testing methods do not capture the variability within ore samples and process performance. Predictions are based on using average values for ore characteristics. It is required to use ore characterisation approaches which are designed for measuring the extent of variability inherent to the orebodies (ie mineralogical, textural and breakage characteristics of orebodies as key drivers to process performance KPIs such as recovery and throughput) and estimate the extent of ore-induced operational variability. This should assist with developing more realistic plans at the Tactical Mine-to-Mill stage in light of diagnosing likely bottlenecks across the value chain over LOM as ore properties change, although this remains a focus of future work.
- *Development of 'more' sophisticated financial models for value-chain studies*: While it is helpful to integrate Mine-to-Mill into strategic considerations, it is equally important to develop sophisticated financial models which can reflect on implemented changes.
- *Accounting for the impact of ore loss/dilution in long-term analyses:* High-energy blasting generally limits control over the outcomes, therefore might be associated with risk of ore loss through dilution. Blast-induced ore dilution is the phenomenon that can directly affect the overall value, NPV over time, and performance by feeding the mill with less valuable material. While it is important to reflect on ore dilution at a strategic level, it is also critical to set-up risk mitigation measures through blast movement modelling and monitoring systems for tuning blast design parameters (ie timing, pattern, explosives properties and distribution of blast energy etc) for reduced ore loss.
- *Application of operational history of the plant, namely 'historic or operational data':* Process plant historian (PI) data are indicative of the state of a process (commonly used for tactical/operational evaluations), but some challenges with 'operational' (PI) data have been inconsistency, redundancy, unreliable instrument readouts and large variations (with unknown sources and amounts). However, careful curation and analysis of PI data could assist with providing insightful information on process performance, constraints and bottlenecks. This would assist with developing strategic evaluations as well as risk assessment in light of operational constraints.

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