Philippines remediation of mine tailings: a new collaborative research initiative

By Professor Mark Tibbett, University of Reading, UK

The world is moving to a low carbon economy that requires a greater amount and variety of metals. More circular approaches to the economy can only partially meet the rising demand for metals – realistically mining will have to continue and indeed increase. The Philippines is the fifth most mineral-rich country in the world, and therefore stands to benefit from this increased demand. However, mines can negatively impact the environment and surrounding communities. Mining and mineral processing consume and contaminate water, contribute to at least 7% of global forest loss each year, are responsible for 8% of the world's CO2 annually, and compete with local communities for land and ecosystem services. They also produce waste, including wet slurries of finely ground minerals left over from processing, known as tailings. Large mines may generate hundreds of thousands of tonnes of such waste every day.

As one of the world's most mineral-rich countries, mineral extraction in the Philippines is a critical industry that offers significant potential benefits and returns to both the economy and local livelihoods. Whilst the global demand for minerals to support clean energy technologies is growing, mining for minerals remains restricted in the Philippines due to past environmental impacts, illegal operations, and mismanagement. To address the causes of the current inhibition of mining in the Philippines, a new program of research is essential to deliver a sustainable pathway for Philippine mineral supplies. Consequently, the Philippine Council for Industry, Energy, and Emerging Technology Research and Development and the UK's Natural Environment Research Council brought forward a new collaborative initiative for sustainable mineral resources in the Philippines. This has led to the development of a series of new research projects (https://www.ukri.org/news/nerc-invests-in-sustainable-future-for-philippine-minerals/).

A key new research program concerns the Philippines Remediation of Mine Tailings (PROMT). This pulled together a wide range of Filipino and UK researchers. The consortium integrates complementary interdisciplinary expertise from Philippines and UK science to build an innovative strategic project to test new sustainable approaches to tailings management and remediation, and ultimately rehabilitation. The consortium is co-led by the Centre for Sustainable Resource Extraction, University of Leicester, and the Philippine Nuclear Research Institute, together with The University of the Philippines Diliman and Los Baños, the British Geological Survey, University of Exeter, Camborne School of Mines and University of Reading. The consortium built between these institutes provides a wide-ranging and interlinked compendium of disciplines to address tailings remediation in a holistic and novel manner (Figure 1).

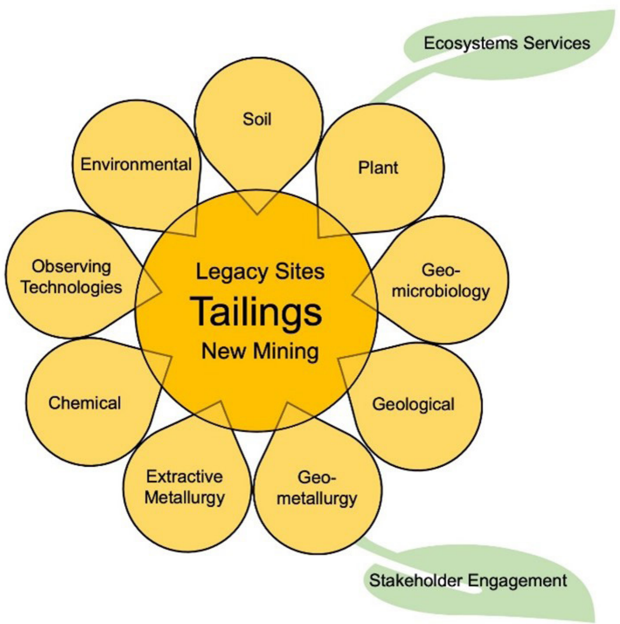

Figure 1. Disciplines involved in the PROMT consortium

The team of interdisciplinary Philippine and UK researchers and industrial partners is building an innovative research program addressing research to test sustainable tailings and mine waste management, remediation and rehabilitation. Our ambitions are to produce tailings with less water consumption and greater stability, and show how they can be monitored and adaptively managed in real time; and to enable the processing of modern and legacy tailings to recover more metals, whilst decontaminating them, encouraging rehabilitation and long-term stabilisation and re-use of the associated ecosystem services. The potential outcomes, impacts and benefits of this integrated research will be to:

1. Reduce community and environmental impacts from tailings.
2. Provide compliance with international standards.
3. Improve social license to operate for mining companies.
4. Reduce long-term liabilities and risks from legacy sites.
5. Create potential sources of revenue by secondary extraction of additional metals and land re-use.

Recent disasters caused by the failure of tailings storage facilities (TSF), including the 2019 Brumadinho event with over 200 lives lost, as well as tailings releases in the Philippines (Marcopper disaster 1996), have brought extra scrutiny to the management of operational and legacy TSF. Investors of over $13 trillion in mining assets have driven the development of new standards in tailings safety in the aftermath. However, for the Philippines, with rugged topography, high rainfall (including typhoons), and regular seismic events, TSF remain at risk of failure, and continue to discharge contaminated water downstream. These issues not only affect operational mines but also include legacy tailings at abandoned or closed mine sites that are persistent environmental hazards. Only with innovation will new sustainable standards for TSF management be achieved. The strategic PROMT project aims to deliver the fundamental science to underpin such innovation, combining interdisciplinary expertise and novel ideas integrating three science areas (Figure 2).

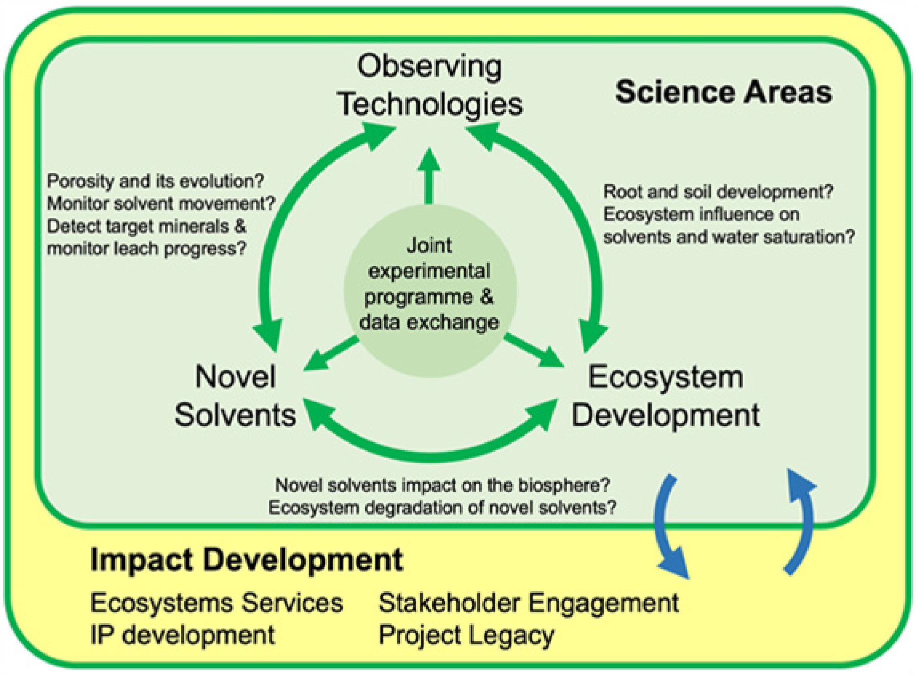

Figure 2. Science areas and examples of novel interdisciplinary research questions.

Science Area 1: Observing Technologies – Geophysical, Geotechnical and Remote Sensing. Here we enable minimally invasive 3D and 4D assessment and characterisation of TSF, with near real-time monitoring of processes including solvent propagation during in situ leaching, biological colonisation and root development, and tailings evolution through compaction, cementation, and pedogenesis.

Science Area 2: Novel Solvents and their Flow. This will address the key knowledge gaps to enable application of novel environmentally benign solvents to leach metals and remove contaminants from tailings by ex situ and in situ reprocessing.

Science Area 3: Ecosystem Development. Here we will assess and understand the development of ecosystems in tailings through plant-soil–biota interactions; how ecosystem development may be manipulated to reduce toxicity and improve tailings stability, water balance and end-use; and the effects of ecosystem perturbation with novel solvents used for in situ leaching.

The PROMT project aims to build an innovative research program to test sustainable tailings management, remediation and rehabilitation. The specific science being undertaken by the project includes a wide range of research based on the novel and interdisciplinary questions in each science area (Figure 2).

The project will undertake in situ geophysical tomographic monitoring of tailings facilities to understand the evolution of tailings mineralogy, structure, water flow, and stability through time and enable adaptive management. Electrical methods such as resistivity and induced polarisation using multi-electrode arrays can be used with machine-learning to image the distribution of minerals and porewater saturation in the near surface. These methods have recently been used in imaging landfills with the aim of mining them[1]. Large permanent arrays are now possible that can image the subsurface in real time allowing monitoring of dynamic processes, such as rainfall infiltration or leachate propagation, in a volumetric and minimally invasive manner[2], but have yet to be widely adopted in tailings monitoring and management.

The project will assess the use of novel environmentally-benign solvents, which exhibit low toxicity and/or enhanced selectivity for specific target metals and metalloids, compared to conventional strong mineral acids. Previous work suggests that certain types of organic acids are able to perform such functions at near-ambient geochemical conditions, due to their additional capability for metal chelation[3]. Similarly, non-aqueous solvents, such as deep eutectic solvents (DES) are capable of leaching a wide range of minerals including chalcogenides, arsenides, and native gold and mercury[4,5,6] with a range of potential benefits including low volatility, high target metal selectivity, and potentially low ecotoxicity. Such solvents can result in a step change in our ability to both remove environmental contaminants and recover metals, including previously discarded by-products, and render the final tailings more amenable to new use such as aggregate or soils. These solvents can also provide an alternative way to process modern ore streams to produce more environmentally benign and stable tailings.

Whilst these environmentally benign solvents may be used for ex situ leaching of mine waste we also aim to investigate whether they can be applied for in situ reprocessing of tailings by injection of solvents to remove contaminants, recover value and facilitate tailings stabilisation and CO_2 sequestration. This has the crucial advantage of not requiring disruption of tailings and may even be used to strengthen them. Metal recovery from pregnant leach solutions can be via a combination of standard techniques such as electrowinning together with novel approaches such as sorption onto engineered nanomaterials[7].

Microbes have long been used in conventional heap leaching of low-grade ores, but to date no research has focused on understanding and harnessing geomicrobiological

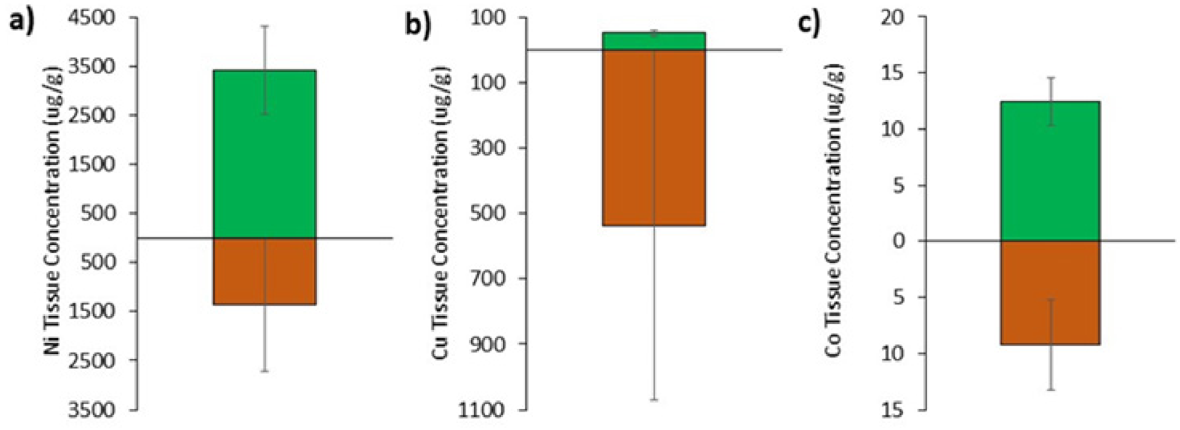

Figure 3. Filipino flora metal concentration for aboveground (green) and belowground (brown) plant parts for (a) nickel (n = 57); (b) copper (n = 83); (c) cobolt (n = 40); +/- standard error of the mean.

Figure 4. Mines, deposit type and collaborate companies

processes when exposed to the novel organic solvents outlined above. Microorganisms can produce and degrade organic acids, with implications for environmental metal behaviour8. Indeed, the presence of residual organic substrates may even be beneficial for microbial community development in nutrient-limited tailings and support the associated provision of ecosystem services that are essential for plant colonisation. This fundamental understanding is needed to (a) predict and numerically model the behaviour and degradation of these novel solvents as a function of time and across different environmental conditions, including the critical zone and (b) inform phytoremediation strategies.

Phytoremediation: Plants are an integral component of restoring soil and ecosystem functions after mining and some species can be employed to accumulate and recover contaminant metals and to stabilise tailings for ecosystem rehabilitation9,10. We intend to identify local plant species that have both the appropriate pH, salinity and metal tolerances to grow on treated tailings and to conduct field and glasshouse trials to facilitate their establishment on these substrates11. We have already gathered preliminary data from a literature review that shows a large number of metal concentrating plants in the Philippines with nickel primarily accumulated in aboveground parts, copper accumulated in the roots, and cobalt being evenly distributed (Figure 3).

The facilitation of pedogenic activity in tailings materials will be required to underpin new ecosystem development and land use for the benefit of local communities.
This will require detailed materials characterisation and understanding of what materials are present from the outset of a mining project and hence what will remain in the tailings and stored overburden with a perspective on soil development and target land end-use. Understanding the interaction of plants, symbionts and the wider soil biotic communities will be essential in facilitating incipient ecosystem development12.

Underpinning all these studies will be a holistic geometallurgical approach to material characterisation to understand all the materials involved including ores, tailings, and soils, and their variability. This will use state-of-the-art material characterisation at various scales, from hyperspectral imaging of mineralogy and μ-CT of textures at the drill-core scale through to automated-SEM (MLA, QEMSCAN, etc.) quantification and mapping of mineralogy and liberation at the grain scale. These data will enable predictive modelling, such as mineral separation performance, the leaching behaviour of metals from tailings with solvents, hydraulic properties of tailings including macropores and the development of soil textures during tailings pedogenesis.

Whilst each of these approaches individually promises significant advances, we propose that it is their integration and synergies that will deliver a step change in innovation and enable us to achieve our ambitions of sustainable tailings management. Furthermore, the interfaces between approaches provide fruitful and timely science opportunities for novel research, e.g.:

- Can novel solvents be used to recover metals from metal phytoaccumulator species? In turn, can plants and the microbiota remediate traces of residual solvents such as DES from tailings?
- Can in situ monitoring be used to assess effectiveness of phytostabilisation or other induced stabilisation of tailings by adaptive management, to identify areas amenable for in situ reprocessing, and to monitor the reaction progress during reprocessing?

The project work has already started and we have secured access and permissions from companies, government agencies, the mining regulator and local communities for fieldwork, which commenced earlier this year.

We already have good contacts and approval from a number of mine sites (Figure 4) including porphyry Cu-Au mines at Philex Mining, Benguet and Carmen Copper, Cebu; Filminera Resources' Masbate gold mine; and NickelAsia's Ni-laterite deposits. Early data is currently pouring in from all three science areas and I look forward to updating you on results at a future Mine Closure conference.

References

1Inauen et al. 2019. Landfill Characterization with a Multi-Method Geophysical Approach - A Case Study from Emersons Green, UK. in 25th European Meeting of Environmental and Engineering Geophysics. 2Tso et al. 2020. Integrated hydrogeophysical modelling and data assimilation for geoelectrical leak detection. J. Contam. Hydrol. 234. 3Crane & Sapsford 2018. Towards "Precision Mining" of wastewater: Selective recovery of Cu from acid mine drainage onto diatomite supported nanoscale zerovalent iron particles. Chemosphere 202, 339-348. 4Jenkin et al. 2016. The application of deep eutectic solvent ionic liquids for environmentally-friendly dissolution and recovery of precious metals. Miner. Eng. 87, 18-24. 5Jenkin et al. 2019. Gold and critical element recovery with environmentally-benign Deep Eutectic Solvents in Life with Ore Deposits on Earth, Proceedings of the 15th SGA Biennial Meeting, 2019, Vols 1-4. 1512-1515. 6Pateli et al. 2020. The effect of pH and hydrogen bond donor on the dissolution of metal oxides in deep eutectic solvents. Green Chem. 22, 5476-5486. 7Crane & Sapsford 2018. Sorption and fractionation of rare earth element ions onto nanoscale zerovalent iron particles. Chem. Eng. J. 345, 126-137. 8Newsome et al. 2020. Manganese and cobalt redox cycling in laterites; Biogeochemical and bioprocessing implications. Chem. Geol. 531. 9Wang et al. 2017. A review on in situ phytoremediation of mine tailings. Chemosphere 184, 594-600. 10van der Ent et al. 2020. Treasure from trash: Mining critical metals from waste and unconventional sources. Sci. Total Environ., 143673. 11Tibbett et al. 2020. The where, when and what of phosphorus fertilisation for seedling establishment in a biodiverse jarrah forest restoration after bauxite mining in Western Australia. Ecol. Eng. 153 12Gil-Martinez et al. 2018. Ectomycorrhizal Fungal Communities and Their Functional Traits Mediate Plant-Soil Interactions in Trace Element Contaminated Soils. Frontiers in Plant Science 9

Professor Tibbett can be emailed at: m.tibbett@reading.ac.uk

M Tibbett
University of Reading, UK

Resourcing for effective asset closure: transition capability assessment and social benefits

By Ken Henderson, GHD Advisory; Dr Pallavi Mandke, GHD; Dr Ceit Wilson, GHD

Careful capability planning is critical to a successful asset closure with significant resources and skills needed for the delivery of execution activities. Asset closure transition is a phased process, and often involves the following five key phases: ramp-down or decommissioning; dismantling and asset recovery; de-energisation; demolition; and rehabilitation.

GHD's closure and transition pathway is a considered process, offering flexibility for it to be tailored to individual operational requirements, while considering the long-term outcomes and community legacy and benefit.

Understanding whether the current operational workforce of an asset possesses the capabilities to safely and efficiently carry out tasks related to each asset closure phase is a critical component of the asset closure planning process. Despite its importance, this task is often not well understood or carried out with sufficient lead time, leading to inefficiencies during the closure execution phase as well as flow-on implications to the socio-economic wellbeing of the communities in which these operations occur.

GHD has developed a methodology to determine to what extent these resourcing challenges exist and how to address them to achieve the most optimal pathway from operations to closure execution. This methodology assesses the workforce readiness for closure execution in a snapshot towards the end of the life of an asset and sets specific actions to closure while identifying specific gaps in the planning process. In this article we explore how retention and maximising the use of existing workforce and contractors throughout the various phases of closure can create a positive legacy for the community and reputation for the operations and/or company.

Challenges to workforce planning during asset closure

When an asset reaches its final years, it is common for key personnel to look for alternative employment rather than staying on until the

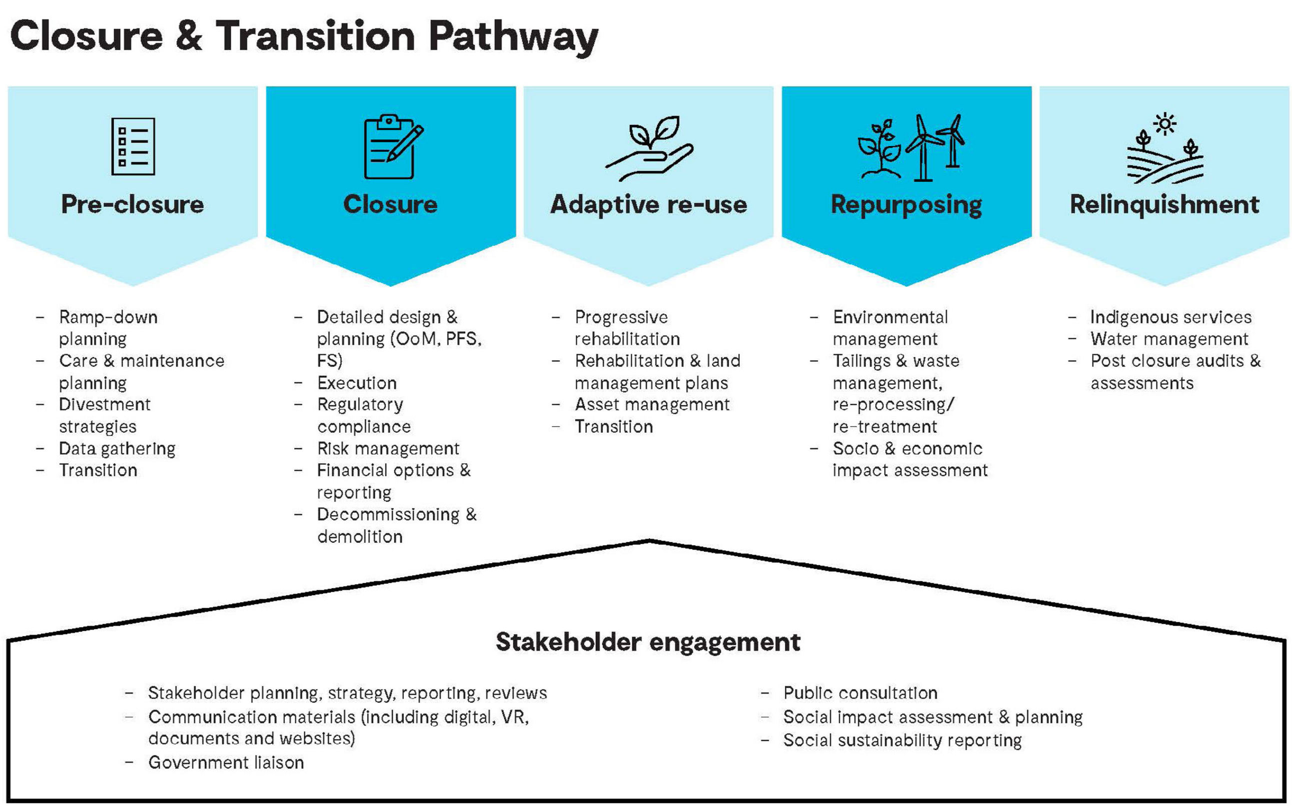

Figure 1. GHD's closure and transition pathway process, 2022

asset closes. However, safe and effective management of asset operations during and post-ramp-down requires key skills are maintained at all levels in the organisation, including managers, engineers, supervisors, planners, operators and trades persons.

In terms of a 'hierarchy of need', while it is necessary to have the appropriate hands-on skills at the trades level, these can often be more readily replaced by suitably qualified contractors. It will be more difficult to replace experienced management, engineers, planners, and supervisors who between them hold the collective knowledge of the organisation and the assets.

Similarly, the retention of key operating skills at all levels in the organisation is essential during the ramp-down period for the efficient and safe operation of the plant. In the lead-up to asset closure, specific reductions in the number of operations personnel commonly occur as a result of: a reduction in the number of shifts required to meet the Business Plan based upon the sales and production forecasts; termination of activities (e.g. development mining); a reduction in training and the need for 'training reliefs'; and a reduction in the need for 'holiday reliefs' as the time of closure draws nearer and less holidays are taken. However, the retention of some operating skills is required post-closure to ensure the critical infrastructure including water, drainage and power remain operational.

The risks associated with loss of key personnel are reduced if a skills/knowledge-based retention plan is established and implemented in the lead-up to asset closure, including incentives to ensure personnel stay for the duration required.

Transition capability assessment: a methodology

To understand the alignment of existing organisational capability and labour skills with the works involved in an asset's future site closure and rehabilitation, GHD has developed a tried and tested transition capability assessment methodology. The assessment findings determine whether the current operations and maintenance workforce possess capabilities to safely and efficiently carry out tasks related to the five defined key phases of closure, while considering appropriateness and several other significant factors. This initial assessment is succinct and high-level in nature and provides meaningful resourcing insights. It also considers if further follow-up assessment is necessary.

GHD's assessment process involves:

– Literature research into similar closure projects to determine recommendations provided in other similar case studies and industry guidance documents.

– Interviews with key personnel in the organisation such as the transition program manager, demolition project manager, operations manager, people (human resources) and culture teams.

– Tapping into GHD internal knowledge and experience by canvassing inputs from key professional staff engaged in other closure projects in Australia and overseas, as well as the input of experienced demolition contractors who have worked with GHD.

Based on the understanding achieved from the above mentioned steps, GHD develops a matrix for the various phases of the project to assess the suitability of each type of personnel/organisation being considered. This includes operations, maintenance, general contractors, specialist contractors and management personnel. The matrix assesses at a high level the relative merits or suitability of the various options to undertake the phases of the closure transition process. Each type of personnel/organisation is assessed for each phase while considering the following criteria:

- knowledge
- skills
- safety systems and awareness
- risk management
- lowest costs and efficiencies
- project management.

Outcomes are then scored to a simple three-level approach:

- Best meets criterion – 3
- Moderately/partially meets criterion – 2
- Least meets criterion – 1.

Outcomes of the assessment for each phase of closure

As a result of GHD's previous work and experience, along with industry insights and guidelines, GHD recommends:

– Ramp-down, decommissioning, asset recovery and de-energisation can be predominantly carried out by operations and maintenance labour, managed by the site operator's (or employer's) own management, with the support of specialist or general contractors, as required. This ensures that the knowledge and experience of the client personnel is utilised well.

– Demolition must be carried out and managed by a specialist contractor. There is a requirement to use trained, licenced personnel for this work. Integration and oversight should be by the site operator's own management.

– Rehabilitation is usually best carried out by specialist contractors. Even when the site operator has significant mining and earthmoving experience and equipment, rehabilitation typically requires specific landform development skills which are not necessarily those held by operators.

A graphical representation, indicating typical relative suitability for the respective phases of closure execution, is shown below. The higher scores indicate the greatest suitability for the resource category to execute the work.

Social benefits of the proposed model

In addition to the benefits of using the existing workforce and contractors throughout the various phases of closure, as outlined in the Transition Capability Assessment, maximising the use of the existing workforce (where and when possible) can bring numerous social benefits. This can also assist in maintaining a 'social license to operate/close'. Some of these additional benefits include:

– Retention of employment opportunities within the local communities and therefore retention of the town economy, community wellbeing, positivity and sense of pride in the workplace and with the employer.

– An opportunity to continue engagement with Traditional Owners and Indigenous community members, especially those who are part of the existing workforce and for assets where the land will be handed back to the Traditional Owners. Continuing engagement with these workers throughout the closure provides an opportunity to tap into local knowledge and aspirations to better inform the closure planning process. It also offers an opportunity to promote participation of Traditional Owners in the closure planning process through positive word of mouth among the existing Traditional Owner employees and those working through closure.

– Continued involvement of Traditional Owners employees and contractors will provide Traditional Owners an opportunity to care for country and a

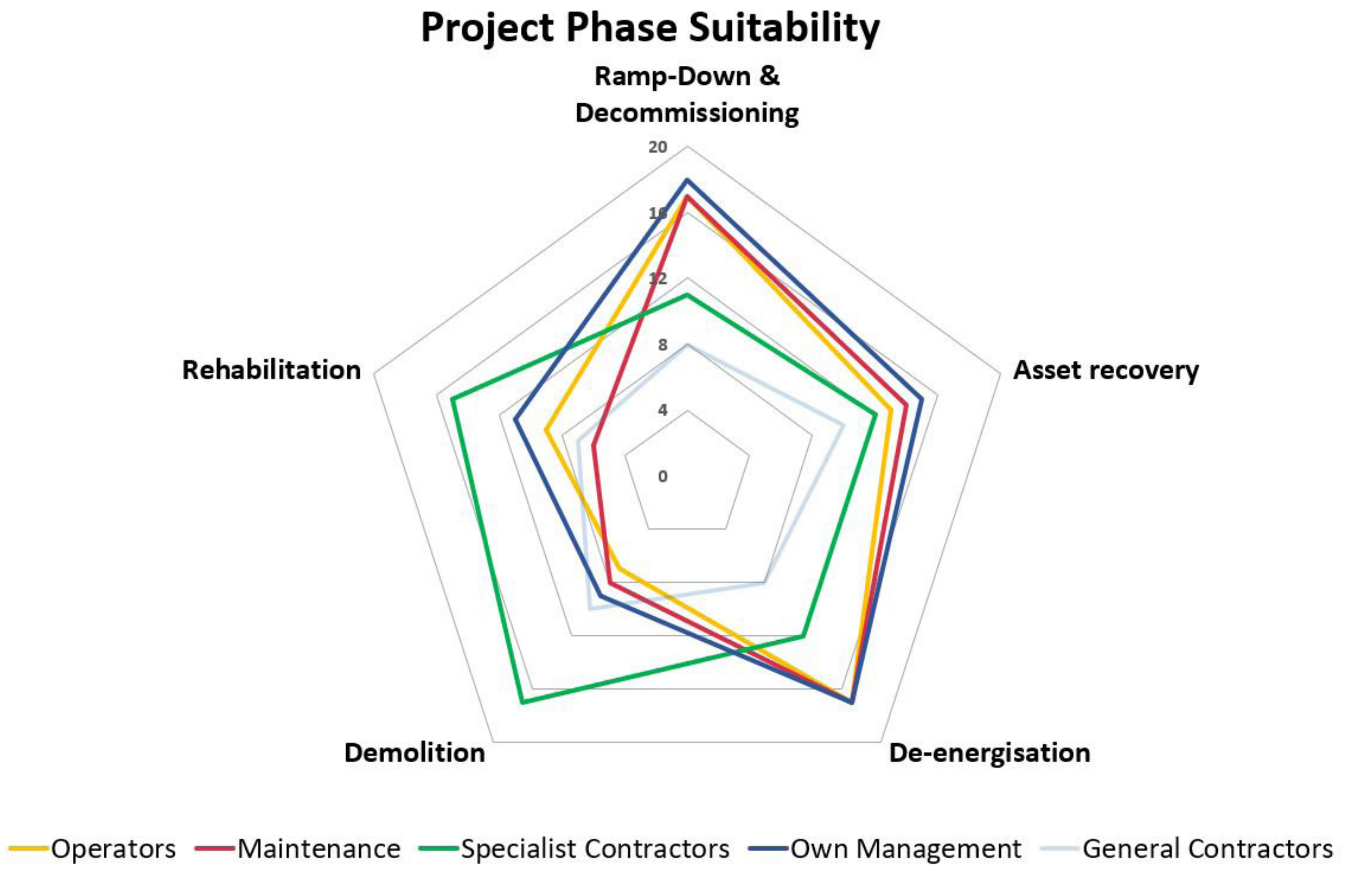

Figure 2. Suitability for closure project phases and execution

greater acknowledgement and awareness of the local environment, culture and land.

– Prolonged employment opportunities and involvement of Traditional Owners in the rehabilitation work would generate opportunities for Traditional Owners to return to country.

– An opportunity to continue knowledge-sharing and capturing information from the existing workforce for delivery of various phases of closure. This may require the upskilling of some workers through training. An investment in training of local staff would likely create greater social return by diversifying skills in the local workforce while potentially increasing their future employability.

– Engaging a number of contractors to provide engineering, mechanical, civil, earth works, type of services, especially when the production and resources assets are significant in size and scale. Where companies are required to supplement the organisational workforce during closure, the existing contractors (who are also often small local businesses) who have existing knowledge of the asset would likely be an appropriate source of supplementary contractor services. They should be briefed on closure opportunities with sufficient lead time to enable them to upskill their staff and availability of closure related business opportunities.

– Engaging the local workforce through the delivery of closure will help prolong the economic contribution by the asset in the local community and the region, gradually reducing the economic dependencies created in the communities. This will allow individuals, families, and the region as a whole to be better prepared for the eventual loss of the economic contribution by the asset, allowing much needed time for other economic diversification activities and processes to take shape.

Overall, maximising the use of existing workforce and contractors throughout the various phases of closure can create a positive legacy for the community and reputation for the company, however, it does require detailed early planning to ensure that the timing of the closure phases supports this approach.

In summary

Careful capability planning is critical to a successful asset closure with significant resources and skills needed for the delivery of execution activities. It is common for key personnel to look for alternative employment rather than staying until the operation is closed and the closure process is complete. However, safe and effective management of asset operations during and post-ramp-down requires key skills are maintained at all levels in the organisation, including managers, engineers, supervisors, planners, operators and trades persons.

The risks associated with loss of key personnel are reduced if a skills/knowledge-based retention plan is established and implemented in the lead-up to the asset closure, including incentives to ensure personnel stay for the duration required.

Understanding whether the current operational workforce of an asset possesses the capabilities to safely and efficiently carry out tasks related to each asset closure phase is therefore a critical component of the asset closure planning process. GHD has developed a methodology to determine to what extent these resourcing challenges exist and how to address them to achieve the most optimal pathway from operations to closure execution. This approach optimises the use of the existing workforce, and where possible, can also bring numerous social benefits while assisting in maintaining a ‘social license to operate/close’.

Ken Henderson, Executive Advisor, Asset Management, GHD Advisory

Dr Pallavi Mandke, Technical Director and National Lead – Social Sustainability, GHD

Dr Ceit Wilson, Senior Social Performance Consultant, GHD