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Building confidence in mine closure cost estimates: a practical approach to risk and uncertainty management

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Abstract

Understanding the associated closure costs of mine sites is crucial for effective business planning, particularly in the final decade of operations when production typically declines. Traditionally, closure cost estimates have relied on deterministic methods, which often overlook the inherent risks and uncertainties involved. This oversight can lead to significant underestimations of closure costs, leaving companies to grapple with unexpected expenses during the execution of closure or from legacy sites. Furthermore, many closure strategies remain in conceptual stages, lacking clear objectives and critical studies. By employing probabilistic models, the approach translates risks into a range of probable closure costs, enhancing the understanding of potential financial outcomes. Moreover, this methodology facilitates the identification of key risk factors that can impact closure costs, allowing companies to develop targeted strategies for risk mitigation. By refining their closure plans based on comprehensive data analysis, organisations can better allocate resources and prioritise investments that align with their closure objectives. This proactive approach not only improves the confidence of closure cost estimates and supports a reflection on the risk identification process supporting the incorporation of potential omissions, but also supports sustainable business practices by ensuring that companies are prepared for the financial implications of mine site closure. In doing so, it fosters a culture of responsibility and foresight in the mining industry, paving the way for more resilient operations in the face of inevitable transitions.

This paper advocates for a paradigm shift in closure cost estimation practices by emphasising a structured, process-oriented approach that integrates existing life of mine cost data with a comprehensive assessment of closure assumptions, risks and uncertainties. The paper outlines key steps – such as internal stakeholder engagement and scenario development – that support the creation of a tailored risk assessment framework. Through the adoption of probabilistic thinking within this guided process, the goal is to improve the transparency, defensibility and reliability of closure cost estimates, ultimately contributing to more sustainable and responsible mining planning.

Keywords: *closure cost, cost estimation, risk mitigation, closure strategies, legacy sites, financial outcomes, resource allocation, life of mine, probabilistic cost, business planning*

1 Introduction

Understanding the associated closure costs of mine sites is crucial for effective business planning, particularly in the final decade of operations when production typically declines. Traditionally, closure cost estimates have relied on deterministic methods that use fixed input values to calculate a single-point estimate of closure costs. These methods do not account for variability or uncertainty in the inputs – each cost component is assigned a specific value based on current knowledge, assumptions or historical data, which often overlook the inherent risks and uncertainties involved. Risks refer to known potential events or conditions that may or may not occur but whose likelihood and impact can be estimated, and are often

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called “known unknowns”. Uncertainties, on the other hand, refer to inherent variabilities or lack of precise knowledge about inputs or future conditions, and are often called “unknown unknowns”. The oversight of deterministic approach can lead to significant underestimations of closure costs, leaving companies to grapple with unexpected expenses from legacy sites.

Furthermore, many closure strategies remain in conceptual stages, lacking clear objectives and critical studies. Based on 2018 projected figures, of 441 assets from a total of 18 ICMM member companies assessed for mine closure preparedness and remaining life of mine, 40% were expected to close within 25 years and 20% of these closures were anticipated to close in the next 10 years (Australasian Institute of Mining and Metallurgy 2020). Considering many closure strategies remaining in conceptual stages, associated with the expected proportion of sites mentioned above to face closure in the next years it is expected substantial efforts will be required for mine closure and the robust financial planning. The dynamics of the metals market and the capital investments required necessitate further scrutiny of operational mines, which can contribute to decisions for sudden closure. The reality of mine closure costing is challenging for the sector. Mine closure programs are often underestimated by four to 10 times (Hesketh & Pedlar 2023) in their financial impact. As a specific example, the preliminary findings from the Ranger rehabilitation project that were estimated to be in the order of USD 669 million in 2019 were reassessed at between USD 1.1 to 1.6 billion in 2019, driven by factors such as emergent technical risks and unbudgeted costs (Energy Resources of Australia 2022). A key approach to risk mitigation is to prepare specific strategies and action plans along with a cost-effective approach to reduce the consequences of escalating costs in closure execution (World Bank 2024). In the context of mine closure cost estimation, the transition from a deterministic to a probabilistic approach typically aligns with the maturity of the asset and the availability of detailed data. During the early stages of a mine’s life – such as exploration and early development – deterministic estimates are appropriate as they rely on limited information and are primarily used for high-level planning and financial modelling. As the operation progresses into the mid-life phase, more site-specific data becomes available and the closure scope becomes clearer. At this point, transitioning to a more refined estimate that begins to incorporate probabilistic elements is beneficial, particularly for financial provisioning and regulatory updates. In the late stages of the asset’s approaching closure or during execution, probabilistic estimates become more appropriate.

Additionally, in the event of a mine’s sudden closure – often triggered by unpredictable factors such as market shifts, regulatory changes or unforeseen operational issues – the existence of an advanced, probabilistic cost estimate becomes especially valuable. In such cases, where traditional planning assumptions may no longer hold, a probabilistic approach offers greater flexibility and insight, helping to manage uncertainty and support rapid, informed responses. This progression ensures that closure cost estimates remain fit for purpose, increasingly accurate, and aligned with both regulatory and financial expectations as the project evolves.

In the universe of closure costing, a key indicator of increasing organisational maturity and effective risk management is the recognition and incorporation of probabilistic tools and models. These tools enable mathematical, computer-based probabilistic analysis, embedding cost risk analysis directly into the closure planning process. By understanding the greatest levels of uncertainty associated with closure activities, efforts can be focused on narrowing them, thereby generating better outcomes. Developing probabilistic cost analysis require a robust, transparent and solid approach that requires building trust and applying a strategic approach through the process.

By employing probabilistic models and using a well-defined methodology, this approach translates risks into a range of probable closure costs, enhancing the understanding of potential financial outcomes. Unlike deterministic methods – which rely on fixed inputs to produce a single-point estimate – probabilistic models use statistical techniques to account for variability and uncertainty in key cost drivers. This allows for the generation of a distribution of possible outcomes rather than a single figure, offering a more comprehensive view of potential cost exposures. While this approach provides deeper insights, it also requires additional resources, including specialised software, skilled personnel with expertise in risk modelling and ongoing data updates to maintain accuracy over time. Despite the added complexity, this refined approach allows organisations to better allocate resources, prioritise investments and develop targeted strategies for risk

mitigation that can better align with their closure objectives. Companies can develop targeted strategies for risk mitigation, improving the accuracy of closure cost estimates and supporting sustainable business practices. By proactively preparing for a range of financial scenarios, companies are better prepared for the financial implications of mine site closure and can foster a culture of responsibility and foresight, paving the way for more resilient operations in the face of inevitable transitions.

As part of ERM's experience in developing and advancing closure cost estimates for several global mining companies, it has incorporated and applied cost risk analysis to numerous mining assets and explored multiple formats and approaches to drive successful outcomes. The execution of these projects has led ERM to identify that a critical factor in the successful use of probabilistic models lies in the team's openness and preparedness to challenge existing cost estimates and technical assumptions. The willingness to question and revise established methodologies is essential to uncovering hidden risks and uncertainties. Additionally, the success of the application of the probabilistic model is strongly dependent on the methodology and approach taken to explore these assumptions and uncertainties. A structured and systematic process that encourages active participation and critical thinking among stakeholders can significantly enhance the accuracy and reliability of closure cost estimations. The work described in this paper explores key factors identified during project execution that were critical in driving successful outcomes for an improved understanding of closure costs and establishing defined work plans to reduce uncertainty in the cost estimates across a portfolio of assets. The approach to engagement, with the various stakeholders providing inputs to the closure cost estimate, was a key factor influencing confidence in the outcomes of the closure cost estimate. By fostering an environment that values innovation and adaptability, organisations can better navigate the complexities of mine closure planning and achieve more sustainable outcomes.

2 Critical aspects in investigating uncertainties

A thorough analysis of the uncertainties and limitations inherent in cost estimates is crucial for developing reliable closure cost models. By developing comprehensive cost estimates, major closure project risks can be clearly communicated and tracked (Mandziak et al. 2023). Establishing a structured approach for this analysis is key to achieving successful outcomes. Several factors influence this process:

- Guided process: it is extremely important to investigate uncertainties through a guided process led by a resource well versed in methodological tools. This individual should be prepared to guide and lead the team in exploring resources and generating meaningful data. The guided process ensures that the investigation is systematic, and that the data collected is relevant and actionable, ultimately enriching the probabilistic models and generating more accurate outcomes.
- Establishment of confidence: high-level commitment to investigating closure costs from a cost risk assessment perspective is crucial. Encouraging participation without fear of judgment is essential for success. When stakeholders feel supported and confident in their contributions they are more likely to engage fully and provide valuable insights that enhance the overall process.
- Openness to challenge current estimates: engaging stakeholders who have long been responsible for generating information is beneficial, though they may feel threatened by challenges to previous decisions. Encouraging openness and fostering a culture of constructive critique is vital. This openness allows for the identification of potential blind spots and the refinement of cost estimates, ultimately leading to more robust and reliable models.
- External expertise: integrating technical experts who can explore scenarios and uncertainties not previously considered is essential. These experts bring fresh perspectives and challenge existing paradigms, which can lead to innovative solutions and a more comprehensive understanding of potential risks. Their involvement helps to break down silos and encourages a more holistic approach to closure planning.
- Understanding of site context: involving resources with a deep understanding of the site, including its unique characteristics and potential uncertainties, is crucial. This knowledge enables a more

accurate identification of site-specific risks and informs the development of tailored strategies. A comprehensive understanding of the site context ensures that all relevant variables are considered, reducing the likelihood of unforeseen challenges.

The successful investigation of uncertainties in closure cost estimation hinges on a combination of deep knowledge, external expertise, openness to challenge, confidence-building and a guided process. Each of these factors plays a critical role in creating a comprehensive and reliable framework for cost estimation. By integrating these elements, organisations can develop more accurate and resilient closure strategies; ultimately supporting sustainable business practices and fostering a culture of innovation and adaptability in the mining industry.

3 Methods for performing cost risk analysis

Performing a robust probabilistic cost risk analysis involves more than just mathematical computations – it requires a structured, collaborative process that integrates expert judgment, data analysis and stakeholder input. The process requires careful planning in data gathering, refinement and the methodical execution of meetings, all of which significantly impact the quality of discussions and the accuracy of input data regarding uncertainties in cost models. The following key components illustrate how these tools are applied:

- Resource mapping: identify and engage critical technical experts who can contribute to discussions on factors influencing uncertainties. These individuals should have the expertise necessary to investigate and address critical aspects of the process, defining probability distributions for key cost elements, unit rates, quantities and schedule durations.
- Onboarding and alignment: engage leadership and key stakeholders by providing a comprehensive overview of the project, identifying necessary resources and aligning expectations. This step ensures everyone is on the same page and committed to the process.
- Information gathering and initial cost model inputs: assemble a core team with expertise in cost modelling, mine closure planning and uncertainty investigation. This team should have access to critical site information to gather key data and establish a framework for exploring uncertainties. This includes historical cost data, engineering assumptions and site-specific variables. Probabilistic distributions are assigned to uncertain inputs based on expert judgment and available data.
- Exploration of uncertainties: conduct guided discussions with involved resources to assess and investigate uncertainties and risks. This collaborative exploration is crucial for identifying potential issues and developing a comprehensive understanding of the uncertainties involved.
- Cost model input and refinement: translate gathered information into inputs for the cost model. The professional leading the uncertainty exploration should work closely with the cost model specialist to ensure data is formatted correctly for model execution.
- Validation of outcomes: model outputs, including probability distributions of total closure costs and confidence intervals, are reviewed with stakeholders. This step allows for feedback, adjustments and calibration of the cost model, and fosters ownership of the results. Sensitivity analysis is also conducted to identify the most influential variables, guiding future data collection and risk mitigation efforts.

These steps create a comprehensive framework for cost risk analysis, enabling organisations to anticipate and mitigate potential risks effectively. By embracing this structured approach, organisations can enhance their strategic planning and improve their ability to navigate complex financial landscapes.

The outcomes of cost risk analysis are significantly influenced by the methods employed during the exploratory sessions. These methods can range from desktop reviews to in-person workshops, each offering unique advantages and challenges. Here are some examples of these methods:

- Desktop method: in this approach, technical resources share information with cost experts primarily through digital means. The process is led by a core team that coordinates requests and receives input from isolated resources, with minimal interaction among participants. The lead team synthesises the information and integrates it into the cost models. Output is then shared with the resources in an informative manner. This method is efficient in terms of logistics and can be useful when resources are geographically dispersed. However, it may lack the dynamic interaction that can lead to deeper insights.
- Remote method: this method involves a coordinated effort where technical resources engage in online meetings and workshops. A lead facilitates the discussions, guiding participants through structured sessions. The lead is responsible for integrating input into the cost models. Outputs are shared with participants, and follow-up discussions may occur to further refine the models. This approach offers flexibility and accessibility, allowing for diverse participation without the need for travel. It can foster collaboration and real-time feedback, although it may still miss the depth of interaction found in face-to-face settings.
- In-person method: this approach combines preparatory online discussions with in-person workshops. Technical resources are engaged in a coordinated effort led by a facilitator who guides the discussions. The in-person workshops allow for more dynamic interactions, enabling participants to engage in deeper, more nuanced discussions. The lead integrates the inputs into the cost models, and outputs are shared for further refinement. In-person workshops have been shown to yield better outcomes in terms of the quality of uncertainties assessed and the level of refinement achieved. The physical presence of participants fosters a collaborative environment, encouraging open dialogue and creative problem-solving.

In-person workshops have proven to provide superior outcomes due to the quality of uncertainties assessed and the level of refinement achieved. The face-to-face interaction allows for immediate feedback, fostering a more comprehensive exploration of uncertainties. Proper time allocation for aligning expectations and defining outcomes is crucial as it positively impacts the overall performance of the cost risk analysis process. By setting clear objectives and ensuring all participants are on the same page, organisations can maximise the effectiveness of these exploratory sessions, leading to more accurate and reliable cost risk analysis outcomes.

4 Sensitive analysis in closure cost estimation

Sensitivity analysis plays a vital role in enhancing the robustness and transparency of closure cost estimation. It helps identify which variables exert the greatest influence on the overall cost outcome, thereby clarifying the impact of assumptions and uncertainties embedded in the model. By systematically analysing how variations' input parameters affect the final cost estimates, sensitivity analysis enables organisations to prioritise efforts in data refinement, risk mitigation and stakeholder communication.

The primary purpose of sensitivity analysis is to pinpoint key cost drivers – those variables that, when changed, significantly alter the total estimated closure cost. These may include unit rates for specific activities, volumes of material to be handled, durations of post-closure monitoring, or assumptions related to inflation and discount rates. Understanding which inputs have the most influence allows organisations to focus resources on improving the accuracy of those variables, ultimately leading to more reliable and defensible cost estimates.

The process typically begins after the probabilistic cost model has been developed and validated. Monte Carlo simulations are run using defined probability distributions for uncertain inputs, generating a wide range of possible cost outcomes. The model then calculates the correlation between each input variable and the total cost output, often using rank-order correlation coefficients. This analysis reveals which variables contribute most to the variability in the cost estimate.

Results from sensitivity analysis are often visualised by ranking variables by their impact on the overall cost range. These visualisations are particularly effective in communicating complex risk information to both technical and non-technical stakeholders. For example, if the analysis shows that the unit cost of water treatment is the most influential variable, the organisation may choose to conduct further engineering studies or engage suppliers to refine that input. Similarly, if the duration of post-closure care emerges as a critical driver, scenario planning or regulatory consultation may be necessary to reduce uncertainty.

Incorporating sensitivity analysis into the closure cost estimation process not only improves the technical quality of the estimate but also builds confidence among stakeholders. It demonstrates a clear, data-driven understanding of the risks and uncertainties involved and supports more informed decision-making. Ultimately, sensitivity analysis transforms closure cost estimation from a static budgeting exercise into a dynamic, risk-aware planning tool.

5 Expected outcomes of a well-structured cost risk analysis

The process of conducting a cost risk analysis through a guided and well-structured approach marks a significant advancement from the initial stage where companies merely recognise the need for closure costing and planning. This transition involves a thorough investigation into incorporating previously overlooked elements, which is crucial for enabling companies to effectively manage and address liabilities. By following a guided and critical evaluation process supported by interactions which incorporate methodologies that maximise in-person resources highly committed to the task, openness to challenge the previous estimate and technical understanding of the site conditions, bolstered by external expertise, organisations can take control of closure planning in a constructive manner, enhancing the accuracy and reliability of the closure cost estimations.

It is also important to note that, when the process of reassessing the cost estimate begins, the outcomes often lead to increasing estimates; higher than those derived from traditional deterministic models. This result should be viewed as an inherent part of the process. These outcomes provide the organisation with a road map to identify critical areas to focus on, thereby facilitating the development and implementation of targeted action plans to refine the closure approach. These plans focus on addressing major uncertainties with well-justified reasons and implications.

As the process matures, the reassessment of costs and uncertainties tends to stabilise, reflecting the organisation’s increased control over the process. At this stage, opportunities to offset liabilities can be explored, marking a complete transition into a process of reassessing, reframing and reshaping closure costing and planning by integrating business planning. Ideally, the process advances towards the perspective of incorporating a business plan that explores alternatives for generating future income through legacy management, leading to the identification and implementation of a strategy that can advance the offset of closure costs. As the idea of repurposing mine lands and assets for future productive uses gains popularity, the approach to mine operations and integrated closure planning and costing is evolving to better prepare for this transition (World Bank 2024). Figure 1 provides an illustration of the transition of mine closure costing to legacy management and business planning.

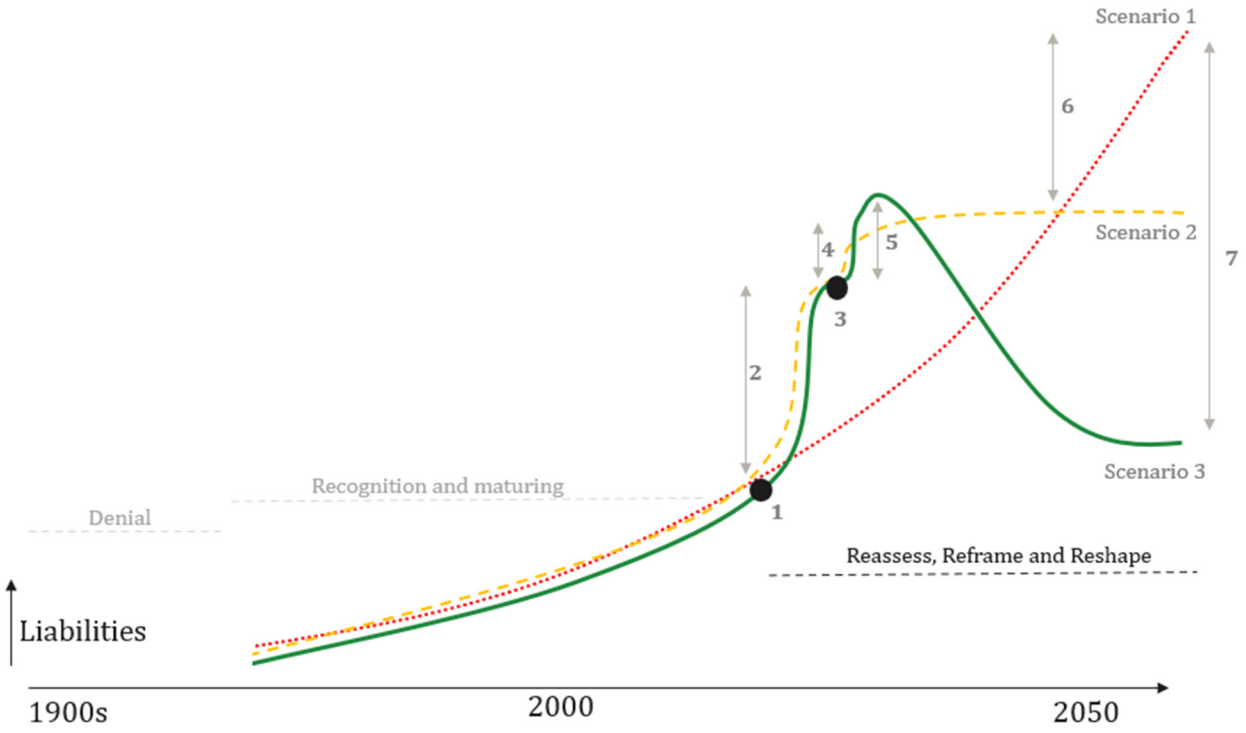

Figure 1 Illustration of the transition of mine closure costing to legacy management and business planning

Scenario 1 demonstrates the closure costs of a site that excluded early mapping of risks and uncertainties in closure planning that, later in the process, continue to generate incremental costs. Scenario 2 presents the closure costs of a site that incorporates risks and uncertainties using a probabilistic approach. Scenario 3 presents the closure costs of a site that incorporates risks and uncertainties using a probabilistic approach and adopts business planning to generate income. Point 1 represents the initial cycle of the probabilistic approach, integrating uncertainties into the mine closure cost estimate for both the green and yellow lines. This cycle involves reassessing, reframing and reshaping the management of closure costs and planning. The cost increase represented by point 2 depicts the sudden realisation of cost increases due to the incorporation of uncertainties for Scenarios 2 and 3. Point 3 illustrates further iterations and reassessments of costs using probabilistic approaches for Scenarios 2 and 3. Point 4 shows the cost increase from embracing uncertainties, with a focus on reducing liabilities for Scenario 2. Although a cost increase might be observed for the yellow line, it is less than during the first cycle. This mature process eventually leads to cost stabilisation. Point 5 highlights the cost increase due to investments in Scenario 3, with a perspective of incorporating a business plan that explores alternatives for generating future income through legacy management. While costs may be higher compared to Scenario 2, the long-term outcomes lead to a reduction in legacy management costs. Cost reduction point 6 represents the minimum expected benefits of incorporating a cost risk analysis between Scenarios 1 and 2. Cost reduction 7 demonstrates the final potential for liability reduction over time, achievable between Scenarios 1 and 3. This reflects the long-term benefits of adopting a structured approach to cost risk analysis in mine closure cost planning.

6 Conclusion

The integration of probabilistic approaches into mine closure cost estimations represents a transformative step forward in the mining industry. By shifting from traditional deterministic models to a more dynamic and comprehensive probabilistic framework, companies can better navigate the complexities and uncertainties inherent in mine closure planning. This paper has outlined the critical importance of understanding and

managing the methodology and approach needed to explore elements of the estimate and achieve better outcomes. This process becomes particularly critical as operations near their end-of-life phase.

Through the adoption of probabilistic models, organisations are empowered to translate risks into a spectrum of probable closure costs, offering a more nuanced understanding of potential financial outcomes. This approach not only enhances the accuracy of cost estimates but also supports strategic resource allocation and investment prioritisation. By identifying and addressing key risk factors, companies can develop targeted mitigation strategies – such as increasing contingency allowances, adjusting closure designs or scheduling progressive rehabilitation to reduce long-term liabilities. In addition, preventative strategies can be identified and implemented to reduce the likelihood of risk events occurring in the first place. These may include early stakeholder engagement to avoid regulatory delays, proactive water management to prevent contamination or routine monitoring programs to detect issues before they escalate. Together, these strategies support more resilient closure planning, ultimately fostering sustainable and responsible business practices.

The success of this methodology hinges on several key factors: the involvement of knowledgeable resources, the integration of external expertise and a willingness to challenge existing assumptions. A structured, guided process is essential for exploring uncertainties and refining cost models, ensuring that all relevant variables are considered. By fostering an environment that encourages innovation and adaptability, organisations can achieve more resilient and sustainable closure strategies.

In conclusion, the transition to a probabilistic approach in closure cost estimation not only prepares companies for the financial implications of mine site closure but also instils a culture of foresight and responsibility within the mining industry. This proactive stance paves the way for more resilient operations, equipping companies to handle inevitable transitions with confidence and strategic insight. As the mining industry continues to evolve, embracing these advanced methodologies will be key to ensuring long-term sustainability and success.

References

Australasian Institute of Mining and Metallurgy 2020, *ICMM's Integrated Mine Closure Good Practice Guide – Then and Now*, AusIMM Bulletin, viewed 20 April 2025, https://www.ausimm.com/bulletin/bulletin-articles/icmms-integrated-mine-closure-good-practice-guide--then-and-now/

Energy Resources of Australia 2022, *Ranger Mine Closure Plan 2022*, Darwin, viewed 20 April 2025, https://minedocs.com/19/Ranger-Mine-Closure-Plan-Sept-2022.pdf

Hesketh, P & Pedlar, R 2023, *Optimizing Financial and Sustainability Value in Mine Closure*, ERM, London, viewed 20 March 2025, https://www.erm.com/insights/optimizing-financial-and-sustainability-value-in-mine-closure/

Mandziak, T, Collyard, J & Subrahmanyan, B 2023, 'The benefits and opportunities realized through an integrated and transparent closure cost model', in B Abbasi, J Parshley, A Fourie & M Tibbett (eds), *Mine Closure 2023: Proceedings of the 16th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, https://doi.org/10.36487/ACG_repo/2315_082

World Bank 2024, *Mine Closure Standards and Improved Post-Closure Risk Management for Surface and Underground Coal Mines*, Washington, viewed 17 April 2024, https://openknowledge.worldbank.org/server/api/core/bitstreams/76ea47ec-6a37-43f0-b000-397413a01be3/content