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A step-by-step guide for evaluating the preferred closure scenarios using a hybrid options assessment model

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Abstract

The achievement of optimal closure outcomes hinges on a robust planning and execution process. Closure planning should be an integral part of an asset's lifecycle, with a formal, detailed planning process being initiated towards the end of operational cessation. Useful guidelines, case studies, and project delivery models exist to assist the closure planning process. While these provide a structured framework for addressing key elements of closure, they do not transcribe all circumstances, complexities, and decisions faced by an asset owner and impacted parties.

The ability to optimise closure execution diminishes once the preferred closure scenario is committed to by the appropriate decision-makers, with a subsequent escalation of change implementation cost over time. From a myriad of interdependent and sometimes conflicting requirements, variables and uncertainties, an asset owner must find a way to achieve a balanced scorecard while meeting its obligations and stakeholder expectations. To this aim, this paper presents a potential process map for determining the preferred closure scenarios, including instructional steps, a hybrid options assessment model, and examples for each component.

Prior assumptions should be verified through data gathering to fill knowledge gaps, establish context and baseline knowledge, and define the relevant closure domains and work elements. With the necessary input of subject matter experts, technical practitioners and project stakeholders, a set of integrated trade-off studies can be carried out using multi-criteria analysis (MCA) to assess the merit and impact of key decisions under each closure scenario. Compatible options between trade-off studies can be linked up to form branches of a decision tree for each closure scenario, where preferences on possible decisions are revealed by the quantitative MCA scoring as well as qualitative ranking of the trade-off studies. Given the subjective nature of these assessments, different perspectives should be adequately considered/challenged, and the results tested through sensitivity analysis. The options selection process should be transparent, rigorous, defensible and well documented to form a robust basis for decisions that will have an enduring legacy.

Keywords: *closure study methodology, closure scenarios, closure options, trade-off study, options assessment*

1 Introduction

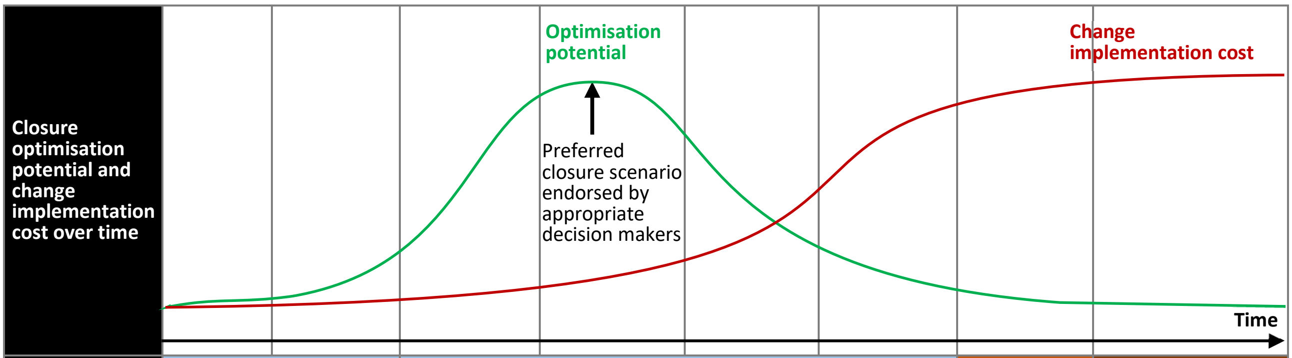
Key elements of asset closure are addressed in various guidelines and case studies published by:

- International standard development organisations (e.g. International Organization for Standardization [ISO] 2021a, 2021b).
- International industry councils (e.g. International Council on Mining and Metals 2019).
- Government agencies (e.g. Department of Mines and Petroleum & Environmental Protection Authority 2015).
- Asset owners (e.g. Grant & Botha 2019; Heyes & Cooper 2019; Knott 2018).

These provide a structured framework for realising opportunities and beneficial outcomes for the environment, employees, asset owners, and wider communities during an asset's lifecycle. Asset owners are compelled to adopt an integrated closure planning and implementation approach for accommodating the requirements and aspirations of relevant internal and external stakeholders and leave a positive and sustainable legacy post-closure.

Uncertainties around the timing of closure may exist throughout an asset's operational phase. Nevertheless, knowledge base, signatory commitments, legal obligations, alternative scenarios, residual liabilities, risks and opportunities around the physical, biophysical and socio-economic aspects of closure should continue to be identified and captured in a preliminary closure plan based on the current projection of the remaining life of asset. The preliminary closure plan should be updated periodically during the operational phase to form the basis of the present closure obligation and total projected cost of closure, accompanied by a range of environmental, progressive rehabilitation, and infrastructure/waste management plans that align with the closure objectives as they are understood at the time.

Similar to the gated approach typically utilised to deliver major capital projects, the closure of a major industrial site customarily incorporates a front-end loading (FEL) process, where a detailed closure plan is developed and refined through successive studies, as shown in Figure 1.



Phase	**Preliminary closure plan**		**Detailed closure plan**				**Closure execution**	**Post-closure monitoring and maintenance**
	Permitting	**Operation and progressive closure**				**Transition**		
	Pre-operation	**Operation**	**Conceptual study**	**Pre-feasibility study**	**Feasibility study**	**Pre-closure**		
Range of scope and design definition	**1% to 5%**		**5% to 15%**	**15% to 40%**	**40% to 70%**	**70% to 90%**	**90% to 100%**	**90% to 100%**
Range of cost estimate accuracy	**Class 5 -50% to +100%**		**Class 4 -30% to +50%**	**Class 3 -20% to +30%**	**Class 2 -15% to +20%**	**Class 1 -10% to +15%**	**Class 1 -10% to +15%**	**Class 1 -10% to +15%**

Figure 1 Closure optimisation potential and change implementation cost over time

This detailed planning process should be initiated with sufficient lead time (notionally five years ahead of closure execution) for operational integration, collection/analysis of relevant data, stakeholder endorsement of completion criteria, execution planning, and workforce/social transitioning. While the process and terminology may differ across industries and organisations, the FEL phase typically encompasses two or three formal studies that progressively increase the scope/design definition, stakeholder alignment and cost certainty of a project. For the three-stage study process outlined in Figure 1, the overarching objectives of each study may be as follows:

- Conceptual study: identify the most likely closure scenario based on preliminary technical and economic evaluation.
- Pre-feasibility study: assess the technical and economic viability of multiple options and recommended a preferred closure scenario for further study in the feasibility phase.

- Feasibility study: produce a well-defined closure scenario, a definitive cost estimate, and a set of detailed execution plans to enable closure execution.

As illustrated in Figure 1, the ability to optimise closure execution diminishes once the preferred closure scenario is committed to by the appropriate decision-makers, with a subsequent escalation of change implementation cost over time. From a myriad of interdependent and sometimes conflicting requirements, variables and uncertainties, how can an asset owner achieve a balanced scorecard in choosing the 'preferred closure scenario' entailing the pre-closure (transition), closure execution, and post-closure monitoring and maintenance (PCMM) phases of an existing operation while meeting its obligations as well as stakeholder expectations? The remainder of this paper presents a structured process to identify, assess, and select the preferred closure scenario that informs the subsequent course of actions with an enduring impact on the business, host communities, and the wider environment as a whole.

2 Closure options identification and selection

Figure 2 presents a potential process map for closure options identification and selection.

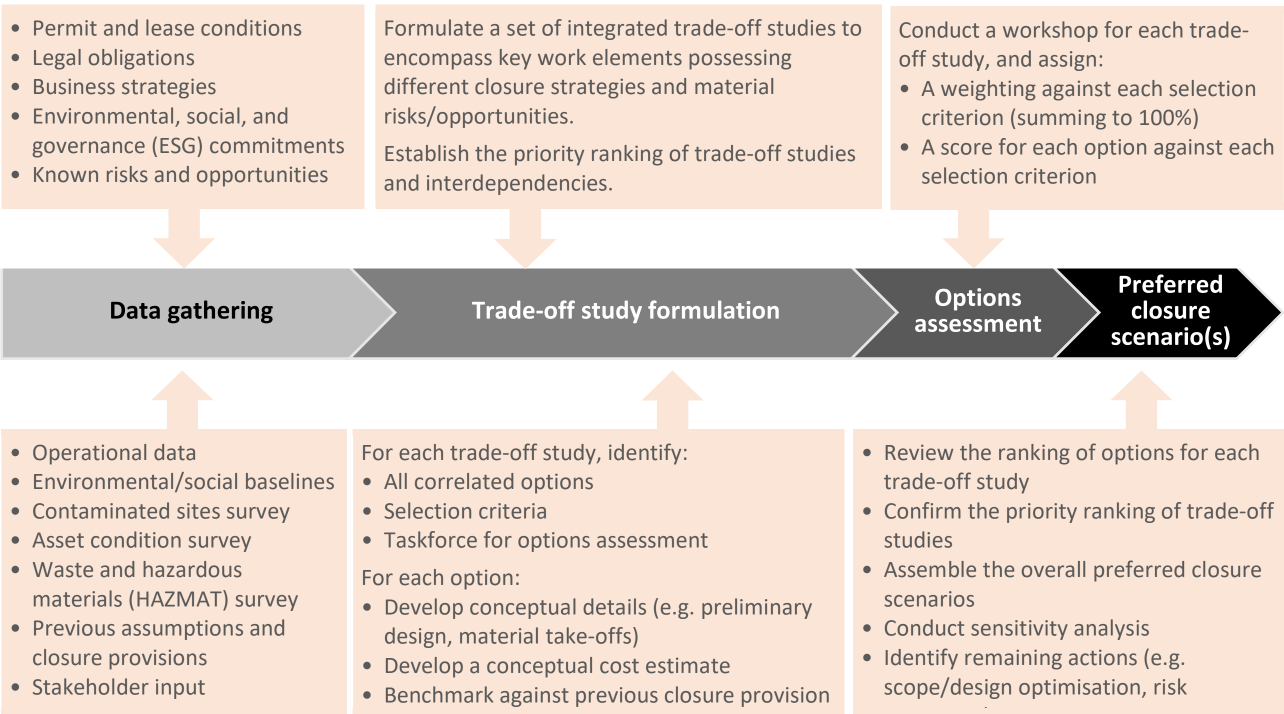


Figure 2 Potential process map for closure options identification and selection

2.1 Data gathering

2.1.1 Study scope and knowledge base

During the data gathering stage of a closure study, the study team should familiarise themselves with:

- The status of the closure planning process.
- The existing knowledge base and any gaps.
- Potential completion criteria and design basis.
- The overall study methodology and budget.
- The required scope, technical input, pricing, and schedule maturity for the particular study phase.

Once the context and baseline knowledge have been established, the study team should then seek to understand the interdependencies between each scope element and adopt a practical approach for bridging key gaps. Knowledge gaps should be addressed to the required level of certainty for the study phase through further desktop studies, field data gathering, engineering design/modelling, and consultations with the relevant subject matter experts (SMEs) and stakeholders.

2.1.2 Closure domains and sub-areas

Physical 'closure domains', defined by groups of landforms or infrastructure with similar rehabilitation and closure requirements, should be defined to encompass the entire land tenure undergoing closure. Example closure domains include:

- Mining areas (e.g. rehabilitated and unrehabilitated areas, haul roads and ramps, production and borrow pits, waste dumps, stockpiles, run-of-mine areas).
- Unimpacted zones (e.g. undisturbed and uncontaminated areas, buffer zones).
- Tailings storage facilities (TSFs).
- Onsite infrastructure (e.g. buildings, access roads, process plant, heap leaches, materials handling systems, utility systems, bridges, wharves).
- Offsite infrastructure (e.g. dedicated power and water supply systems, airport, accommodation camp, warehouses).
- Water management facilities (e.g. sediment ponds, extraction bores, water storage dams, culverts and drains, wetlands).
- Waste disposal facilities (e.g. stockpiled waste materials, landfills).

Closure objectives, completion/acceptance criteria, specific requirements from existing permitting documents and management plans (some of which may have already been communicated with regulators and other external stakeholders), and alternative options should be compiled for each closure domain. Some closure domains may need to be split into 'sub-areas' with different closure options and completion criteria.

2.1.3 Work elements

Previously identified assumptions, risks, and opportunities should be consolidated under each 'work element' and updated to align with the current set of closure strategies and options. Work elements can be thought of as groups of work breakdown structures with correlated closure provisioning decisions, such as:

- Operational transition (e.g. ramp down, de-energisation, make-safe, human resources).
- Temporary and enabling works (e.g. alternative or relocated utility supply infrastructure, laydown areas, new or relocated infrastructure to support closure execution).
- Waste management (e.g. management of raw materials, by-products, TSFs, liquid waste and residues, stockpiled/landfilled solid waste).
- Decontamination and demolition of fixed infrastructure (e.g. removal of residues, HAZMAT handling, demolition, scrap management).
- Soil remediation (e.g. excavation and/or treatment of contaminated soil).
- Rehabilitation/revegetation (e.g. all areas needing various levels of rehabilitation/revegetation, including areas to be backfilled, sub-standard rehabilitated areas, TSFs and landfill covers).
- Final landform (e.g. bulk earthworks to backfill mining, demolition or soil remediation voids, cover system construction, site regrading, drainage and sediment features, surface water management).
- PCMM (e.g. environmental/asset monitoring and maintenance during/after closure execution).

- Owner's costs and indirect costs.

A wide range of SMEs, technical practitioners, and stakeholders will need to be involved to adequately address and integrate these work elements.

2.2 Trade-off study formulation

2.2.1 Closure scenarios

'Closure scenarios' can be thought of as the combination of closure execution and PCMM works that will need to be carried out in order to achieve various completion criteria across the site. Potential closure scenarios can range from mothballing to full rehabilitation (i.e. bookends) and anything in between. Four example closure scenarios are described in Figure 3 to demonstrate the concept.

Closure Scenario 1 Mothballing	Closure Scenario 2 Partial demolition and repurposing	Closure Scenario 3 Full demolition and alternative land use	Closure Scenario 4 Full rehabilitation and relinquishment
• **Mining areas – rehabilitated** Weed eradication, PCMM	• **Mining areas – rehabilitated** Weed eradication, PCMM	• **Mining areas – rehabilitated** Weed eradication, PCMM	• **Mining areas – rehabilitated** Weed eradication, PCMM
• **Mining areas – unrehabilitated** Backfill/rehabilitate/ revegetate land, PCMM	• **Mining areas – unrehabilitated** Backfill/rehabilitate/ revegetate land, PCMM	• **Mining areas – unrehabilitated** Backfill/rehabilitate/ revegetate land, PCMM	• **Mining areas – unrehabilitated** Backfill/rehabilitate/ revegetate land, PCMM
• **Unimpacted zones** Environmental PCMM	• **Unimpacted zones** Environmental PCMM	• **Unimpacted zones** Environmental PCMM	• **Unimpacted zones** Environmental PCMM
• **TSFs** Decommission, renew required permits, PCMM	• **TSFs** Full closure, PCMM	• **TSFs** Full closure, PCMM	• **TSFs** Full closure, PCMM
• **Onsite infrastructure** De-energise, decontaminate and make-safe, PCMM	• **Onsite infrastructure** Demolish redundant infrastructure, refurbish select infrastructure, backfill/ rehabilitate/revegetate land, PCMM	• **Onsite infrastructure** Demolish all fixed infrastructure except the wharf, backfill/rehabilitate/ revegetate land, PCMM	• **Onsite infrastructure** Demolish all fixed infrastructure, backfill/ rehabilitate/revegetate land, PCMM
• **Offsite infrastructure** PCMM	• **Offsite infrastructure** Demolish redundant infrastructure, refurbish select infrastructure, PCMM	• **Offsite infrastructure** Demolish all fixed infrastructure except the airport and accommodation camp, backfill/rehabilitate/ revegetate land, PCMM	• **Offsite infrastructure** Demolish all fixed infrastructure, backfill/ rehabilitate/revegetate land, PCMM
• **Water management facilities** Make-safe of retained facilities, PCMM	• **Water management facilities** Demolish redundant facilities, make-safe of retained facilities, backfill/rehabilitate/revegetate land, PCMM	• **Water management facilities** Demolish redundant facilities, make-safe of retained facilities, backfill/rehabilitate/revegetate land, PCMM	• **Water management facilities** Demolish all facilities, backfill/rehabilitate/revegetate land, PCMM
• **Waste disposal facilities** Renew required permits, PCMM	• **Waste disposal facilities** Add demolition and soil remediation waste to existing landfills, renew required permits, PCMM	• **Waste disposal facilities** Add demolition and soil remediation waste to existing landfills, renew required permits, PCMM	• **Waste disposal facilities** Relocate all stockpiled and landfilled waste offsite, backfill/rehabilitate/revegetate land, PCMM

Figure 3 Example closure scenarios

2.2.2 Hybrid options assessment model

A set of 'integrated trade-off studies' can be formulated to encompass the key work elements possessing different closure strategies and material risks/opportunities. Trade-off studies can be structured so that there is at least one viable option that correlates with all other viable options under every closure scenario. In this way, a decision tree (Department for Communities and Local Government 2009; Magee 1964) can be created for each closure scenario, as shown in Figure 4 (noting that not all branches are shown). Miscellaneous scope items can be introduced as fixed provisions so that a complete closure scope and cost estimate can be established for every branch of a decision tree. The example tree branches depicted in Figure 4 show that specific sets of options under each closure scenario can be defined by the combined attributes and cost estimates for the selected leaf nodes.

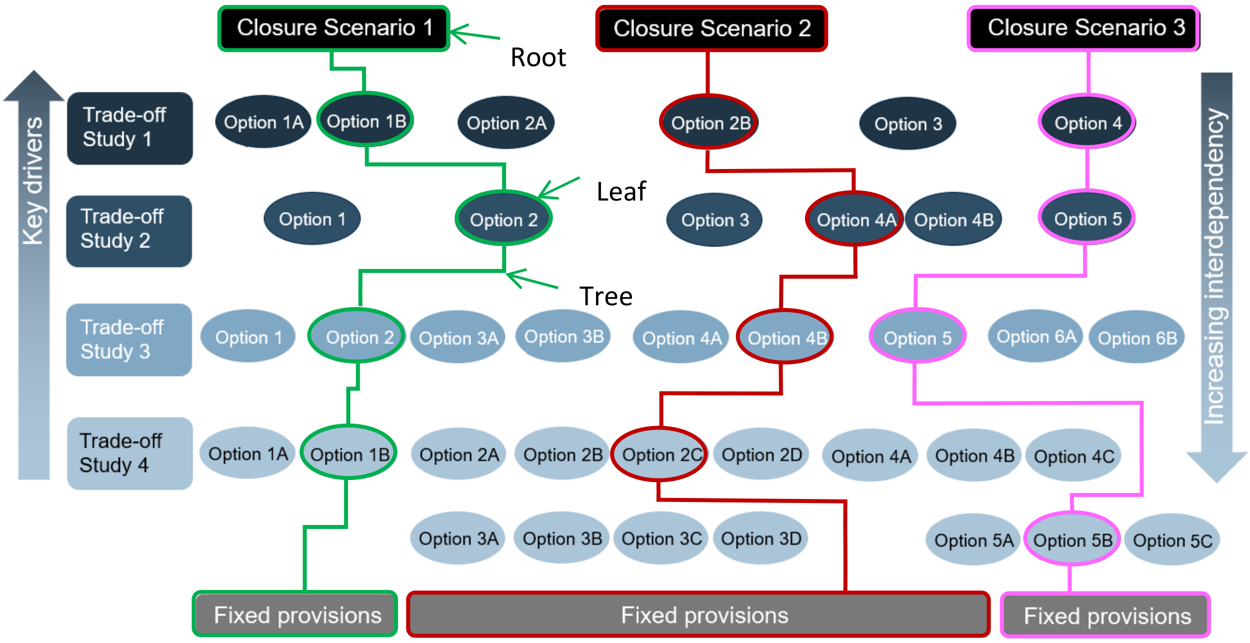


Figure 4 Example hybrid options assessment model

The proposed hybrid options assessment model utilises:

- Multi-criteria analysis (MCA) (Infrastructure Australia 2021) along the horizontal axis across multiple trade-off studies.
- Decision tree analysis along the vertical axis to show sets of compatible options under each closure scenario.

Section 2.2.3 to 2.4 provide a step-by-step guide in forming the relevant trade-off studies, defining selection criteria, developing individual options, completing the scoring process, constructing decision trees, and testing the sensitivity of the results.

2.2.3 Trade-off study framework

Trade-off studies can answer key questions by comparing and contrasting a range of potential options. The identified options for each aspect of closure, such as timing and completion criteria for each work element, often carry implications on other aspects of closure. In other words, the majority of decisions to be made are not independent of one another.

It is possible to formulate a set of trade-off studies to fully divide the variable components of closure, with the addition of fixed provisions that do not represent decision drivers. Depending on the particular circumstances, trade-off studies can be formed by grouping:

- Key decisions that carry a material impact.
- Work elements (see Section 2.1.3) or potential execution work packages.
- Existing physical, functional, or leased/owned boundaries.
- Closure domains affected by key opportunities, threats, or constraints.
- Closure domains with common post-operational land use and/or completion criteria.
- Closure domains or assets having different closure execution time frames.

- The required temporary or permanent processes or services.
- Elements controlled, regulated, or influenced by external parties.

Consensus on the priority ranking of the trade-off studies should be fostered, so that preferences from each trade-off study can guide the overall decision-making. Referring to Figure 4, the trade-off study representing the most important decision driver should be placed on the top of the decision trees. Going down on the decision trees, each subsequent tier of trade-off study plays a decreasing role as a decision driver while being more dependent upon the tiers above.

As an example, the most critical decision may be derived from a trade-off study on the top of the decision trees to evaluate the preferences for the management of waste, contamination, or the extent of rehabilitation. The available options from this tier-1 trade-off study may then drive the next tiers of trade-off studies that examine the associated options for the infrastructure, land use and time frame, or the required services. All the available options may culminate in a range of landform options on the bottom of the decision trees. These examples are elaborated further in Section 2.2.5.

The priority ranking of the trade-off studies may be altered at any time, as long as all interdependencies and correlated options are mapped out. Endorsement of the overall approach by the relevant stakeholders at the onset is of crucial importance for attaining the ultimate buy-in of the outcomes.

2.2.4 Selection criteria

Given the linkages and complexities, a high level of coordination is required to complete the trade-off studies. A taskforce consisting of relevant SMEs, technical practitioners, and project stakeholders should be established for each trade-off study, under appropriate guidance of the study management and corporate governance groups. Each taskforce should agree on the set of 'selection criteria' to be used in their particular trade-off study, which may include:

- Regulatory compliance.
- Environmental value.
- Stakeholder expectations.
- Community benefits.
- Health, safety and environmental (HSE) risks.
- Operational or asset transition impact.
- Transport and logistics considerations.
- Technical risk or complexity.
- Residual liability.
- Cost.

The chosen selection criteria should be used to guide options development, characterise and score the identified options, and flag additional SMEs or stakeholders that may need to be included in the process.

2.2.5 Options development

Correlated options between trade-off studies will need to be developed in an iterative manner to eliminate inconsistencies, gaps and overlaps. Example trade-off studies and options are provided in Table 1 to demonstrate the concept. It is essential to develop at least one viable option for each closure scenario and track the dependencies between each tier of options to uncover decision branches, as illustrated in Figure 4.

Table 1 Example trade-off studies and associated options

Example trade-off studies	Example options
Trade-off Study 1 Waste management options	Options for stockpiled mineral waste (e.g. reprocess, export, landfill) TSF closure options (e.g. reprocess, consolidate, cap, partial reclaim) Options for the existing landfills (e.g. retain, re-encapsulate, remove)
Trade-off Study 2 Infrastructure retention/demolition options	Different groupings of new (temporary/permanent), retained (refurbished/relocated) or demolished assets – independent or dependent upon the options above Different demolition depth options – independent or dependent upon the options above
Trade-off Study 3 Services provision options	Different options for power, water and fuel supply – independent or dependent upon the options above Different options for sewage management – independent or dependent upon the options above
Trade-off Study 4 Landform options	All independent and dependent landform options

2.3 Options assessment

The selection criteria (see Section 2.2.4) established for each trade-off study can now be used to score each option using an MCA. Based on the context and scope of each trade-off study, the taskforce should conduct a robust discussion to align on the relative importance of each selection criterion and derive a weighting out of 100%, as illustrated in Figure 5.

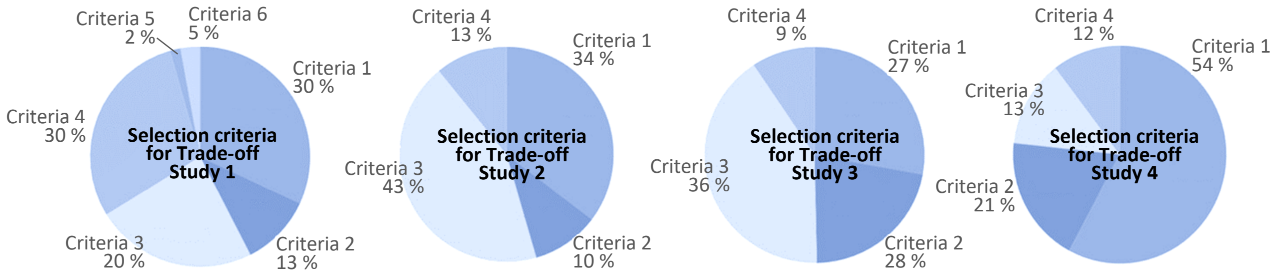


Figure 5 Example selection criteria weightings

The taskforce should then evaluate the details and costings developed for the options against each selection criterion, and assign a score against each selection criterion utilising a standardised scoring system. For instance, a score of 1 to 10 can be used to indicate the least to the most favourable option against each selection criterion.

The weighting and scoring process should be facilitated to ensure that different perspectives are adequately expressed, considered, and challenged among the group before reaching a consensus or a majority view. Given the subjective nature, the options assessment process should be transparent, rigorous, defensible, and well documented. All relevant assumptions, qualifications and limitations should be communicated, accounted for, and recorded to provide context.

2.4 Preferred closure scenarios

Scores from the individual trade-off studies can now be applied to determine the preferred set of options under each closure scenario, as illustrated in Figure 6.

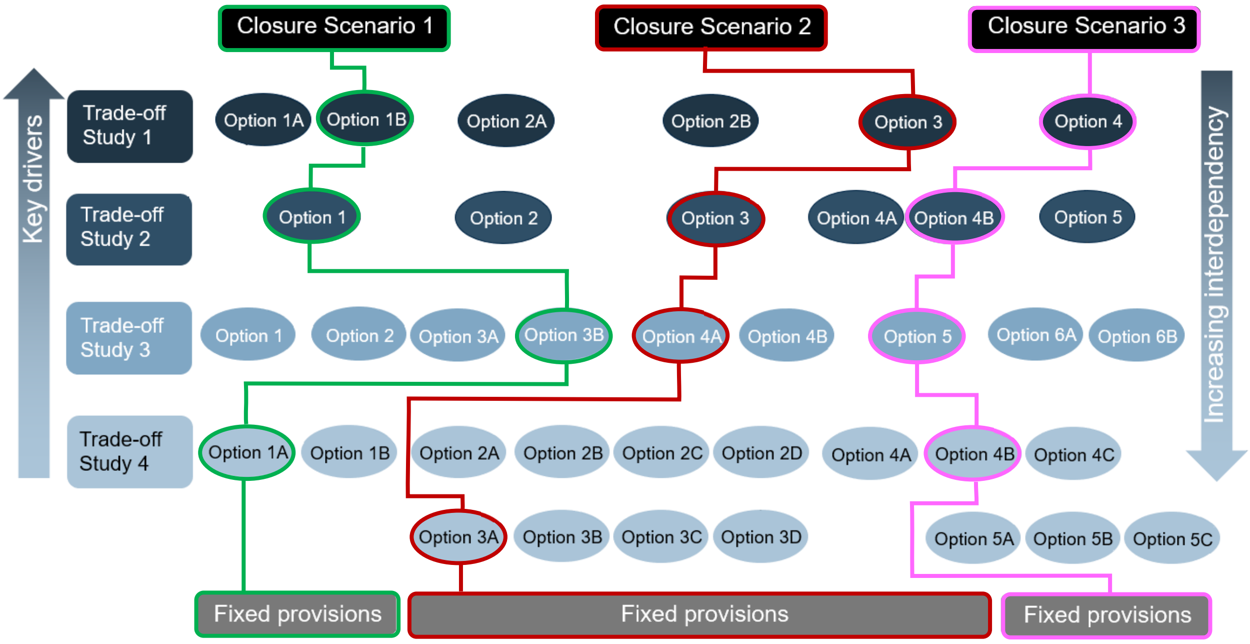


Figure 6 Example tree branches showing the preferred set of options under each closure scenario

The initial results should be cross-checked against the closure objectives stated for each closure scenario to determine if there are anomalous or counter-intuitive findings. Sensitivity analysis should then be carried out to test how preferences change when the following are adjusted:

- Selection criteria weightings.
- Scoring against each selection criterion.
- Ranking of the trade-off studies.

Apart from the hybrid options assessment model presented in this paper, other analytical methods (both qualitative and quantitative) can be applied to evaluate closure options. In any case, people engaged in the analysis should not lose sight of the complexities and real-world implications of closure. The chosen closure scenario will ultimately need to align with the asset owner's obligations and its ability to deliver the intended outcomes. There may be a need to carry multiple closure scenarios forward for further analysis until a final funding decision can be made.

3 Optimisation

Once the preferred closure scenario is endorsed by the appropriate decision-makers, each work element can then be developed further to meet the required level of engineering, pricing, and schedule maturity. The chosen closure scenario should be refined to:

- Optimise scope division (i.e. work packaging), resource utilisation, sequence, and timing.
- Reduce operational, regulatory, HSE, technical, third-party, and execution risks/uncertainties.

As further scope and design definitions are developed, previously identified assumptions, completion criteria, success indicators, risks, and opportunities will need to be updated so that all supporting details of an updated closure plan can form a consistent and robust basis for a funding decision. Care should be taken to align the technical design with the desired execution/contracting strategy to prevent inconsistencies, gaps, and/or overlaps between the various work elements. The updated closure provision should contain the necessary budget to address any remaining gaps and uncertainties.

4 Summary

Closure of a major industrial site carries significant real-world implications for the environment, employees, asset owners, and the wider community. Closure planning should be an integral part of an asset's lifecycle to leverage the ongoing operational activities, reduce the site's closure liabilities, and advance any progressive rehabilitation goals. Useful guidelines, case studies, and project delivery models exist to assist the closure planning process. These provide a structured framework for identifying, assessing, and consolidating the relevant business goals, signatory commitments, legislative requirements, and stakeholder expectations so that these can be incorporated within the closure plan and the associated documentation and provisions. The detailed closure planning process should be initiated with sufficient lead time to build-up the required scope, design, and cost certainty ahead of closure execution. Through a formal study process, the requisite knowledge can be developed and applied by practitioners of various technical and study/project delivery disciplines to verify assumptions, mitigate known risks, and maximise beneficial outcomes.

Closure objectives, completion/acceptance criteria, specific requirements from existing management plans, and alternative options should be compiled for each closure domain, so that a set of potential closure scenarios can be formed to characterise how the entire land tenure will progress through to closure. The hybrid options assessment model presented in this paper can be used to evaluate a wide range of correlated options across multiple trade-off studies to identify the preferred set of options under each potential closure scenario. People engaged in options analysis should be cognisant of the assumptions, subjectivity and limitations of the chosen analytical method. The process should be transparent, rigorous, defensible, and well documented. Different perspectives should be adequately considered and challenged to shine light on the complexities and achieve a balanced scorecard.

The chosen closure scenario should continue to be refined through subsequent pre-closure phases to improve scope division, resource utilisation, sequencing and timing, and reduce operational, regulatory, HSE, technical, third-party, and execution risks/uncertainties. As further scope and design definitions are developed to inform an updated closure plan, changes in assumptions, completion criteria, success indicators, risks/opportunities, and externally driven factors will need to be recognised to form a consistent and robust basis for a funding decision.

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