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A framework for developing completion criteria for mine rehabilitation and closure

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Abstract

The mining industry is a major contributor to Australia's economy, accounting for 7.4% of GDP and AUD 151 billion in exports in 2016/2017. Such gains, however, may come at high environmental and social costs, including loss of biodiversity or heritage values. Across the globe, and in Australia, companies have the obligation to rehabilitate their sites to a state that supports post-mining land uses, while avoiding negative environmental impacts. While guidelines on mine rehabilitation and closure are regularly updated, there is a lack of guidance on how to define achievable and measurable criteria that reflect rehabilitation success. Discrepancies between mining proponents and regulators, and difficulty in managing altered and changing environments often result in completion criteria not being achieved, thus hindering the process towards mine closure and relinquishment. For many jurisdictions, unclosed mines represent an ongoing liability, while for companies they translate into costly remedial works and reputational risks to their social licence to operate. To address this lack of guidance, the purpose of this study was to develop a transparent, consistent framework for defining completion criteria for mine rehabilitation. The research was informed through a global review of the literature and study of the Western Australian resources sector including multiple stakeholder interviews, a wide-reaching stakeholder survey, and three case studies. This framework is the first to provide a step-by-step guide for defining site-specific completion criteria and apply a risk-based monitoring approach throughout the life of mine. The framework can be adapted across jurisdictions and industries that require similar rehabilitation of disturbed lands.

Keywords: closure criteria; mine closure; mine site rehabilitation; risk-based prioritisation; relinquishment; Western Australia

1. Introduction

The mining industry sits at the core of Australia's economy, accounting for 7.4% of GDP (2016-17) and AUD 151 billion, equivalent to over half of all revenue from exports (Britt et al. 2017). Australia is among the world's top five producers of over a dozen commodities, including iron ore, gold, zinc, lead, coal, and mineral sands (Britt et al. 2017). Alongside economic benefits, such a large mineral resources sector imparts significant environmental impacts, namely disturbance to native landscapes and ecosystems. To limit critical negative impacts, such as high loss of biodiversity or soil contamination, the process of mine rehabilitation and closure is strongly regulated. It is recognised that mining is a temporary land use and the sustainability of the industry depends on its capacity to achieve high-quality rehabilitation outcomes that will support beneficial post-mining land uses (Commonwealth of Australia 2018).

In Western Australia (WA), like many other mineral-rich areas such as Canada (Cowan et al. 2010) and South Africa (Fourie & Brent 2006)*,* mining proponents are required to outline their proposed rehabilitation practices and expected outcomes, which are assessed against a set of so-called "completion criteria" (DMP & EPA 2015). These completion criteria have been defined as agreed standards or levels of performance that indicate the success of rehabilitation and determine when liability for an area can cease (LPSDP 2016b). Throughout the life of mine, there are opportunities for continual refinement to ensure completion criteria are robust and best demonstrate that the mine site is on course to meeting its closure objectives (Mackenzie & Lacy 2006). Since 2011, it is a legal requirement in WA that mine closure plans are regularly reviewed to update and refine completion criteria as mining and rehabilitation tasks progress.

It is not until all completion criteria have been met, that financial liabilities can be removed, and the land may transition towards its future use. Relinquishment from obligations, liabilities, and land tenure can ultimately occur only if the area is in a state with acceptable environmental, health, and safety risks, and the agreed future land use can commence (DMP & EPA 2015). Best-practise for mine closure is that mine closure planning commences during the early stages of the mine development process (DMP & EPA 2015; Nehring & Cheng 2016). However, this is often not the case, which leads to increased costs over the life of mine and potentially adverse environmental and social impacts (Laurence 2006).

In the mining context, regular monitoring of critical environmental attributes (e.g. flora, fauna, structural stability, water quality etc.) is required to understand the extent to which a rehabilitated area has achieved or is trending towards achievement of completion criteria (Thompson & Thompson 2004). While monitoring is recognised as an important mechanism for adaptive management and refined risk assessments (DMP & EPA 2015), there is limited guidance on how practitioners should incorporate monitoring results into the refinement of competition criteria throughout the life of mine.

Considerable progress has been made in mine closure and rehabilitation planning in WA (Brearley 2003; DMP 2016; Gardner & Sommer 2012; Morrison-Saunders & Pope 2013; Risbey 2016), yet there remains a need to build an understanding of how to set practical outcomes and best evaluate rehabilitation success with measurable completion criteria. Previous attempts to standardise the process for definition of mine completion criteria remain mostly limited to prescriptive propositions (i.e. what criteria *should* be like) and idealised examples of adequate criteria (Holmes et al. 2015).

In the current study, we develop a framework to provide a step-by-step guide to defining site-specific completion criteria and apply a risk-based monitoring approach throughout the life of a mine. In practice, the framework will support regulators by providing greater consistency in the development of mine closure plans across companies. It will also help mining proponents through the provision of a government-endorsed method that will respond to the needs of rehabilitation over time and across multiple sites. For the wider community and environment, a better process for the definition of mine completion criteria will assist in leading to a greater number of mines achieving closure and, ultimately, being relinquished. Although developed in WA, the framework's relevance extends to other jurisdictions and industries requiring rehabilitation in Australia and internationally.

2. Materials and methods

2.1. Background, Principles and Context for Risk-based Completion Criteria and Monitoring

The importance of completion criteria in the mining life-cycle are well recognised in numerous international and national handbooks and guidelines for mine closure planning. While there is no international or national standard for the definition of completion criteria (Blommerde et al. 2015), more than 30 documents with guidance for the establishment of completion criteria were identified. Table A1 (in the Appendix) provides a selection of documents from state and federal jurisdictions within Australia and internationally. Much of the literature on mine closure identifies objectives and completion criteria as being important, but there has been little detailed guidance on how to define these.

The most relevant and detailed sources of publicly-available guidance for establishing mine closure/rehabilitation criteria in our study setting are those from the WA Environment Protection Authority (EPA 2006) and the WA Department of Mining and Petroleum (DMP & EPA 2015)—now Department of Mines, Industry Regulation and Safety (DMIRS). These most recent guidelines (DMP & EPA 2015)[1] state that: DMP's principal closure objectives are for rehabilitated mines to be (physically) safe to humans and animals, (geo-technically) stable, (geo-chemically) non-polluting/ non-contaminating, and capable of sustaining an agreed post-mining land use. The EPA's objective for rehabilitation and decommissioning is specified as "to ensure that premises are decommissioned and rehabilitated in an ecologically sustainable manner". The guideline further recommends that completion criteria should be developed in consultation with the regulators, and that these completion criteria should be S.M.A.R.T: *Specific* enough to reflect a unique set of environmental, social and economic circumstances; *Measurable* to demonstrate that rehabilitation is trending towards analogue indices; *Achievable*, that is realistic in the sense that the criteria being measured are attainable; *Relevant* to the objectives that are being measured and the risks being managed and flexible enough to adapt to changing circumstances without compromising objectives; and *Time-bound* so that the criteria can be monitored over an appropriate time frame to ensure the results are robust for ultimate relinquishment (DMP & EPA 2015 p. 30).

[1] These were being revised at the time of writing

2.2. Methods

The aims of the project were to conduct a science review and deliver a framework for developing site-specific completion criteria for mine sites requiring rehabilitation. The project was initiated following industry consultation by the DMIRS advising that the results of the project would provide a scientific basis to support Government policy, provide direction for future research and assist Industry in the development of rehabilitation actions for mine closure plans. Thus, our project aimed to:

- Review the rehabilitation completion criteria and monitoring knowledge base, and
- Develop a science-based framework for mine-site completion criteria and monitoring.

The work was conducted in partnership with representatives from key mining industry and regulatory agencies in Western Australia through the Western Australian Biodiversity Science Institute (WABSI). Frequent stakeholder consultation helped to ensure that the project output best meet the requirements for: (1) Mining companies and service providers operating across all biogeographic regions in WA; and (2) Regulatory and policy making agencies of government.

The transdisciplinary approach to the project was underpinned by a governance model that integrated industry, government and academic knowledge, and expertise across ecological, economic and social domains. The framework was developed between December 2017 and December 2018, and informed by the following processes: (1) a comprehensive literature review, as detailed in Young et al. (2019); (2) in-depth interviews and a survey with 101 stakeholders comprising mining proponents, regulators and; (3) three case studies across; (4) four workshops with the project advisory group, composed of eight mining proponents, two regulators, and six research institutions; and (5) feedback from a presentation delivered in November 2018 attended by 59 stakeholders (Young et al. 2019).

3. Results and Discussion

The framework identifies six key components in the definition of mine site completion criteria that are further detailed in the sections below: 1) selection of Post-Mining Land Uses (PMLUs); 2) aspects and closure objectives; 3) selection of references; 4) selection of attributes and risk-based prioritisation; 5) definition of completion criteria; and 6) monitoring (Figure 1). The framework is described following a linear pathway for greater clarity, but it should be noted that it can also be applied in alternative forms, e.g. developing multiple components consecutively, or in a different order. Further, the framework also allows for application across multiple spatial domains within a mine site, recognising that different PMLUs, closure objectives, and completion criteria may be developed across a single site.

Importantly, it should be noted that for adequate application of the framework, the first step is to understand the legal frameworks that govern operations at the mine-site. These may include federal or state legislation, company commitments, as well as regional or local land planning schemes.

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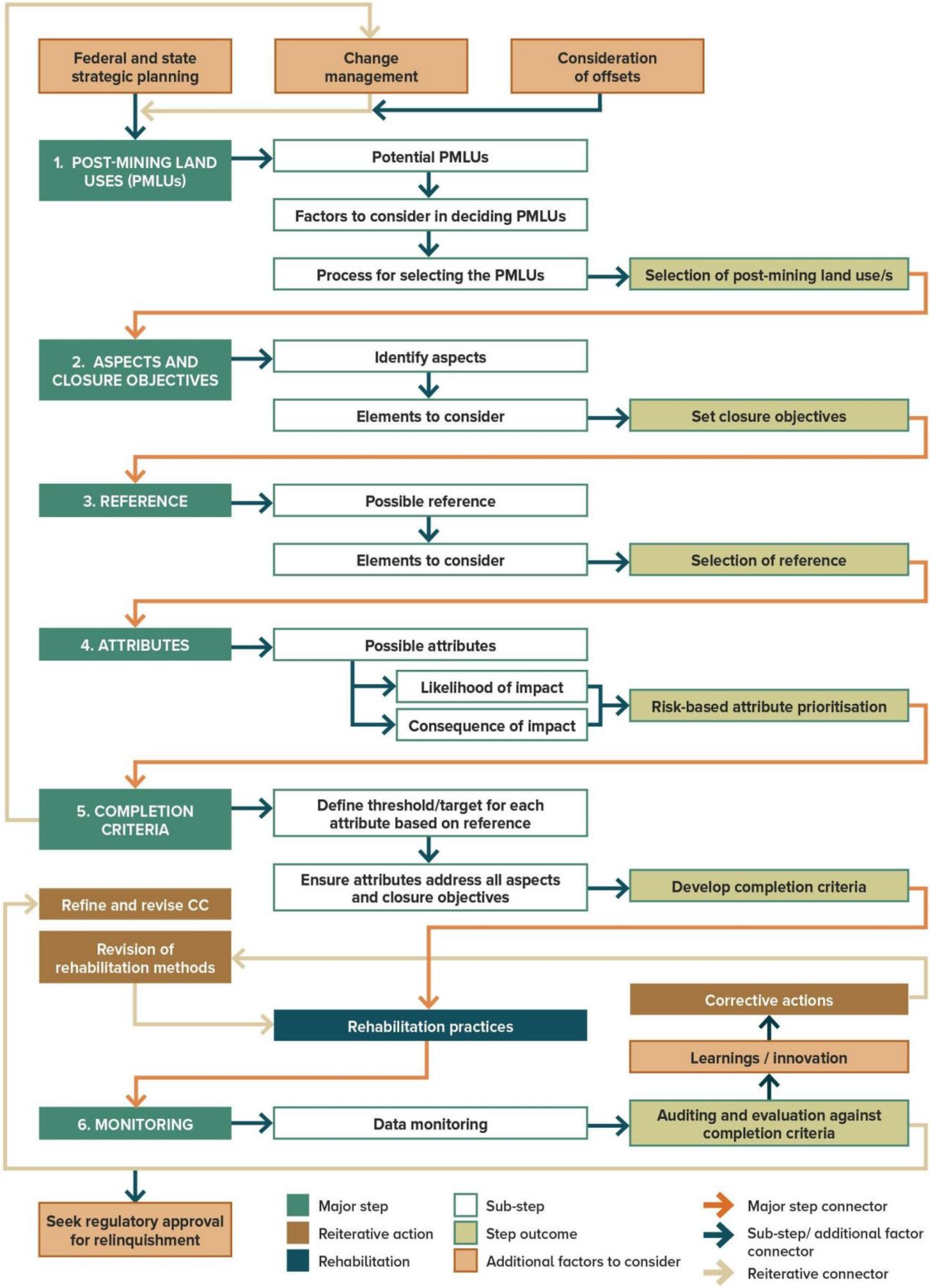

Figure 1 Framework for the definition of completion criteria

3.1. Component 1 - Post-mining land uses (PMLUs)

It is widely agreed that mining is a temporary land use and thus, an appropriate post-mining land use (also referred to as end land use) should be identified (LPSDP 2016e). The WA Guidelines for Preparing Mine Closure Plans DMP and EPA (2015) provide a hierarchy that prioritises natural ecosystems, before alternative land uses. Returning the mine site to its "previous land use" is typically considered the preferred and less risky option by regulators, thus resulting in most mining proponents adopting it "by default" (DMIRS 2019). However, if the targets are unachievable, it may lead to failure to close and relinquish a site and to exacerbated rehabilitation costs (McCullough 2016). Changes in the social environment, as well as in landforms, substrates, and hydrology mean that return to pre-existing conditions may no longer be attainable or practical (Gould 2011).

A large number of post-mining land uses are described in the literature (Kaźmierczak et al. 2017; Narrei & Osanloo 2011; Pearman 2009; Soltanmohammadi et al. 2010), although there is no consistent framework for their definition or selection. The framework presented in this study adopts the Australian Land Use and Management classification (ABARES 2016) for the definition of PMLUs. The Australian Land Use and Management classification provides a comprehensive, yet concise definition of land uses in a manner that is systematic, consistent, and regularly updated. Six primary classes are defined (e.g. 1. Conservation and natural environments), which are then sub-divided into secondary classes (e.g. 1.2.0. Managed resource protection) and then into tertiary classes (e.g. 1.2.1 Biodiversity).

The process to identify the most suitable PMLU could be based on techniques such as Mined Land Suitability Analysis (Soltanmohammadi et al. 2008) and/or informed by multi-attribute decision-making[2] (Huang & Tzeng 1981), Analytical Hierarchy Processes (Bascetin 2007), or Technique for Order Preference by Similarity to Ideal Solution (Shih et al. 2007). In practice, the widespread application of these tools is hindered by the subjective nature of weighting and their methodological complexity (Dobes & Bennett 2009; Ergas 2009). Other systems used in rural planning systems include Land Suitability/Capability Assessments, which is based on the capacity of land to sustain specific land uses such as cropping, irrigated agriculture, or forestry (van Gool et al. 2005). Another method for land use planning is Benefit-Cost Analysis, which includes financial effects, social cost, and non-financial (non-marketed) values (Pearce et al. 2006).

Whichever process for selecting a PMLU is applied, it is now a requirement in WA that PMLUs should be identified and agreed upon through consultation before approval of new projects (DMP & EPA 2015). This should take into account the operational life span of the project and all elements that may constrain or favour the various options (Table 1). Over the life of mine, these factors may vary and, in some circumstances, may warrant reconsideration of the initially agreed PMLUs.

[2] Also referred to as multi-criteria decision analysis, multi-criteria analysis or multi criteria decision making.

Table 1 Factors to consider in the selection of PMLUs

Factors	Description
Acceptability to key stakeholders	Feedback received through continuous stakeholder engagement.
Added value	Value generated as a result of the PMLUs.
Compatibility with surrounding area	Integration of the PMLUs with the surrounding landscape in terms of aesthetics, land capability, etc. taking into account the changes that have occurred over the life of mine.
Consistency with other mines in the area	PMLUs proposed by other nearby mines where applicable and justified as the most acceptable approach.
Environmental and ecological impact	Impact associated with the PMLUs on flora and fauna communities; water bodies; carbon emissions; etc.
Environmental offsets	An offsite action(s) to address significant residual environmental impacts of a development or activity. Environmental offsets may specify what some areas PMLUs will be and thus influence content of completion criteria.
Feasibility/viability	PMLUs should be achievable based on post-mining land capability.
Heritage (natural, cultural or historical)	Impact associated with the PMLUs on heritage and agreement with relevant government departments and stakeholders.
Land tenure	Existing Land Tenure that specifies what the PMLUs will be.
Legislative constraints	Conditions pertaining to any relevant legislation and Acts.
Physical, chemical and biological hazards (anthropogenic and naturally occurring)	Hazardous materials, unsafe facilities, contaminated sites, radioactive materials, among others.
Pre-mining condition	Condition of the area prior to mining.
Strategic planning	Local and regional land planning schemes by relevant authorities such as Department of Primary Industries and Regional Development; Department of Planning, Lands and Heritage; Pilbara Development Commission.

3.2. Component 2 - Aspects and closure objectives

As mining activities disturb the natural environment (e.g. flora), alter the landscape (e.g. landforms) and create new infrastructure (e.g. tailings facilities), the range of impacts needs to be identified so they can be managed and mitigated in order to achieve closure. Not all mines will have the same impacts, which is why it is important that a site-based assessment identifies which impacts are relevant. Examples provided in this framework proposed multiple “aspects” as key themes or elements that potentially need to be addressed during closure. Aspects that could be considered include, for example, physical and surface stability, flora and vegetation or water and drainage. A specific site may include more or less aspects depending on site complexity and company procedures for environmental impact management. Within each *aspect*, several *attributes* may be selected for the definition of completion criteria (See Section 3.4).

Once *aspects* are identified, *closure objectives* are to be set as an indication of the proponent’s commitment to addressing each *aspect*. Closure objectives define the closure outcomes and should be i) realistic and achievable; ii) developed based on the proposed PMLUs; and iii) as specific as possible to provide a clear indication on what the proponent commits to achieve at closure (DMP & EPA 2015). For example, for the “Physical and surface stability*” aspect,* a suitable *closure objective* may be “Creation of safe and stable landform that minimises erosion and supports vegetation”. Multiple closure objectives may be required to adequately address each identified aspect.

3.3. Component 3 - Reference

The definition of completion criteria relies on comparison with a reference based on analogue native ecosystems or other desirable PMLU (Table 2). For ecological attributes, a reference ecosystem is selected, which informs completion criteria based on direct comparison or trajectory analysis (SER 2004). In WA, baseline or analogue ecosystems are the most commonly used references, namely for sites returning to the pre-mining land use (McDonald et al. 2017). However, in some situations the altered physical properties of the landscape post-mining may prevent the return to pre-mining conditions (Doley & Audet 2013; Doley & Audet 2016). An alternative approach is to use an actual rehabilitation outcome or conceptual model based on evidence obtained from research trials (Table 2). This approach has been accepted at very few sites in WA, and is appropriate only where a sound understanding of the restorative nature of the ecosystem, robust data, and detailed documentation is available and of an acceptable standard to the regulators. Additionally, references may be static, indicating a desired state at completion, or dynamic, indicating desirable change through time, such as ecosystem succession following a natural disturbance. Finally, references can be defined in terms of a post-mining land use that is distinct from the pre-mining land use (Table 2). For each rehabilitation site, progress should be regularly monitored, assessed against the reference, and the learnings incorporated into the knowledge base to inform rehabilitation practice and, where appropriate, refine completion criteria.

Table 2 References that could be used in the definition of completion criteria

References	**Definition**
Analogue	Adjacent or near-by sites from which the necessary attributes to can be quantified to define completion criteria for the sites agreed upon PMLUs.
Baseline	Conditions present at the site prior to mine use.
Conceptual model	Synthesis of several data-based references including existing sites, field indicators and historical and predictive records.
Dynamic	Desirable rehabilitation trajectory towards baseline or other reference
Leading-practice outcome	The conditions that most closely define the values desired for the site and that can be realistically achieved. Such conditions are defined based on effective leading-practice techniques demonstrated through laboratory trials, on-site trials, and industry standards more generally.
Other	Example sites for alternate PMLUs, such as renewable energy farm or residential development.

3.4. Component 4 - Attributes

Attribute identification

International, national and state guidelines for mine closure (Table A1) identify many different attributes that could be used in the definition of completion criteria. An attribute is defined as a specific parameter that can be quantified or task that can be verified to have been achieved. Although most guiding documents list similar attributes, the terminology is often inconsistent, with no document providing a single comprehensive attribute list. As examples of the large number and diversity of attributes, Muñoz-Rojas (2018) listed 20 key soil indicators with application to restoration, while Jasper (2002) identified 58 individual measures of soil properties or processes, including 22 physical, 15 chemical, and 21 biological measures.

To facilitate the definition of completion criteria, this framework assembles a comprehensive list of potential attributes (Table 3), based on a thorough expert consultation and literature review of guidelines (ANZECC & ARMCANZ 2000; ANZMEC & MCA 2000; DEC 2010; ICMM 2003, 2008, 2012; INAP 2014; LPSDP 2006, 2016c, 2016d, 2016e, 2016f, 2016g, 2016h; Standards Reference Group SERA 2017) and scientific papers (Barritt et al. 2016; Blanchette et al. 2016; Grant & Koch 2007; Jasper 2007; Nichols 1998; Smith et al. 2004). Attributes are grouped relative to aspects, although certain attributes may be relevant to more than one aspect, e.g. slope of waste dumps may affect drainage, waste, and physical stability. While most attributes are quantitative in nature (i.e. they can be measured through a numerical scale), others may be categorical (e.g. presence or absence) or process-based (e.g. construction of landforms to applicable standards).

Table 3 Possible attributes applicable for the definition of completion criteria

Aspect	Possible Attributes	Type*
Water & drainage	Design and construction of landforms and drainage features	P
	Quality, quantity and fate of surface water flow	Q
	Integrity of drainage structures	Q/C
	Connectivity with regional drainage (lakes & rivers)	Q
	Pit lake bathymetry	P/Q
	Pit lake sediment quality	Q
	Pit lake water quality	Q
	Surface water quality, quantity and timing	Q
	Surface water chemistry and turbidity	Q
	Aquatic biota (algae, macrophytes; invertebrate and vertebrate fauna)	Q
	Riparian vegetation	Q
	Surface water chemistry and turbidity	Q
	Groundwater chemistry	Q
	Level of groundwater table	Q
Mine waste and hazardous materials	Landform design and construction	P
	Particle size and erodibility	Q
	Strength	Q
	Acid, alkali or salt production potential	Q
	Total and soluble metals and metalloids	Q
	Spontaneous combustion potential	Q
	pH and electrical conductivity	Q
	Radiation	Q
	Asbestiform minerals	Q/P
	Design and construction of containment structures for hostile wastes	P
	Physical integrity of containment structures for hostile wastes	Q
	Dust	Q
	Sediment quality	Q
Physical and surface stability	Soil coarse fraction content	Q/P
	Soil fraction particle size analysis (texture)	Q
	Hydraulic conductivity	Q
	Sodicity, slaking and dispersion	Q
	Soil strength	Q
	Surface resistance to disturbance	Q
	Erosion rills, gullies, piping	Q
	Sediment loss	Q
	Placement of appropriate surface materials	P/Q
	Earthworks as designed	P

Aspect	Possible Attributes	Type*
Soil fertility & surface profile	Bulk density, depth of ripping and soil strength	Q/P
	Aggregate stability	Q
	Water infiltration	Q
	Plant-available water	Q
	Soil profile as designed	P/Q
	Electrical conductivity	Q
	Nutrient pools (N, P, K, S)	Q
	Plant-available nutrients; cation exchange capacity	Q
	Heavy metal bioavailability	Q
Flora & vegetation	Numbers of species and quantities of viable seed in seed mix	P
	Number of seedlings planted	P
	Vegetation cover	Q
	Species richness	Q
	Vegetation composition	Q
	Litter cover	Q
	Presence/abundance of keystone, priority or recalcitrant species	Q/C
	Presence of key functional groups	Q/C
	Community structure – presence of all strata	Q/C
	Weed species presence and abundance	Q/C
	Aquatic biota (algae, macrophytes; invertebrate and vertebrate fauna)	Q
	Riparian vegetation establishing	Q
Fauna / habitat	Constructed habitat features (breeding and refuge)	P
	Vegetation and litter habitat (foraging, breeding and refuge, in general or for conservation significant species)	Q
	Presence of keystone or significant species	Q/C
Ecosystem function & sustainability	Rainfall capture and infiltration	Q
	Soil microbial function – respiration	Q
	Presence of different successional groups	Q/C
	Indicator species group richness and composition	Q
	Plant growth, survival, rooting depth, physiological function	Q
	Plant species reproduction and recruitment: flower, seed production, soil seed banks	Q
	Capability for self-replacement: soil seed banks, seedlings mature 2nd generation	Q
	Connections with nearby systems in place, functioning: corridors; pollinator, gene movement	Q/P
	Key threats absent or managed: feral grazers, predators, pathogens, weeds, etc.	Q/C/P
	Resilience to disturbance (such as fire, drought, extreme weather events)	Q
Social/Economic	Recreation opportunities provided, maintained	P
	Heritage values protected	P
	Aesthetics (visual amenity)	P
	Access and safety	P
	Infrastructure removed	P
	Sustainability of utilities	P
	Social progress: health, education, employment, livelihoods and incomes	P/Q

** **Type:**
P = installed/built as planned – a process for emplacing these attributes is approved initially and then certified as and when constructed;
C = categorical – the feature is required to be present or absent;
Q = quantitative – the attribute can be measured and compared against a numerical target.

Attribute selection

Mine site completion criteria are often set based on rehabilitation objectives, particularly for biodiversity targets, such as species abundance or density. Such indicators are referred to as 'lagging', because it may take a long time before they can be evaluated, sometimes many years after rehabilitation works have been completed (LPSDP 2016a). Alternatively, 'leading' indicators are those that can be measured at early stages of rehabilitation and provide an indication of future rehabilitation outcomes, such as soil nutrient levels or initial plant populations. Leading indicators can also serve as "proxies" whereby the attribute of interest is not directly measured, but instead an alternative feature is used in the definition of completion criteria. For instance, Alcoa uses seeding rates and legume plant density as leading/proxy indicators of soil nitrogen (Koch & Hobbs 2007). Mine closure plans adopting leading and proxy indicators ought to clearly explain the supporting science.

A recurrent roadblock in mine closure plans being approved in WA is the inappropriate selection of closure attributes, which is typically guided by past examples or by proponents' and regulators' subjective judgment. In reality, not all possible attributes (Table 3) are relevant to all mine sites, and among those that apply, some may be more critical than others. A prioritisation method is required to identify what attributes are most relevant to which site and those that pose the greatest risk to a mine not meeting its closure objectives. Attributes identified as 'high priority' should be monitored and audited with a greater level of detail and higher frequency compared to 'medium or low priority' attributes (Young et al. 2019).

As an example, a mine site could be within a river catchment that supports a rich community of water-dependent ecosystems where the PMLU is nature conservation (Young et al. 2019). The site may, thus, be subject to completion criteria based on 'surface water quality' and 'construction of fauna habitat features'. Both heavily polluted surface water and an insufficient number of habitat features would result in failure to meet completion criteria. Nonetheless, the former poses a much greater risk for closure outcomes i.e. the site being non-polluting and able to self-sustain the agreed PMLU.

3.5. Component 5 - Completion criteria

Once attributes have been selected and prioritised, completion criteria may be defined by setting a target that will allow the fulfilment of closure objectives. Here, completion criteria are defined as agreed standards or levels of performance that indicate the success of rehabilitation, and determine when an operator's liability for an area may cease. Targets are informed by the reference value for the attribute and must be set to levels that makes them attainable for the particular site and, where appropriate, within a specified timeframe, recognising that the outcome must be supportive of the agreed PMLUs. At the same time, standards must be high enough to ensure that, once they are met, the risk of non-fulfilment of closure objectives is low or zero.

In early stages of mine closure planning, it is often unknown what the attainable and necessary levels of performance will be at time of closure. Hence, information from reference sites may provide an evidence-based indication of adequate standards for each attribute. Importantly, standards in natural ecosystems may take a long time to be achieved post-disturbance—often much longer than mining companies may prefer to manage the site. Therefore, completion criteria should consider the expected trajectory post-closure, and the likelihood of the attribute reaching the expected level. For this reason, it is important that completion criteria are time-bound, that the same targets at different points in time can reflect different levels of performance. As depicted in Figure 2, the first monitoring point represents only a slight deviation from the planned rehabilitation trajectory. However, the same performance level later in time (2nd monitoring round) constitutes a significant gap between the planned and measured level of performance and may trigger corrective rehabilitation actions.

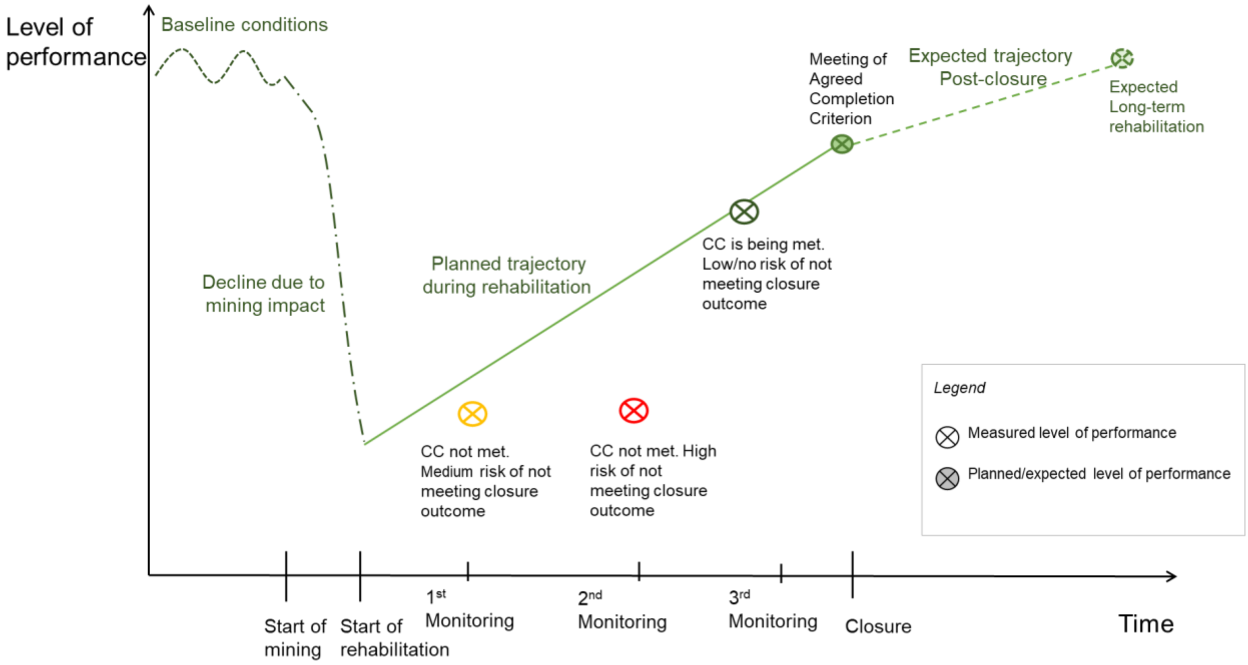

Figure 2 Example of a trajectory approach for the definition of completion criteria (based on return to baseline conditions). Source: Adapted from Grant (2006) and Young et al. (2019).

3.6. Component 6 - Monitoring

The main objectives of completion criteria monitoring are to assess whether they have been met or are likely to be so; and to track rehabilitation progress overtime. While the term “monitoring” is often used to refer to data collection, this framework distinguished three distinct steps: data monitoring; auditing and evaluation; and corrective action. *Data monitoring* consists of collecting and interpreting information that is necessary to assess the progress towards meeting completion criteria. In accordance with the risk-based attribute prioritisation, it is advised that the level of detail and frequency of data monitoring are consistent with the criticality of each of the attributes monitored. Once the data are collected, through *auditing and evaluation*, the observed level of rehabilitation is compared against the set targets to assess whether criteria have been met or are trending towards the agreed outcomes. When auditing identifies that there is a risk of not meeting completion criteria, this should trigger investigations into the causes of such failure. Finally, in those cases where a significant risk of non-compliance has been identified, *corrective actions* are necessary to ensure closure objectives are met. Depending on the cause of non-compliance, corrective actions may include modifying rehabilitation practices, redefining completion criteria or both.

4. Conclusion

Extractive industries worldwide face the challenge of supporting an ever-rising demand for raw materials whilst, at the same time, protecting the natural and social environments within which they operate. Operators and regulators must constantly work, learn, and adapt to rapidly changing conditions, fuelled by changes in markets and industry, climate change, growing community needs and expectations, and exponential advances in rehabilitation and monitoring technologies. Across the globe, and in Australia, companies have the obligation to rehabilitate their sites to a state that supports post-mining land uses, and mitigating environmental and social impacts. This obligation results in the need to define closure objectives and completion criteria that determine whether the necessary outcomes are achieved for the mine to become eligible for relinquishment. Our research addressed how closure objectives and completion criteria could be defined, and how progress towards meeting completion criteria should be monitored. In this paper, we describe a framework that provides a roadmap for the definition of mine completion criteria with associated monitoring through six key components:

1. Post-Mining Land Uses;
2. Aspects and closure objectives;
3. References;
4. Attributes;
5. Completion Criteria; and
6. Monitoring.

The framework provides a method that can be applied across mining operations of different size, location, or commodity type. If regularly applied, this framework will allow greater consistency in the definition of completion criteria which, in turn, will facilitate the review of mine closure plans by the regulators. Ultimately, the long-term goal is to improve mine site rehabilitation outcomes and for those outcomes to be demonstrated, thus leading to more mines being closed and relinquished. While this project was undertaken within the regulatory framework of Western Australia, the processes described can readily be applied to other Australian and international jurisdictions, as well as to other industries that require similar rehabilitation of disturbed lands, such as residential developments or oil and gas fields.

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Appendix A

Table A1 Selection of published guidelines relating to mine closure and/or completion criteria relevant to different regions and level of jurisdictions.

Reference	Region	Document title	Details
	International		
AANDC (2013)	Canada - Northwest Territories	Guidelines for the Closure and Reclamation of Advanced Mineral Exploration and Mine Sites in the Northwest Territories	Strongly focused on water as the key aspect/ environmental factor. The closure goal is supported by closure principles which guide selection of clear and measurable closure objectives for all project components. Closure criteria can be site-specific or adopted from provincial/territorial/federal standards and can be narrative statements or numerical values.
APEC (2018)	Australia-Pacific Economic Cooperation	Mine Closure Checklist for Governments	A checklist for governments that promotes consideration of the proposed post-closure land use, including closure objectives and closure criteria.
Department of Environmental Affairs (2015) South African Government (2015)	South Africa	Regulations pertaining to the financial provision for prospecting, exploration, mining or production operations	Indicates a clear requirement for closure plans to be measurable and auditable, and to provide a vision, objectives, targets and criteria for final rehabilitation, decommissioning and closure. Does not contain guidance on criteria development.
Environment Canada (2009)	Canada	Environmental Code of Practice for Metal Mines	Detailed summary of recommended environmental management practices for all stages of the mining life cycle, including rehabilitation and closure. Contains extensive list of additional sources of information.
Gann et al. (2019)	Global	International standards for the practice of ecological restoration. Second Edition.	Sets out a framework of ‘goals’ and ‘objectives’ (criteria/standards), together with examples of specific objectives (criteria) for soils and biological elements.
Heikkinen et al. (2008)	Finland	Mine closure handbook	General guidance and examples for developing objectives and performance criteria in relation to environmental quality.
ICMM (2008)	Global	Planning for Integrated Mine Closure: Toolkit	Encourages development of closure goals (equating to criteria with a measurable standard) and monitoring, to demonstrate progression towards them and their achievement. Includes examples of aspects to consider, their related goals and intermediate (partial) goals to mark progress.
	Australia - National		
ANZMEC and MCA (2000)	Australia and New Zealand	Strategic Framework for Mine Closure	Promotes establishment of completion criteria that are developed and agreed with stakeholders and, where possible should be quantitative and capable of objective verification. Identifies the importance of developing performance indicators to measure progress in meeting the completion criteria, indicating appropriate trends or enabling early intervention where required.
LPSDP (2016d)	Australia	Mine closure	Promotes monitoring and reporting against agreed closure objectives and closure criteria. Relatively detailed guidance on objectives, principles and nature of criteria. Discusses a phased approach for criteria (development and mining; planning and earthworks; vegetation establishment; monitoring and closure).

Reference	Region	Document title	Details
LPSDP (2016e)	Australia	Mine rehabilitation	Promotes Specific, Measurable, Achievable, Realistic and Time-bound (SMART) targets and objectives, with success criteria that have been developed with stakeholders. Recommends comparison with analogues, not to replicate them but to inform in relation to composition, structure and function.
LPSDP (2016a)	Australia	Biodiversity management	Touches lightly on objectives and criteria with respect to biodiversity. Identifies that direct measures of abundance for fauna are lagging indicators.
LPSDP (2016b)	Australia	Evaluating performance: monitoring and auditing	Provides clear guidance on the nature and role of criteria, including the relationship of criteria to monitoring. Links strongly to related LPSDP handbooks. Gives examples of typical elements of completion criteria, for landforms, water, biodiversity, though without discussing matching of specific criteria with different stages of rehabilitation process.
SERA (2017a)	Australia	National standards for the practice of ecological restoration in Australia	Sets out a framework of 'goals' and 'objectives' (criteria/standards), together with examples of specific objectives (criteria) for soils, and biological elements.
Australia - State			
DEHP (2014)	Queensland	Rehabilitation requirements for mining resource activities	Sets out clear hierarchy for rehabilitation goals, objectives, indicators and criteria. Detailed example of objectives, indicators and criteria.
DMP (2016)	Western Australia	Guidelines for Mining Proposals in Western Australia	Identifies the need for performance criteria for each environmental outcome. Closure outcomes together with related completion criteria, should be outlined in a Mine Closure Plan (MCP). Principles and purpose of monitoring for each criterion is discussed. Includes example tabular framework of factors, objectives, risks, outcomes, criteria and monitoring.
DMP and EPA (2015)	Western Australia	Guidelines for Preparing Mine Closure Plans	Specific guidance on identifying land use, closure objectives, completion criteria. Refers to ANZMEC/MCA (2000) for additional information. Includes example tabular framework of factors, objectives, criteria and measurement tools.
EPA (2006)	Western Australia	Guidance for the Assessment of Environmental Factors	Aims to encourage best practice in setting appropriate and effective objectives for rehabilitation and assessing subsequent outcomes. Promotes more effective monitoring and auditing of outcomes.
NSW Dept Trade & Investment (2013)	NSW	Mining Operations Plan (MOP) Guidelines	Clear expectation to provide objective criteria to establish whether rehabilitation objectives have been met and have outcomes, which are demonstrably achievable through experience in comparable situations or through site trials. General guidance and examples on where criteria should be directed, but not on their development or structure.