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Statistical and Probabilistic Closure Cost Estimating

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Abstract

This paper describes a statistically based framework for determining mine closure costs. A range of future potential mine closure scenariosare established and described using a decision tree approach. This allows for consideration of a large number of combinations of closure elements for the various mine facilities. The decision tree is used to establish a cost probability curve that in turn provides for determining closure costs at different levels of confidence. It is also used to identify the high risk and high cost elements. Monte Carlo techniques are also employed to determine the cost variability of individual mine closure scenarios such as the expected cost or the most likely closure scenario. This approach avoids the difficulty of trying to establish a single closure cost estimate and provides closure cost and probability information that can be used in feasibility evaluations, budgeting, reserve setting and also for the prioritization and management of high cost risks.

Introduction

Incorporating true life cycle (i.e. from cradle to grave) costs into financial feasibility studies for mines is an essential feature of sound mine development planning. This requires, however, that reliable mine closure and post-closure costs be established before the mine is even put into production. The technical challenges in forecasting what closure elements will be required, particularly in wetter climates where water management can be a significant part of closure, or in areas where extreme events (earthquakes, floods) may occur and then consequently dealing with the uncertainty as to how the regulatory framework may evolve, makes reliable cost forecasting difficult, and requires a significant amount of judgment.

The requirements for mine closure and closure standards at the mine planning stage are typically uncertain and generally must be based on mine waste characteristics determined from drilling and sampling of in-situ rock and laboratory testing of relatively small samples of the material. Added to the uncertain future waste characteristics, which typically include leachate and mine water quality, final configuration of the tailings and water pile, as well as open pits and underground mines are usually altered during the mining operations. Finally, regulatory standards can change over the life of the mine introducing further uncertainty to the closure requirements and costs.

This paper describes a technical and statistically-based cost estimating approach that can be used to deal with the uncertainties in a systematic way. Two case histories are presented that illustrate the cost risk profile associated with a high-risk and a low-risk closure. The sections below describe how the range of potentially applicable mine closure elements are established, how costs are estimated for these and then how these elements and costs are combined using decision trees and Monte Carlo techniques to generate useful cost-probability information.

Mine closure elements

It is usually easier to estimate the minimum and maximum costs for a future activity and a closure, than to determine a specific cost. The proposed technical approach is based on this premise.

The first step involves listing the major elements of the mine that will require closure. Typically these include amongst others:

- Open pits or underground mines
- Waste rock disposal facilities
- Heap leach residue piles
- Tailings impoundments
- Ore processing facilities including any mine backfilling plant and equipment
- Transportation facilities, such as roads, staging areas, pipelines, and fuelling facilities
- Infrastructure. such as administrative complexes and water, power supply and communication systems

The next step is to determine the best and worst case mine waste characteristics and the associated water balance elements such as leachate from waste rock and heap leach residue piles, pit water volumes and potential overflow rates, underground mine discharge rates, etc. In addition, the minimum and maximum dimensions of the waste management and other facilities are determined and used as a basis for estimating the minimum and maximum costs. Where possible, the most likely size, the waste characteristics, and the water balance elements should also be determined.

The final step involves establishing the range of mine closure elements that may have to be implemented when the mine is ultimately closed. For example, for a heap leach residue pile, the elements may include a soil cover, an impermeable layered cover, leachate infiltration basins, and leachate treatment systems. The need for any of these elements will depend on the waste characteristics at closure and the applicable regulatory requirements, amongst other aspects. It is important that realistic elements be established, for example in a wet climate where a highly mineralized acid generating residue is generated, provision should be made for either the installation of an impermeable cover or a leachate treatment system, or a combination of both. In an arid climate, these elements may be ruled out and the focus will be more on dust control, establishment of a vegetative cover, etc.

Two example case histories have been considered and the closure elements associated with these are shown in Figures 1 and 2. These examples are based on actual experience at several mine sites in the Western Unitized States. Figure 1 represents a high-risk closure of acid generating materials in a humid climate (Site A). Figure 2 represents a low-risk closure site (Site B); i.e., one involving more benign waste materials in an arid climate. The different closure elements for each site are shown on these figures, as are the probabilities of each of these being required for the three closure scenarios.

The minimum, most likely and maximum cost estimates for each mining element should be done to a conceptual engineering level and based on engineering drawings and sketches, chemical and water balance modelling, and appropriate cost unit rates for the area in which the mine is located.

The costs presented in Figures 1 and 2 are net present value (NPV) costs at the time of closure. In other words, the long-term maintenance and operating cost (for any treatment systems) have been converted to NPV using a discount rate typically used by the mining company to evaluate investments. This closure NPV cost would then be included in the year of closure and used in any mine life cycle financial analyses that are performed.

Closure elements and probabilities

Uncertainties in mine closures are dealt with in two ways. The first is to postulate the probabilities of each of the postulated closure elements. For Site A (Figure 1), the most likely scenario includes a comprehensive heap rinsing program (Rinsing 1), installing a soil cover over the residue pile and discharging and infiltrating any residual leachate, grading and re-vegetation of the waste rock piles and treatment of pit water that continually discharges.

A range of probabilities are assigned to the other elements for three different closure scenarios. Less likely, but significantly more costly Scenarios #2 and #3 have been estimated to have 20% and 30% probabilities of occurrence. Scenario #3 is the most expensive since after rinsing the leachate water quantity is still not adequate for release and an impermeable cover needs to be installed to reduce the quantity sufficiently to allow leachate discharge and infiltration. Scenario #2 provides for extended rinsing and then discovering that the leachate quality and quantity cannot be improved and a soil cover and long-term treatment of leachate would be required. While Scenario #2 is less costly than Scenario #3, it does include the prospect of having to provide for long-term, possibly in perpetuity, treatment. Both Scenarios #2 and #3 are included because of the uncertainty associated with the future leachate quality, future discharge water quality standards and the decision not to determine beforehand whether long-term treatment or a more costly impermeable cover would be installed.

Closure Element	Scenario #1	Scenario #2	Scenario #3	Minimum NPV Cost	Most Likely NPV Cost	Maximum NPV Cost
Site Permitting and Management				$ 1,200,000	$ 1,500,000	$ 3,000,000
Heap Leach Pad Closure	**50.0%**	**20.0%**	**30.0%**	$ -	$ -	$ -
Rinsing 1	✓		✓	$ 300,000	$ 500,000	$ 1,000,000
Rinsing 2		✓		$ 200,000	$ 300,000	$ 500,000
Soil Cover	✓	✓		$ 4,000,000	$ 6,000,000	$ 10,000,000
FML Cover			✓	$ 10,000,000	$ 12,000,000	$ 16,000,000
Leachate Discharge	✓		✓	$ 500,000	$ 750,000	$ 1,500,000
Leachate Treatment & Discharge		✓		$ 2,000,000	$ 3,000,000	$ 5,000,000
Waste Rock Closure	**20.0%**	**30.0%**	**50.0%**	$ -	$ -	$ -
Grading and Soil Cover	✓	✓		$ 5,000,000	$ 6,000,000	$ 8,000,000
Underdrain Collection Discharge	✓		✓	$ 800,000	$ 1,000,000	$ 2,000,000
Grading and FML Cover			✓	$ 15,000,000	$ 16,000,000	$ 18,000,000
Underdrain Collection, Treatment and Discharge		✓		$ 3,000,000	$ 4,000,000	$ 8,000,000
Pit Lake Closure	**50.0%**	**50.0%**	**N/A**	$ -	$ -	$ -
Maintain Pit Lake	✓			$ 300,000	$ 500,000	$ 1,000,000
Treat and Discharge		✓		$ 3,000,000	$ 4,000,000	$ 6,000,000

Figure 1: Site A – High Risk Closure

Similar scenarios and probabilities are assigned for Site B and are shown in Figure 2.

Closure Element	Scenario #1	Scenario #2	Scenario #3	Minimum NPV Cost	Most Likely NPV Cost	Maximum NPV Cost
Heap Leach Pad Closure	**50.0%**	**30.0%**	**20.0%**	$ -	$ -	$ -
Rinsing 1		✓	✓	$ 300,000	$ 500,000	$ 750,000
Rinsing 2	✓			$ 200,000	$ 300,000	$ 400,000
Soil Cover	✓		✓	$ 5,500,000	$ 6,000,000	$ 7,000,000
Direct Revegetation		✓		$ 2,000,000	$ 3,000,000	$ 4,000,000
Leachate Discharge			✓	$ 500,000	$ 750,000	$ 1,250,000
Leachate Infiltration	✓	✓		$ 250,000	$ 300,000	$ 550,000
Waste Rock Closure	**50.0%**	**30.0%**	**20.0%**	$ -	$ -	$ -
Direct Revegatation	✓			$ 2,500,000	$ 3,000,000	$ 3,500,000
Grading and Revegatation		✓		$ 4,000,000	$ 4,500,000	$ 5,500,000
Grading, Soil Cover and Revegetation			✓	$ 5,500,000	$ 6,000,000	$ 7,000,000
Leachate Infiltration	✓	✓	✓	$ 200,000	$ 300,000	$ 400,000
Pit Lake Closure	**70.0%**	**30.0%**	**N/A**	$ -	$ -	$ -
Maintain Pit Lake	✓			$ -	$ -	$ 150,000
Discharge and Infiltrate		✓		$ 450,000	$ 550,000	$ 750,000

Figure 2: Site B – Low Risk Closure

Statistical Approach

There are two aspects to the statistical approach. The first recognizes that estimates for each of the closure elements are subject to uncertainty and can vary depending on, for example, the ultimate size of a waste management unit, the amount of soil needed to construct a cover, the cost of the soil needed, the amount of rinsing a heap is subjected to, etc. These uncertainties are captured by establishing a wide enough range between the minimum and maximum costs as those shown in Figures 1 and 2, for example.

For each of the closure elements, a "most likely" closure cost is also established to allow a statistical distribution to be established. A large number of statistical distributions can be used to describe how costs may vary between the minimum and maximum ranges, i.e. normal, log normal, uniform, triangular. Each is unique and reflects the type of uncertainty that can occur. For purposes of this paper, a Program Evaluation & Review Technique (PERT) distribution is used.

The PERT distribution is defined by three values: a minimum value, a most likely value, and a maximum value. The PERT distribution is a special form of the Beta distribution, with the range defined by the minimum and maximum values and the shape parameter calculated from the defined most likely value. It is generally considered to be superior to the Triangular distribution, as the smooth shape of the PERT curve focuses a higher density of values closer to the most likely value and places less emphasis in the direction of the skew when the parameters result in a skewed distribution. The PERT distribution can also be compared to a Normal distribution in that it takes on a symmetric 'bell shape' when the most likely value is defined as the average of the minimum and maximum values. The key difference between the two is that the PERT distribution is bounded by the minimum and maximum values, whereas the Normal distribution is open ended and can accommodate more extreme 'tail' events. Where reasonable bounds can typically be defined, it is not necessary to make allowance for such extreme events. Also, in the PERT distribution, the most likely value can be set either closer to the minimum or maximum value depending on whether there is a higher likelihood of it being closer to either of these values.

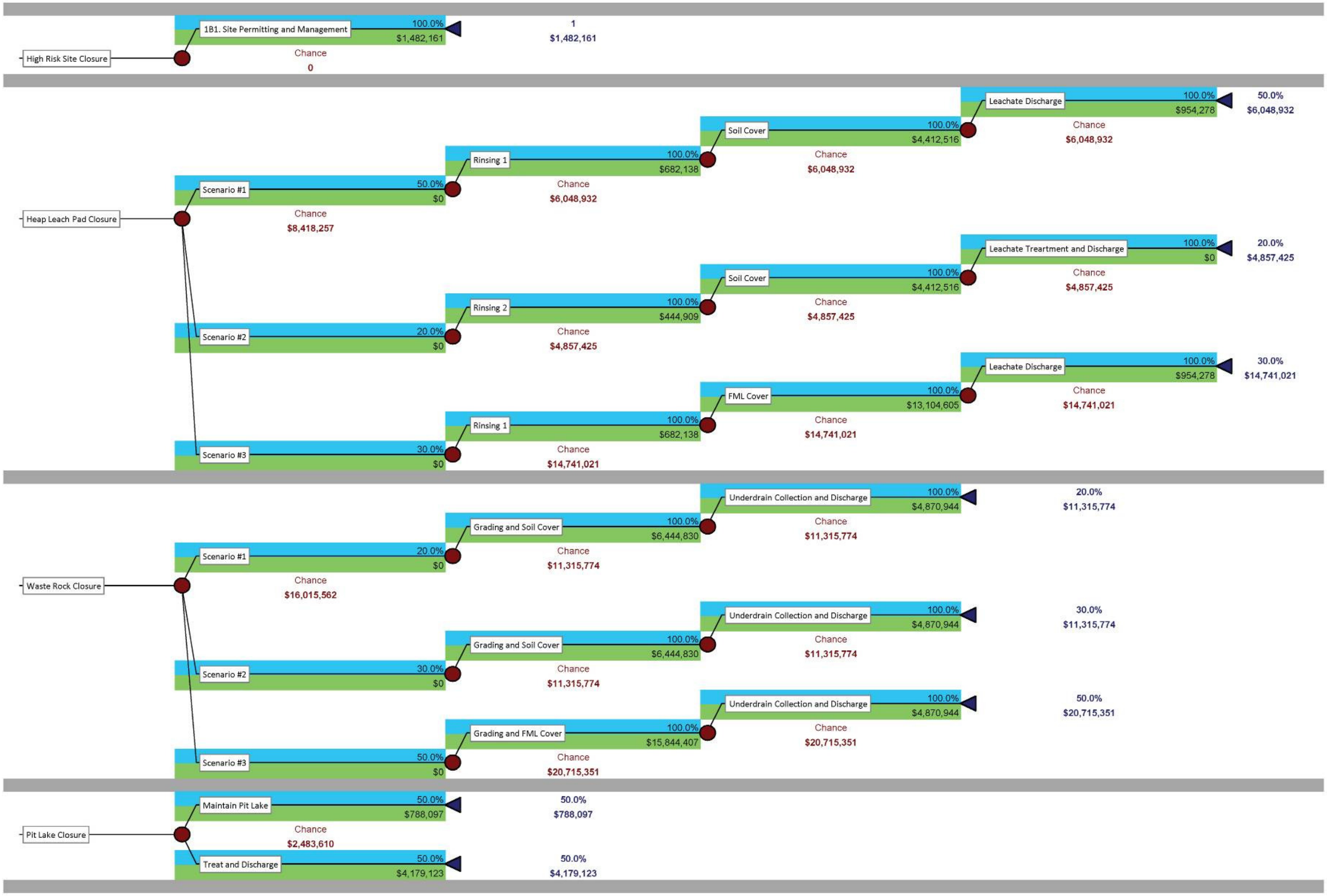

Figure 3: Site A – Individual Sub-Decision Trees

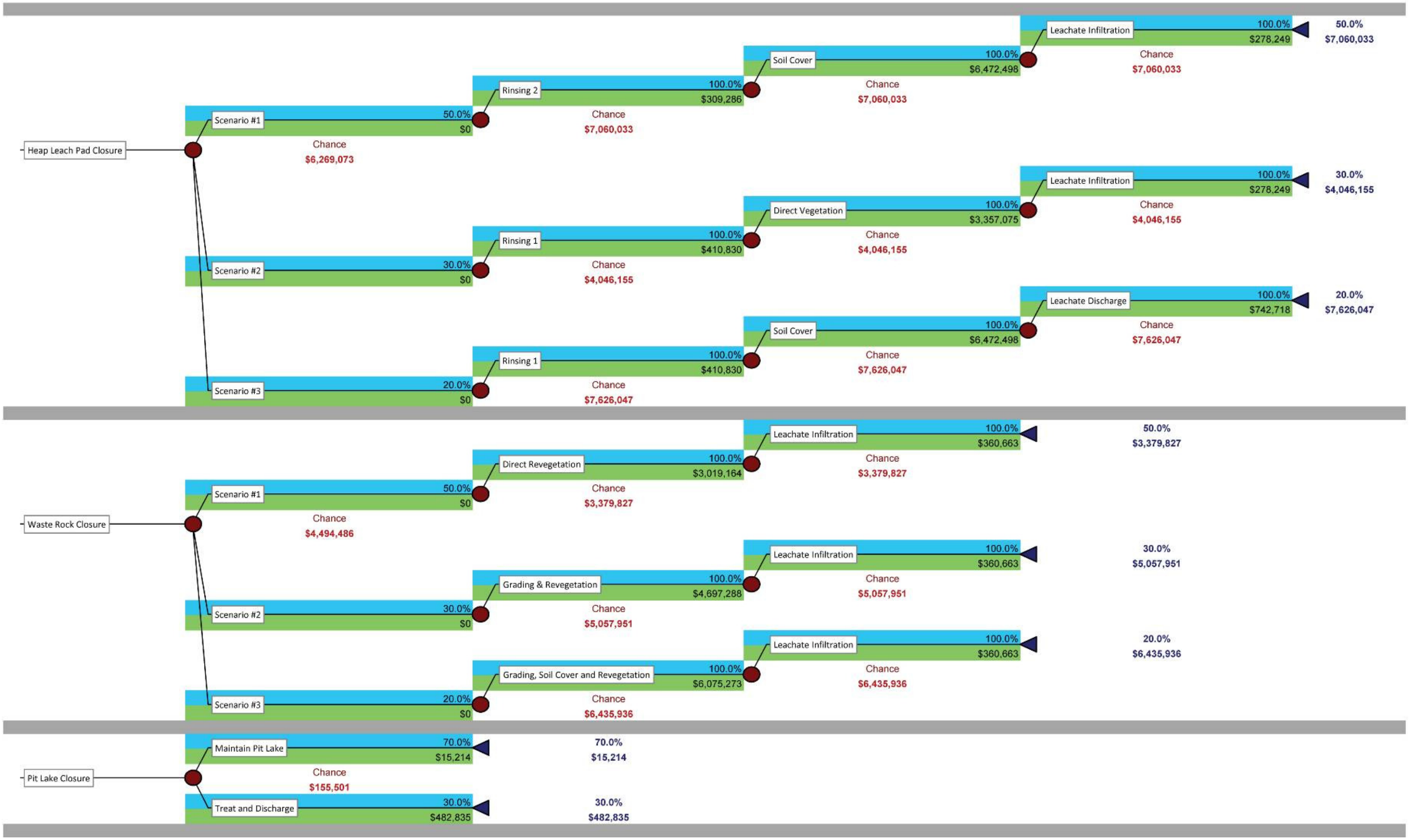

Figure 4: Site B – Individual Sub-Decision Trees

The second statistical approach is to construct a “decision tree” that incorporates all potential future combinations of the mine closure elements contained in Figures 1 and 2. Figures 3 and 4 illustrate decision trees constructed for each aspect of closure, i.e. heap leach pad closure, waste rock closure, and pit lake closure. These individual decision trees must then be combined to provide one comprehensive tree that encompasses all branches, as shown in Figures 5 and 6. In these examples, each decision tree has 18 outcomes (i.e. three heap leach closure scenarios x three waste rock closure scenarios x two pit closure scenarios). Actual real world cases would typically have a larger number of outcomes.

Following the design of costs and probability distributions for the various closure elements and assembling the comprehensive trees for the two sites (A and B), standard statistical tools are used to generate a cost versus probability of exceedance curve for each site, as shown in Figures 7 through 10. Monte Carlo simulation methods are used to generate average costs (PERT Costs) for the specified minimum to maximum ranges. Decision tree analyses are used to calculate expected closure costs, most likely closure costs, the statistical distribution of each of these, and the cost probability of exceedance curves for all of the potential closure scenarios. For purpose of the analyses presented in this paper, PrecisionTree and @Risk software tools by Palisade Corporation have been used to calculate the following:

- The most likely closure costs at different levels of certainty (Figures 7 and 8)
- The expected closure costs at different levels of certainty (Figures 9 and 10)
- The cost versus probability curve for the various closure scenarios (Figures 11 and 12)

The important conclusions that can be derived from the cost data provided in Figures 1 and 2 and each of the cost probability curves are as follows:

<u>Site A: Most Likely (High Risk Closure)</u>

- Using an “optimistic” approach and assuming that the lowest cost elements are going to be required yields a total closure cost of \$16.1 million (Figure 1). This has been the approach in some instances in the past. Using the worst case assumptions yields an unrealistically high cost of \$57.0 million.
- Using the conventional approach and selecting the most likely costs for the highest probability closure elements yields a total closure cost of \$29.8 million (Figure 1). This is often the approach used in the mining industry.
- The statistically based expected closure cost is \$29.0 million (Figure 9).
- The statistically based most likely closure cost is \$34.3 million. At a 90% confidence level the most likely cost is \$36.4 million (Figure 7). These costs are higher than the conventionally estimated costs.
- The 90% confidence level closure cost estimate, considering the range of potential closure scenarios illustrated in Figure 5, yields a closure cost of \$34.5 million (Figure 11). This takes into account the variability in the types of closure scenarios that may have to be implemented. The 20% level confidence closure cost is \$20.7 million. This latter cost, which has a high probability of being expended (i.e. 80%), has been used by the authors at various sites to represent the “probable and reasonably estimable” reserve cost.

<u>Site B: Most Likely (Low Risk Closure)</u>

- Using an "optimistic" approach and assuming the lowest cost elements are going to be required yields a total closure cost of $6.6 million (Figure 1). The worst case cost amounts to $17.2 million.
- Using the conventional approach and selecting the most likely costs for the highest probability closure elements yields a total closure cost of $10.9 million (Figure 1).
- The statistically based expected closure cost is $10.6 million (Figure 10).
- The statistically based most likely closure cost is also $10.6 million. At a 90% confidence level the most likely cost is 11.0 million (Figure 8).
- The 90% confidence level closure cost estimate considering the range of potential closure scenarios illustrated in Figure 6 yields a closure cost of $13.0 million (Figure 12). The 20% level confidence closure cost is $9.0 million.

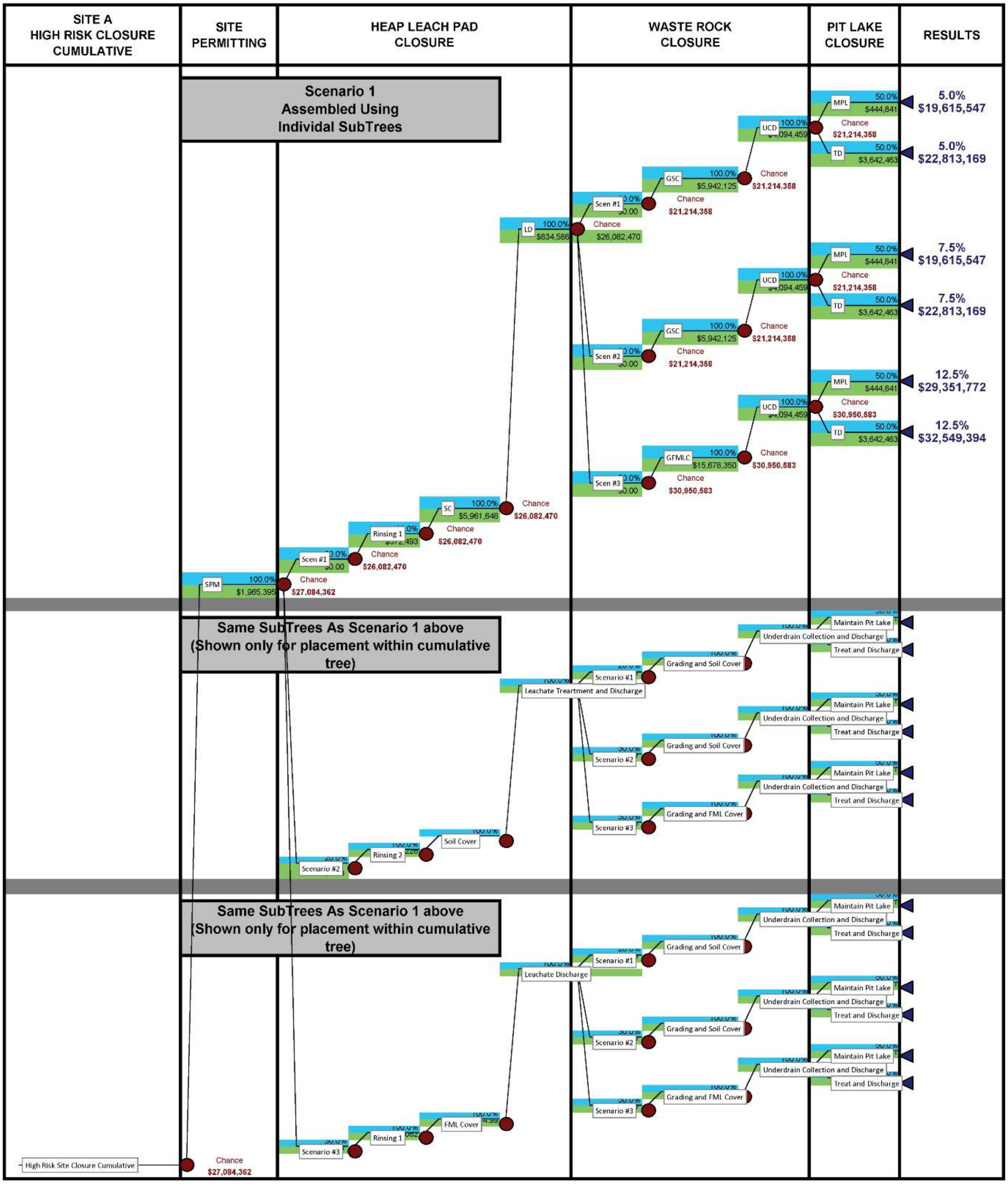

Figure 5: Site A – Combined Decision Tree

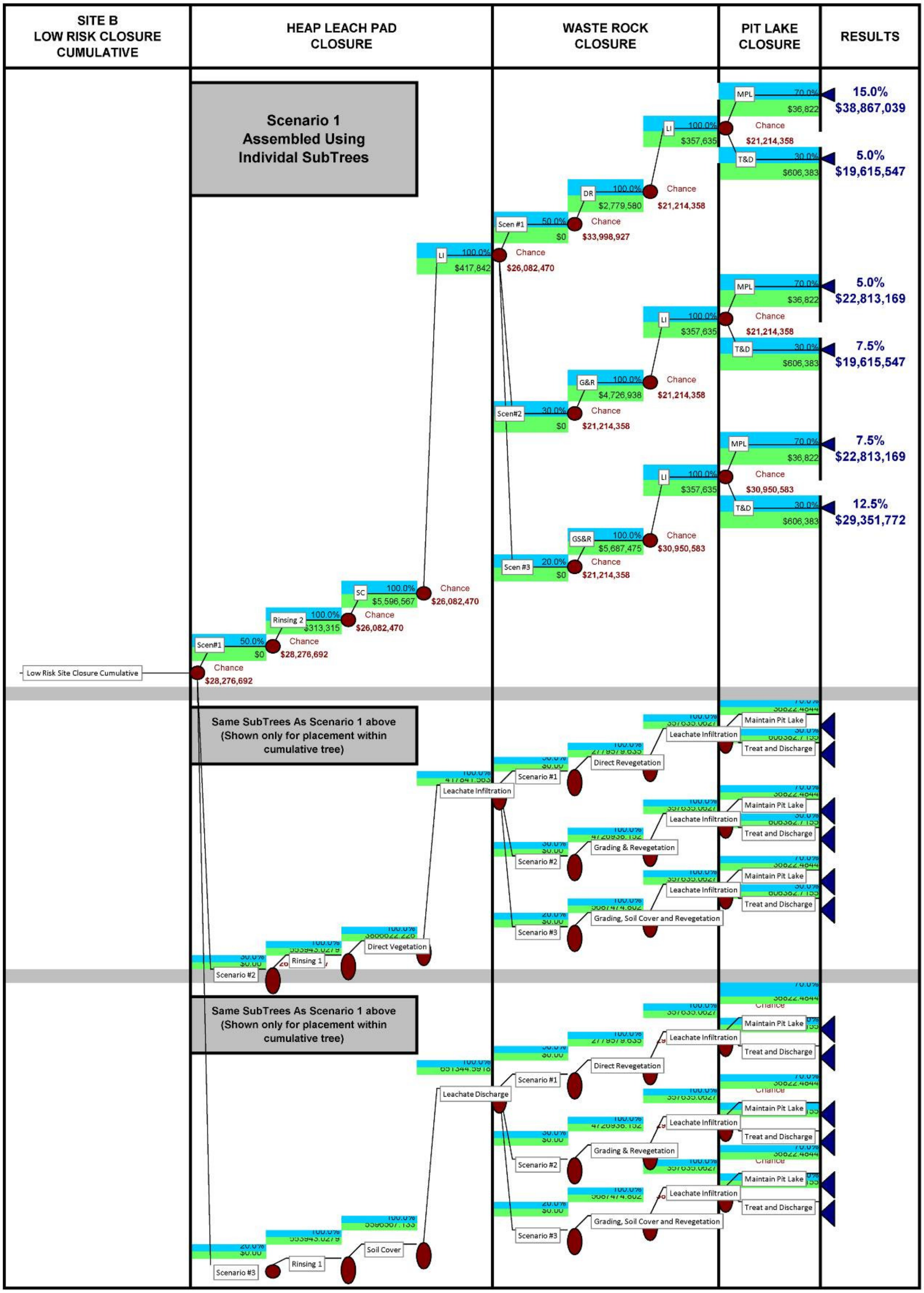

Figure 6: **Site B – Combined Decision Tree**

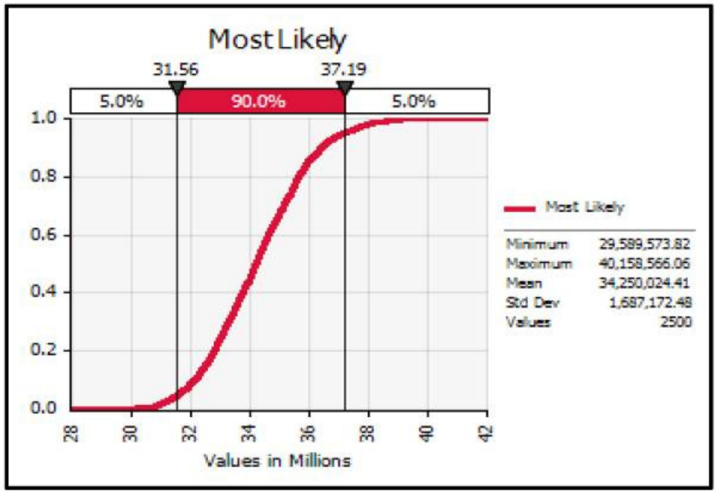

Figure 7: Site A – Most Likely Cost Probability of Exceedance

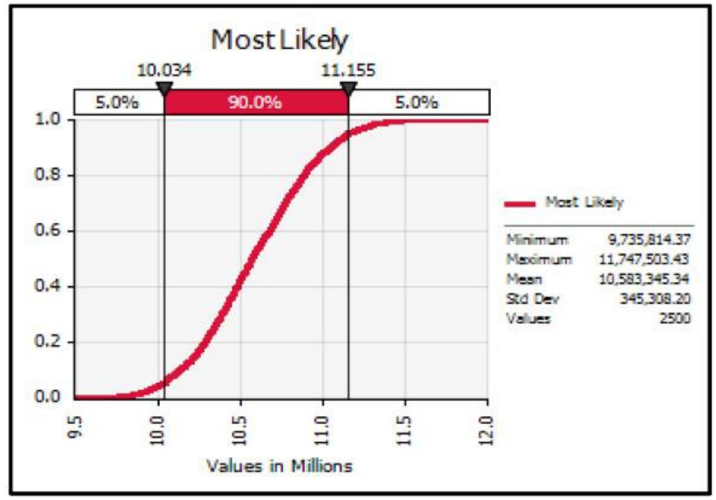

Figure 8: Site B – Most Likely Cost Probability of Exceedance

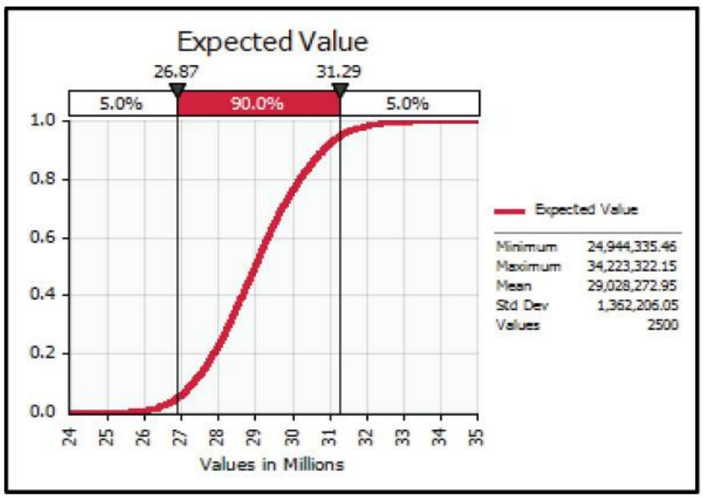

Figure 9: Site A – Expected Value Cost Probability of Exceedance

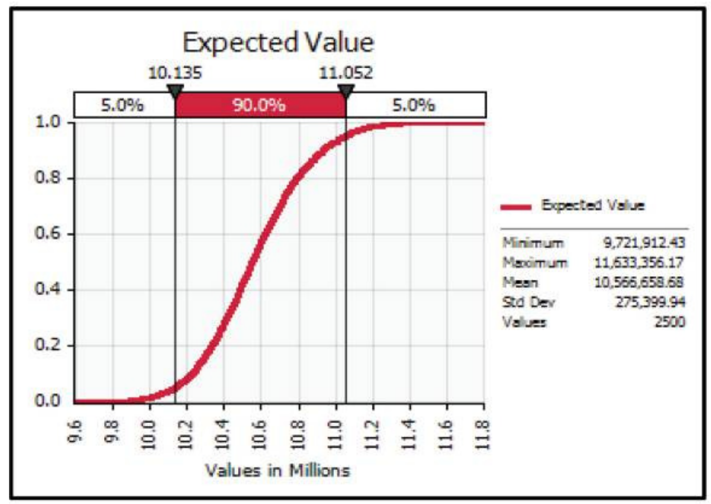

Figure 10: Site B – Expected Value Cost Probability of Exceedance

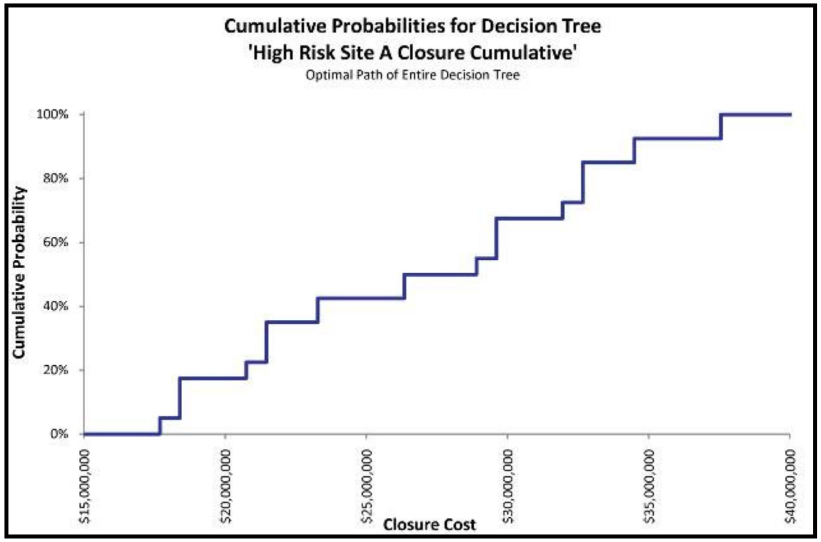

Figure 11: Site A – Cost Versus Probability

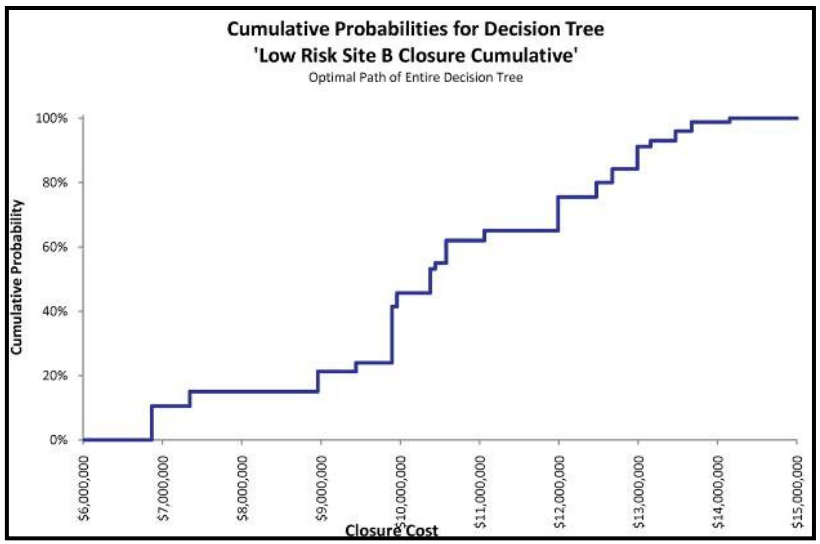

Figure 12: Site B – Cost Versus Probability

Conclusions

The statistical approach described here will provide mining companies with a more comprehensive characterization of their financial closure liabilities. The approach accommodates different closure scenarios incorporated into a decision tree, which if correctly selected, will cover the spectrum of potential future requirements. Using the @Risk element to reflect the change of potential costs associated with the specific elements in each closure scenario provides further quantification of future uncertainties.

The statistical approach narrows the potential range of costs that may be hypothesized. The ranges for the above examples are $16.1 to $57.0 million and $6.6 to $17.2 million respectively. The statistical analyses yield expected and most likely values with much narrower ranges, as indicated above.

The cumulative cost exceedance probability curves that result from the decision tree analyses provide closure estimates for different probabilities of exceedance. Costs that have a higher probability of being exceeded can be used in reporting financial reserves. Typically, accounting requirements for such reserves demand that there be a high probability that the costs will be expended. As indicated by the above examples, these costs could be set at $20.7 and $9.0 million, respectively, for Sites A and B.

Costs that leave a very low probability of being exceeded can be used for the financial feasibility analyses of the project. For example, the 90% confidence level costs for Sites A and B of $34.5 and $13.0 million, respectively, could be used. These are higher than the conventionally estimated most likely costs of $29.8 and $10.9 million, respectively.

The conventionally estimated closure costs of 67.5% and 62.0%, have similar probabilities of not being exceeded. These may be considered adequate for some mining companies. However, without at least going through the rigour of establishing the closure element costs and probabilities in Figures 1 and 2, even this level of confidence may not be achievable.

Identifying the elements and probabilities that contribute to the high end cost of the cumulative cost exceedance probability curve will allow a mining company to focus its effort on identifying the major cost risks early on in a mine's life cycle and will provide for sufficient data collection and research to minimize these costs and/or probabilities. These elements include the need to provide impermeable covers to the residue and waste rock piles in order to limit leachate formation and the need to treat excess water that accumulates in the mine pits after closure.

Recommendations

Those responsible for mine closure planning and cost estimating would do well to adopt the approaches described here. These approaches provide a more formalized structure for identifying all possible future outcomes, as well as a statistical basis for select costs for financial analyses and reserve establishment, each with appropriately different exceedance probabilities, which may result in the use of higher, more conservative closure cost estimates.