Mine Closure 2022 - M Tibbett, AB Fourie & G Boggs (eds)
© 2022 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-4-1
doi:10.36487/ACG_repo/2215_51

A Peruvian case study: optimising mine planning through mine closure decision assessment

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Abstract

Mine planning sets the goals and decisions required for the extraction of mined minerals at desired quality and quantities. Mine planning involves short-term and long-term decisions to facilitate implementation of strategic business objectives. However, mine planning business value drivers may not be aligned with closure strategies and obligations, which results in closure risks/opportunities not being managed. This makes it difficult to manage closure costs over time, particularly relating to potential long-term water quality impacts associated with mine rock and tailings management.

Confirming that business value drivers align with closure objectives and the decision assessment process captures closure risks and opportunities is crucial to reduce potential for long-term liabilities and costs. Establishing a closure strategic plan supported by clear objectives and success criteria is important as it helps align mine planning stakeholders. While this is not a new concept, implementation of closure strategies into mine planning varies across the industry.

This paper discusses a recent case study at a mine in Peru, in which a set of mine closure 'strategic pillars', decision-analysis tools, and a supporting integrated water quality model (WQM) were used to inform short-term and long-term mine planning. The WQM allows for potential future water quality impacts of mine plan options to be quantified, ranked, and the associated long-term mitigation costs considered within life of asset costs.

This paper details the innovative approach taken to integrate decision analysis, integrated WQM and closure costing tools to inform mine planning and life of asset costs. The motivation for developing this paper is due to an observed need to increase dialogue on this topic, with a broader vision to improve the mining industry's reputation in closure outcomes and maintaining social trust.

Keywords: *mine planning, decision assessment, closure strategy, water quality model*

1 Introduction

Mine planning involves implementing strategic business objectives into tactical plans. However, mine planning business value drivers must be aligned with closure strategies and communicated amongst closure stakeholders so that closure risks/opportunities are managed, and life of asset costs are representative.

The mining industry involves complexity, uncertainty, and reliance on short-term decisions. The cumulative effect of these decisions over the life of mine (LOM) is typically observed at the end of operations where the actual cost of closure materialises, typically with a long trail of residual risks/costs persisting.

Core to the Environment, Social and Governance (ESG) journey for the mining industry is water stewardship. Water stewardship is defined as "the use of water in ways that are socially equitable, environmentally sustainable, and economically beneficial." (International Council on Mining and Metals [ICMM] 2017). In simple terms, water stewardship is a holistic strategy for surface water and groundwater that extends past the mining lease-boundary. It requires meaningful collaboration and partnerships with stakeholders. Poorly managed change over the life of the asset is a common issue and barrier to this process (Sanders et al. 2018).

Water stewardship and impacts from poor mine waste management is arguably the most important aspect of residual mine closure risk. The water quality associated with interactions with waste storage facilities presents an especially important consideration in mine planning. The ability to accurately simulate the chemical evolution within such facilities, flow pathways and potential impacts on downstream receptors is a fundamental goal for integrated closure planning.

Our paper discusses a recent case study at a Peruvian mine in which a set of strategic pillars together with decision-analysis tools and a supporting integrated water quality model (WQM) was used to inform short and long-term mine planning. We describe the innovative approach taken to integrate decision analysis, integrated WQM and closure costing tools to inform mine planning and life of asset costs.

The following sections provide an overview of the mine asset context, decision support approach and how this approach was applied to the case study. The authors present a summary of key conclusions and broader vision of greater use of these methods in mine planning.

2 Background

2.1 Case study site

The case study site is located at a large porphyry metal mine in the Andes Mountains of Peru. The site is mature, having been in operation for several years, and comprises an open cut pit, concentrator, waste rock piles, tailings and ancillary infrastructure. The site directly employs hundreds of workers and has a regionally significant influence on community employment and infrastructure with interaction with over 50 neighbouring communities.

The future land use plan is to establish a modified natural ecosystem and repurpose infrastructure for beneficial community use. A key closure risk that has been identified and actively managed is long-term water management. Water is a determining factor in economic and social development, which, at the same time, fulfills the basic function of maintaining the integrity of the natural environment.

The site has various Life of Mine (LoM) planning horizons, each with multiple areas of opportunity for improved closure outcomes. The site maintains a Closure Management System that integrates inputs from closure planning into the LoM plans. This integrated planning process allows for closure issues, opportunities, and knowledge gaps to be assessed with closure stakeholders to best meet the closure vision and reduce risks and uncertainty over the life of the asset. An intended outcome of this planning is to improve the certainty in closure costing and continually reduce this over time.

As such, there were numerous benefits for early integration of closure aspects into LoM planning given the size and complexity of the mine assets. A summary is provided in Table 1.

Table 1 Benefits for integrated mine closure planning

Costs/profit	LoM planning risks	Reputation/social license
Improved cost efficiency through designing closure outcomes into operational plans. Reduced materials rehandling rework. Reduced water management costs (e.g. treatment, storage, pumping, etc.). Reduced long-term monitoring and maintenance costs. Improved closure cost estimate accuracy. Focussed closure studies that address key risks/uncertainties.	Early identification of opportunities, risks, and uncertainties. Reduced silos and improved outcomes with reduced rework. Reduced rework at the end of the asset LoM.	Improved certainty in post-mining land uses, closure objectives and success criteria. Improved support for current and future permitting. Improved compliance with regulators and governance groups.

Business value drivers influence the decision-making process for the asset's LoM planning considerations and ultimate net-present value (NPV) creation. Key value drivers identified that must consider mine closure risks/opportunities and life of asset costs included:

- Capital expenditure (CAPEX): including civil works (e.g. re-sloping, reclamation materials, bulk materials rehandling, etc.), infrastructure decommissioning/repurposing and dam safety risk reduction measures, and active water management (e.g. pumping, treatment, etc.).
- Operational Expenditure (OPEX): economic mineability including the operational costs of managing mine waste and water management, such as location and method of placement.
- Post-closure/residual risk: including long-term requirements for monitoring, maintenance, operation of active water management measures, site management, and social transition aspects.

To define the final closure measure to support costing and implementation, the appropriate or preferred closure option must be identified early in the LoM plan and progressed to approval and permitting. The approach for this follows a structured decision support process summarised in the following sections.

2.2 Decision support approach

The importance of assessing closure options is highlighted in ICMM (2019) and other guidance material. Decision support and options assessment is not a new concept, however, the process is often under-utilised or not facilitated in a structured approach, resulting in bias decisions (often tied to shorter term production key performance indicators) that can have lasting impacts.

There are various tools available to support a decision assessment. The Mine Closure Standard ISO-DIS-21795-2 DRAFT International Standard – 'Part 2: Guidance (International Organization for Standardization 2021) identifies a general process, as does Environment Canada's Mine Waste Guidelines for the assessment of options for mine waste disposal (Government of Canada 2016). The 'Kepner Tregoe' decision approach also provides a useful decision support approach.

Regardless of the tools or methods applied, a structured approach is valuable to mine closure planning practitioners to identify and evaluate options and make unbiased choices in complex decision situations. The steps create opportunities for dialogue between closure stakeholders that can make decisions more transparent and efficient.

Figure 1 summarises the steps documented in the site's Closure Management System and centred around a series of key stakeholder dialogue required with mine planners.

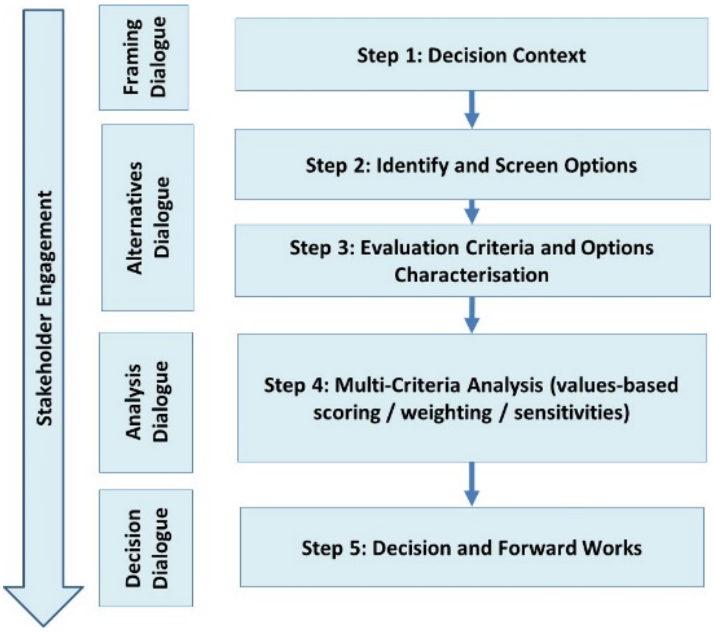

Figure 1 Decision support dialogue process

3 LoM planning case study

The following sections summarise the above method and application to the case study.

3.1 Step 1: Decision context

A first step in good decision making involves defining what (and why) the problem or opportunity is, identifying who needs to be involved, process for decision making, and clarifying the roles and responsibilities of the decision team. The objective of initial framing is to ensure the right problem is assessed from the right perspective and by the right people.

A decision statement was used to help focus the decision group and intended outcomes. The decision outcome informs LoM planning and strategic closure planning forward works that aim to improve certainty in closure design and success criteria.

The decision statement for this project was "*for each LoM scenario, identify a preferred option that leads to an improved mine closure outcome for water quality and supporting post-mining outcomes*".

3.2 Step 2: Identify and screen options

Good options should share several characteristics. By the time they are presented to decision makers they should be value-focused, technically sound, clearly defined, and developed collaboratively with the stakeholders most affected.

An opportunity framing exercise was conducted by brainstorming a list of all possible (i.e. reasonable, conceivable, and realistic) candidate options. This list was developed based on professional judgement, preliminary benchmarking, and site stakeholder input. A source-pathway-receptor type model was used as a useful model to frame up a range of potential options. The ICMM closure maturity framework (ICMM 2020) was used to guide the closure knowledge base as a preliminary task to highlight areas of knowledge certainty.

An infinite number of mine planning options were available for assessment which included a combination of mine plan, mining or milling method, landform construction method, and water management. Table 2 provides a summary of potential combination of closure planning options that were reviewed and selected, organised from most effective (managing sources) to least effective (managing receptors) for managing long-term water quality. This created an opportunity, but also a challenge to focus on a select few number of options that best met the decision statement.

Table 2 Potential closure planning options identification

Water quality sources	Water quality pathways	Water quality receptors
Mining/processing method: No change Selective mining within orebody New mining method New processing method (e.g. desulphurised circuit, etc.) Waste disposal location/staging: No change New footprint Backfill disused voids Remove/reprocess waste	Mine rock placement strategies (see Earth Systems & O'Kane 2020): No change Change to lift construction approach Engineered layers/base up layered compaction Addition of oxygen consuming materials Sulphide passivation Tailings placement strategies: No change Co-mingling Dewatering technologies (various – paste, filtered, etc.) Landform/erosion: No change Re-sloping Cover material type/construction approach Final landform cover design: No change Lower permeable covers Water management infrastructure: Active measures (e.g. ditches, pumping, pipelines, seepage attenuation, etc.) Passive measures (e.g. natural attenuation)	Water treatment: No change (centralised treatment) Water treatment plan (decentralised at sources) Passive treatment (wetlands, natural attenuation, etc.) Receiving environment: No change Change receptor location Change receptor criteria (risk-based performance objectives)

To focus and optimise the decision-making process, the above range of options were screened against the following policy objectives (i.e. must haves/fatal flaws):

- Options assume no change to the business case LoM planning horizons and current mining/milling method.
- Options must not impact dam safety.
- Options must address the business 'value drivers' influencing mine closure outcomes.
- Options must be a proven technology.
- Options must meet the minimum regulatory requirements and legal obligations (i.e. a 'do nothing' option is not possible).

Once options were screened against the above policy objectives, a range of options were then identified based on the closure strategic objectives and intent of the decision statement.

A description of specific LoM plans and closure options is not presented in this paper due to confidentiality. Approximately 50 LoM closure options were agreed for characterisation by combining:

- LoM Plan of tailings, mine rock and disturbance for various time planning horizons (*focus: mine waste sources and placement locations*).
- Tailings and mine rock placement strategies (*focus: mine waste source and pathway controls).*
- Final landform cover design options (*focus: reduce scale of active water treatment required*). Consideration of water management infrastructure trade-offs (i.e. pumps and pipelines/ditching) is a tactical decision as part of design and was not considered under this assessment.

3.3 Step 3: Evaluation criteria and options characterisation

Strategic objectives (i.e. 'wants') are evaluation criteria of high importance to the decision team and are used to characterise screened options and create the MCA ledger with supporting indicators and scoring criteria. They define an end of concern and a preferred direction of change. The strategic decision objectives are used to guide development of the screening criteria required to select the preferred option.

Evaluation criteria will change depending on the decision context and strategic values/objectives. Table 3 summarises the evaluation criteria used in this assessment to support the decision statement (Step 1). Supporting each indicator is scoring criteria used to compare each of the options assessed. While the focus and largest weighting was given to water quality, additional supporting criteria was included in the decision to reflect the closure value drivers.

There were numerous evaluation criteria considered important, but non-differentiating to the decision. These included aspects pertaining to physical stability (i.e. tailings dam stability), ecological and cultural elements. Assessment of final landform shaping, and landform erosion improvements occurred in parallel to this decision assessment and was identified as a 'bolt-on' opportunity for the preferred LoM option.

Table 3 LoM planning evaluation criteria

Account/closure focus	Category/ sub-account	Indicator/criterion	Indicator type	Indicator rationale
Chemical Stability/hydrology	Minimise scale of active water management (pumping, treatment, storage, etc.)	Predicted Water Quality Index (WQI) based on scope, frequency, and amplitude	Quantitative (WQM output)	The WQI uses three factors: F1 (scope), F2 (frequency) and F3 (amplitude) to provide an overall indication of water quality at closure. Combined with flow, this provides an indication of residual risk at closure and potential effort required for active water management. A catchment-based and average MCA score is taken across mine waste locations.

Account/closure focus	Category/ sub-account	Indicator/criterion	Indicator type	Indicator rationale
Ecological stability/end land use	Minimise additional land disturbance	Incremental land disturbance (Ha) – includes surface disturbance footprint for water treatment, etc.	Quantitative (GIS)	Locating mine waste within existing mine footprint/disturbance area reduces impacts on catchment areas, potential reduced impact on unknown areas of cultural/ community, significance greater confidence/baseline knowledge.
Social transition	Minimise, mitigate and/or compensate long-term socio-economic impacts	Level of support from community and reduced long-term dependency (e.g. immediate impacts to community infrastructure, long-term reliance on active monitoring/maintenance, social license/trust	Qualitative (professional opinion)	Maximise opportunity to use land where community stakeholder support is anticipated, given stakeholder engagement to date/continuation of agreements with existing parties. Stakeholders include local communities, government, business/industry and NGOs.
Financial	Minimise net present closure costs	CAPEX/direct cost of closure	Quantitative	Estimate of capital cost compared to least expensive site option. Estimate is based on key differentiating CAPEX items (water treatment based on flow rate and acidity, cover placement, re-sloping, etc.). Cost assumed at year 35 post-closure and 50 years post-closure. Cost assumes that a discharge location that does not have a WQI of 95–100 requires treatment for that flow.

Account/closure focus	Category/ sub-account	Indicator/criterion	Indicator type	Indicator rationale
		OPEX and maintenance costs over closure/ post-closure period (indirect)	Quantitative	Estimate of operating cost compared to least expensive site option. Cost assumed at year 35 post closure.

Characterisation of each identified option was advanced to the same level of detail that supported comparison against the criteria scoring. This included:

- Water quality predictions using the WQM outcomes as the basis for scoring, including water, materials and the chemical loads generated and transferred between locations across a range of post-closure time horizons.
- Incremental land disturbance.
- Qualitative measures including potential impact to community infrastructure and level of support from stakeholders.
- Comparative costing for key CAPEX and OPEX closure drivers. This utilised a modified version of the site's internal closure costing, targeting key cost items (i.e. >$10M) such as water treatment, landform shaping, cover design, material rehandling, long-term water management, etc. The WQM also included as an output, the likely water treatment CAPEX/OPEX costs based on a range of cost indicators (e.g. effluent inflows, acidity, key metals, etc.). This helped guide the cost comparison and provided additional justification for the potential cost range.

The WQM was a key tool that supported LoM options characterisation. The WQM concept and construction approach has been built in progressively by the site as the knowledge base has improved. The WQM is based primarily on site observations and fundamental geochemical principles: monitored water qualities provide the provisional WQM calibration. The water balance and water quality components of the WQM are continually updated as more information becomes available.

Supporting the predicted water quality evaluation criteria was the Canadian Council of the Ministers of the Environment Water (CCME) WQI. The WQI is a single value quantitative expression of water quality. This calculation accounts for the time, magnitude, and the number of parameters (scope) that exceed a water quality criterion. The equation produces a value from 0–100 that can be value-categorised to five ranges, which in turn can be directly correlated to the MCA scores (Table 4).

The WQM also integrated water quality predictions and WQI results to a range of water management costs (e.g. water treatment CAPEX/OPEX). This integration and WQM flexibility allowed for various additional 'what if' options to be assessed and cost outputs included in the revised closure costing estimate.

Table 4 CCME Water Quality Index (WQI)

WQI	Score Range	MCA score	Description
Excellent	95–100	5	Water quality is protected with a virtual absence of threat or impairment; conditions very close to natural or pristine levels.
Good	80–94	4	Water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels.
Fair	65–79	3	Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels.
Marginal	45–64	2	Water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels.
Poor	0–44	1	Water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels.

3.4 Step 4: Multi-criteria analysis (MCA)

3.4.1 Overview

A multi-criteria analysis (MCA) was the tool used to assess the options and inform a balanced decision between technical risk and costs. The MCA combines scoring the alternative against the evaluation criteria (done by the subject matter expert in that field and exclude bias) and applying a weighting (relative importance of that evaluation criteria compared to others).

Key to a successful MCA workshop is establishing buy-in with decision makers in the previous steps and facilitating dialogue that reaches a non-bias outcome that best answers the decision statement. A series of workshops were facilitated that focussed on gaining alignment with key closure stakeholders for each of the above steps prior to an MCA decision assessment workshop. Comparison of MCA scoring, weighting and sensitivity analysis was done via a simple Excel tool and supported by a Microsoft PowerBI and GIS interface.

3.4.2 Scoring

Each LoM alternative was assessed against the identified evaluation criteria. The subject matter specialist conducted scoring most knowledgeable in that discipline. Quantitative indicators were used where possible to assist in scoring each option relative to each other. Criteria were scored on a scale of 1 to 5 with a score of 1 denoting a lower preference/high constraint and a score of 5 indicating a higher preference/low constraint.

3.4.3 Weighting and Sensitivity Analysis

Weighting of evaluation criteria is a values-based function of an individual's perspective on the relative importance of each objective/indicator against each other. Weighting involved first an individual approach and then, as a group, reaching consensus on the weighting. Weightings were assigned on a scale ranging from 1 (lowest importance) to 10 (highest importance).

Once a base case weighted score was completed, a range of sensitivity analyses were undertaken to reflect the inferred 'wants' of difference stakeholder perspectives that may not be reflected within the workshop team. A range of sensitivities on the evaluation criteria weighting were provided to reflect the viewpoints of potential additional closure stakeholders not involved in the workshop.

3.4.4 MCA results and opportunities

Specific outputs of the MCA weighted scoring are not presented in this paper due to the commercial nature of the results and ongoing mine planning decision making. Key outcomes included:

- LoM option that included alternate approaches such as tailings/mine rock management constructability focussed on source control/interim operational covers presents several closure benefits. This includes improved predicted water quality outcomes, reducing mine waste footprints, potentially increasing physical landform stability, and reducing long-term water treatment closure costs.
- Review of waste dump constructability approaches may provide an opportunity for more robust, thicker layered, interim 'covers' that may be effective for oxygen control. This supports international good practice in mine waste placement strategies to enhance operational and closure performance.
- The reduction in net percolation and acidity loading from the mine rock facilities through ongoing segregation, selective placement and operational covers has the benefit of reducing contact water volumes that may require treatment. A focus on water treatment will continue to be on acidity loads and reducing flows to reduce the magnitude of potential long-term water treatment.

3.5 Step 5: Decision and forward works

Through the MCA process, the decision team selected two preferred LoM plan options to advance to the next stage of design (and potentially be adopted as a base case in the LoM plan and included in permitting and future Regulatory Closure Plan updates). One of the mine plan options selected was a step change from the base case mine plan option and presents a more holistic picture of the closure risks and costs related to long-term water management.

The outcomes identify areas of common opportunity and uncertainty requiring greater definition in the next phase of design (e.g. additional baseline data collection, laboratory/field testing, studies to understand potential impacts, engineering to improve construction sequencing, lifecycle cost estimate assumptions, etc.).

Identified opportunities common to the preferred options included:

- Improved refinement of the closure objectives and success criteria through improved post-mining land use planning and social transition.
- Landform/re-sloping/cover design (waste rock, tailings).
- Improved certainty around reclamation materials sources and characterisation.
- Water treatment trade-offs (size, location, staging, costing, pit lake attenuation, etc.).

Additional improvements could be made in future to the decision support process through utilising more sophisticated technology including artificial intelligence (AI) and Internet of Things (IoT). This presents a potential opportunity to both improve mine planning/production, but also assess a wider range of variables aimed at improved source control (e.g. mining method, milling/processing, block model/waste characterisation, etc.).

4 Conclusions

The mining industry involves complexity, uncertainty, and reliance on short-term decisions. The cumulative effect of these decisions over the life-of-mine (LOM) is typically observed at the end of operations where these closure residual risks may persist for hundreds of years.

Integrated mine planning is required to improve the outcomes of these decisions. It involves both mine planning decision makers (i.e. mine technical services and engineers) and influencers (i.e. mine closure planning practitioners) to incorporate intended closure outcomes into LoM business plans. The success of this planning is improved by a dedicated and informed management group guided by a structured decision support process that facilitates meaningful dialogue.

This paper summarises a case study where through structured dialogue and support decision tools, an improved mine plan that mutually supports the business and closure objectives can be achieved. The strategic decisions made as an outcome, can then progress to tactical decisions/mine plans that include the full range of potential life of asset costs and opportunities for closure risk reduction.

Decisions we make now and in the future affect the social acceptability of the industry. Now, more than ever, companies need to demonstrate improved water stewardship and mine closure performance to meet market expectations from investors, insurers, and community.

Acknowledgement

The authors of this paper would like to acknowledge the site team for their contributions.

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