A framework for a sustainable approach to mine tailings management: disposal strategies

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Abstract
The aim of mine tailings management strategy is to protect the environment and humans from risks associated with mine tailings. It seems inevitable that future production from lower grade ores in mines will increase, generating a higher tonnage of tailings. Approximately 14 billion tonnes of tailings were produced globally by the mining industry in 2010. The need for a comprehensive framework for mine tailings management (including dewatering) that promotes sustainable development is therefore becoming increasingly recognised by the mining industry. In this paper, we review existing frameworks for tailings management and propose an improved framework that considers key sustainable development pillars: technological, economic, environmental, policy, and social aspects. This framework will be able to guide the mining sector to choose its mine tailings management strategy based on sustainable development concepts. It incorporates a range of tools for determining trade-offs inherent in different tailings management methods during operation and throughout the Life of Mine (LOM); these include Life Cycle Assessment (LCA), Net Present Value (NPV), Hierarchy System Model (HSM), and Decision Analysis. In particular, this proposed recognises the highly case-specific of tailings management by explicitly integrating physicochemical characterisation of tailings properties as a first step. In future, the framework could be expanded through integration of reuse/recycle principles of industrial symbiosis.

Keywords: mine tailings management; disposal options; framework; sustainable development

1. Introduction

1.1 Background
Mineral processing plants produce two types of products, categorised as either economic or non-economic. The non-economic product, usually known as tailings, consists of waste (by-product), small quantities of valuable minerals or metals, chemicals, organics, and process water (Lottermoser, 2010, TI, 2014). The volume of tailings generated by mines can be almost equal to the volume of raw material processed for example, a mine producing 200,000 tonnes of copper ore per day will also produce nearly the same tonnage of tailings per day (MMSD, 2002). Some mining operational data showed that the volume of tailings generated is around 97-99 percent of total ore processed (NDM, 2005, NNT, 2011). In other words, the amount of concentrate produced is only 1-3 percent.

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TSF: Tailings Storage Facility
MCMPR: Ministerial Council on Mineral and Petroleum Resources
MCA: Minerals Council of Australia
DITR: Department of Industry, Tourism, and Resources
MAC: Mining Association of Canada
RTD: Riverine Tailings Disposal
STD: Submarine Tailings Disposal
LPSDP: Leading Practice Sustainable Development Program
TT : Thickened tailings
TP : Tailings paste
Therefore, one study revealed that 14 billion tonnes of tailings were produced by the mining industry in 2010 (Jones and Boger, 2012).

The large volume of tailings results in a large environmental footprint both spatially in terms of the storage area as well as temporally in terms of the long-time scales over which tailings must be managed and rehabilitated (DITR, 2007). Mine tailings management is a crucial issue in mining operations because of the irreversible impacts of tailings. The physico-chemical makeup of tailings presents a myriad of additional challenges to achieve physically and chemically stable landscapes that do not present risks such as acid mine drainage. Failure to manage tailings can result in costly with severe and sometimes catastrophic consequences. There have been 237 cases of tailings accidents worldwide since 1917 to 2009 where 17 cases occurred in the 2000s (Lottermoser, 2010, Rico et al., 2008, ICOLD, 2001). Catastrophic failure of the Los Frailes tailings dam has resulted in 3,600 hectares of agricultural land flooded with tailings, a loss of 5,000 jobs in various sectors, and contamination of water stream with acid, metals, and metalloids (Coleman and Ana, 1998, Lottermoser, 2010). Another example is the failure of a gold mining tailings storage facility in Baia Mare Romania Year 2000 that resulted in environmental disaster, with significant kills of freshwater organisms and contamination of water supplies of more than 2 million people (Lottermoser, 2010). Such accidents often occur as a result of poor tailings management, including poor water control. Considering the severe and sometimes irreversible economic, social and environmental consequences of poor tailings management, the need for considered and careful tailings management in the mining industry is obvious.

The environmental, economic, social and governance pillars are the most common sustainability aspects of mine tailings management. The detail of each pillar is shown on Table 1 below though specific mine setting might open possibility to adjust the components of each pillar.

Table 1
Sustainability issues in tailings management

<table>
<thead>
<tr>
<th>Environment</th>
<th>Economy</th>
<th>Social</th>
<th>Government (Regulation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air and water pollution</td>
<td>Capital expenditure</td>
<td>Health issues</td>
<td>Legal compliance</td>
</tr>
<tr>
<td>Water resources depletion</td>
<td>Operating expenditure</td>
<td>Safety issues for public (after closure)</td>
<td></td>
</tr>
<tr>
<td>Ecosystem destruction</td>
<td>Reagent loss</td>
<td>Stakeholder perception</td>
<td></td>
</tr>
<tr>
<td>Ecosystem alteration</td>
<td>Energy cost</td>
<td>Cultural impacts</td>
<td></td>
</tr>
<tr>
<td>Land footprint</td>
<td>Closure cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emissions</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sustainable development principle in mine disposal waste by minimising inputs such as water and energy (Franks et al., 2011) is also covered by those pillars above particularly in environmental and economic pillars. In a condition where the final tailings product has been treated such as by dosing with lime to raise the pH, the sustainability issues of tailings spin primarily around the water content during transport and placement. This is because water plays an important role in determining the
behaviour of the tailings when it is placed and after placement. The largest water sink at most mine site is the tailings storage facility (TSF) (Gunson et al., 2012). Around 186 m$^3$/h of water is required for transporting of platinum tailings in 50% mass solids (Moolman and Vietti, 2012) and 4,783 m$^3$/h of water is consumed to transport copper tailings (30% mass solids) from tailings flotation into TSF (Gunson et al., 2012). All of the water is deposited in TSF with tailings. The reclamation of water from tailings impoundments is therefore a common strategy used by mine sites to reuse water and reduce tailings dam risks, particularly in semi-arid and arid climatic regions (Wels and Robertson, 2003, Ritcey, 2005).

There are currently nine key principles for effective mine tailings management, as developed by the Ministerial Council on Mineral and Petroleum Resources and the Mineral Councils of Australia. These principles include adoption of a risk-based approach, minimizing tailings production and increasing tailings re-use, and considering relevant economic, environmental, and social aspects (MCMPR and MCA, 2003). Though these principles cover almost all issues related to tailings management, they are too general and do not describe detailed steps for determining an appropriate mine tailings disposal method. Increasingly, it is being recognised that the framework must also consider synergies and trade-offs between components such as energy and water involved in different management options (Nguyen et al., 2014). A robust tailings disposal strategy framework should ideally consider the interaction between these competing factors in order to achieve a safe and environmentally sustainable mining operation.

1.2 Objectives

This paper aims to assess current mine tailings management frameworks and review the tailings disposal strategies applied. As part of tailings management, focus of this paper is how to determine more appropriate tailings disposal strategies from sustainability perspective. A generic framework for tailings disposal strategy will subsequently be proposed. This proposed framework takes into account various considerations relevant to tailings disposal strategy in all mines. The geochemical parameters should be taken into account for mine site with reactive tailings such as sulfidic tailings. The application of this generic framework is presented in section 4.2 to enable a mine site to determine a preferred tailings disposal strategy that also meets principles of sustainable development.

In order to achieve the above objectives, a literature review was conducted to examine current frameworks and applications of mine tailings management strategies, and ascertain current gaps and challenges. The following subsection outlines the ongoing global discussions around mine tailings. Section two outlines mine tailings disposal strategies applied worldwide, with specific reference to direct and indirect disposal and to mine tailings volume. Section three reviews current tailings management frameworks in terms of their context, approaches, and concepts. The paper concludes with a discussion of potential improvements for tailings management framework.

1.3 Current discussions relating to mine tailings management

Using search engines such as Scopus, Google Scholar, Google, and the Curtin library catalogue, a number of relevant documents were identified, including documents associated with tailings management in Australia and Canada. The first framework (Strategic framework for tailings management) considered was issued by the Ministerial Council on Mineral and Petroleum Resources (MCMPR) and the Mineral Council of Australia (MCA). The second (Tailings management) forms part
of the leading practice sustainable development program (LPSDP) for the mining industry and was issued by the Department of Industry Tourism and Resources (DITR) Australia. These two documents use slightly different approaches to develop tailings management frameworks. The approach taken by MCMPR (2003) is more focused on the operational phase; this can be seen from one of the chapters that discusses implementation. Some of the principles outlined in the implementation chapter detail implementation of appropriate operational controls (including procedures, monitoring, and audit programs), and reporting tailings management operations to appropriate stakeholders (MCMPR and MCA, 2003). Meanwhile, the DITR (2007) examines tailings management from the perspective of Life of Mine (LOM). In the latter, tailings management is deployed at all stages of the mine cycle: planning and design, construction, operation, and closure planning (DITR, 2007). A third framework introduced by the Mining Association of Canada (MAC) adopts the principles of the International Organization for Standardization (ISO). These general principles are close cycle activities consist of Plan, Do, Check, and Act (P-D-C-A) and a continual improvement is the main goal of this process. Another approach proposed by Boger (2011) designs tailing management from the so-called ‘disposal point’ toward upstream stages (technologies option). Related technologies include thickened and tailings paste. There are three main stages proposed: determining a disposal method, pumping and pipeline requirements, and thickener design (Boger, 2011). However, Chryss et al. (2012) argue that this approach is too general and needs to be further developed. McLellan et al. (2009) states that sustainable development tools such as environmental and social impact assessment, multi criteria decision analysis are not currently integrated into a comprehensive framework (McLellan et al., 2009). It is thus evident that further development of current tailings management frameworks is essential in order for these to be applied to all types of mines. Such an overarching framework can be referred to as a generic tailings disposal framework.

Currently, most mines apply the conventional method of disposing of tailings by transporting tailings slurry through pipes into a TSF or a Tailings Dam. This method requires a high percentage of water and is chosen primarily because of its cost effectiveness. There are two important cost components considered in calculating tailings costs - Operational Expenditure (OPEX) and Capital Expenditure (CAPEX). OPEX and CAPEX are mainly influenced by pump type, energy consumption, and chemicals used. A centrifugal pump is commonly used. This consumes less energy than the positive displacement pump used in the tailings paste method. However, Boger et al. (2012), Boger (2013), Fourie (2012), and Moolman and Vietti (2012) argue that the OPEX and CAPEX of tailings management can be reduced through implementation of thickened tailings (TT) and tailings paste (TP) technologies. Boger (2012) claims that the implementation of TT and TP will reduce the future cost of mine closure (rehabilitation and maintenance) and these two items are not costed properly. In addition, TT and TP increase the mine liability and the possibility to reduce tax payment in terms of rehabilitation and long-term maintenance cost (Boger, 2011). Fourie (2012) concludes that the OPEX of TT may be lower than that of conventional methods. He presents examples of mine sites that apply TT and TP and compares their net present value (NPV) in the case that they were to use conventional methods.

There are two main components involved in applying TT and TP: water and energy. Some studies have examined the correlation between these two components (Nguyen et al., 2014, Gunson et al., 2010, Norgate and Haque, 2012). Other studies have focused on modelling mine water management without considering energy consumed (Cote et al., 2010, Gunson et al., 2012). One case study by Moolman andVietti (2012) details the connection between water recovery and power cost (capital
and operating) in tailings management of a platinum project on the Eastern Limb of the Bushveld Complex. Results revealed that the thickened tailings option had the lowest total cost per tonne of tailings discharged. Such studies indicate that the emerging technologies of TP and TT represent a breakthrough in the mineral industry for increasing the volume of recycled water used and preventing fresh water utilization. The development of TT and TP has therefore been an emerging breakthrough associated with tailings management. The implementation of such technologies is now very feasible due to their maturity (Verburg, 2001, Patil et al., 2007, Mudd et al., 2013, Jones and Boger, 2012, Fourie, 2012, Fourie, 2009, Chryss et al., 2012, Boger, 2000). Furthermore, understanding tailings flow behaviour (rheology) is key to successful implementation of TT and TP assuming that tailings reactivity is not a concern.

2. Current application of tailings disposal strategies

There are two strategies commonly applied by mines for the disposal of tailings: direct and indirect disposal. Direct disposal is conducted by discharging tailings directly into rivers, oceans, and lakes. There is debate concerning this strategy’s operational feasibility in technical, social, and environmental fields. There are two strategies of direct disposal: riverine tailings disposal (RTD) and submarine tailings disposal (STD). There are currently 16 mine sites (representing 0.6% of total mines worldwide) that use RTD or STD (IMO, 2012), with these concentrated in Europe and Asia.

Collectively, these mine sites produce more than 294 million tonnes of tailings per year, of which 93% are produced by mine sites in Asia, most notably in Indonesia and PNG (Fig. 1). Around 62% of total tailings directly disposed of (182.7 million tonnes per year) are discharged to rivers using the RTD method. RTD is the simplest tailings disposal method and occurs where tailings are transported to the river by a pipe and discharged. The application of RTD across the world has created irreversible environmental impacts and these detrimental impacts are the reason why RTD is no longer applied, except at four mine sites (one in Indonesia and three in Papua New Guinea (IMO, 2012, MMSD, 2002).

![Fig.1. Mine tailings: worldwide direct disposal](image)

The other strategy of direct disposal is STD. Similarly to RTD, the STD method uses pipes to transport mine tailings into the sea at a certain depth. Prior to STD implementation, a number of mine sites used to dispose of tailings on the ocean surface. This created close interactions between tailings and the abiotic and biotic environments, resulting in high contamination risk for the latter (Franks et al., 2011). In order to reduce the impact of mine tailings on oceans, STD was introduced and implemented by a number of mining companies. The proponents of STD (Ellis et al., 1995, Jones and Jones, 2001, Poling et al., 2002, Hadi, 2009) claim that the application of STD is safe as long as it
fulfils certain requirements. These include the requirement that the point of discharge be positioned below the surface mix layer, the thermocline layer, and the euphotic zone, and the requirement that tailings are non-toxic at the mixing point and do not leach contaminants. However, opponents of STD argue that its implementation will create the potential for environmentally-damaging incidents, such as pipe leakages, increased turbidity and metal concentrations in the marine environment, and decreases in benthic organism populations (Coumans, 2002). STD application therefore requires strong and comprehensive environmental monitoring and management programs (Bachtiar, 2011, Hadi, 2009, PTNNT, 2011) to reduce its negative impacts.

The second tailings disposal strategy is indirect disposal. In this strategy, tailings are disposed of to an impoundment, cell, or dam. There are a number of options for indirect disposal including conventional tailings, tailings paste, thickened tailings, and tailings cake. The most common method of indirect disposal currently applied is conventional tailings, where tailings are transported in slurry that consists of approximately 25-30% solids (Fourie, 2012, DITR, 2007). As the water content of the tailings slurry is quite high, this method is suitable for areas where precipitation levels are lower than evaporation levels, such as arid and semi-arid regions (Franks et al., 2011). The high percentage of water in slurry is one of the main causes of tailings dam failures when the dams neither are nor well designed. Reducing water content by increasing the percentage of solids in tailings is therefore one effective solution for minimizing the risk of dam failure and for increasing water efficiency levels. This strategy has been chosen by a number of mine sites, particularly in arid and semi-arid environments, through the application of alternative tailings disposal including tailings paste, thickened tailings, or tailings cake technologies as shown in Table 2. However, these methods require a mining company to allocate more capital annually for operational and capital costs (Moolman and Vietti, 2012).

<table>
<thead>
<tr>
<th>Mine site</th>
<th>Location</th>
<th>Type of mine</th>
<th>Production rate (Mt/y)</th>
<th>Tailings mass solids (%)</th>
<th>Disposal strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kidd Creek Mine: copper-zinc</td>
<td>Canada</td>
<td>Surface</td>
<td>3.6</td>
<td>80.4</td>
<td>Thickened</td>
</tr>
<tr>
<td>Alcoa World: alumina</td>
<td>Australia</td>
<td>Surface</td>
<td>7.3</td>
<td>70</td>
<td>Dry stacking</td>
</tr>
<tr>
<td>Bulyanhulu Mine: gold</td>
<td>Tanzania</td>
<td>Underground</td>
<td>0.91</td>
<td>73</td>
<td>Paste backfill</td>
</tr>
<tr>
<td>Sunrise Dam: gold</td>
<td>Australia</td>
<td>Surface</td>
<td>1.5</td>
<td>77</td>
<td>Thickened</td>
</tr>
<tr>
<td>Esperanza Mine: copper-gold</td>
<td>Chile</td>
<td>Surface</td>
<td>29</td>
<td>67</td>
<td>Thickened</td>
</tr>
<tr>
<td>Boliden Garpenberg: lead-zinc</td>
<td>Sweden</td>
<td>Underground</td>
<td>2.5</td>
<td>70</td>
<td>Paste backfill</td>
</tr>
</tbody>
</table>


The application of alternative tailings disposal depends on yield stress value. The yield stress value indicates the physical behaviour of material for example alumina thickened tailings which has yield stress ranging from 30 – 100 Pa (Boger et al., 2012) will have slurry to paste behaviours. As can be seen in Fig.2 that the yield stress correlates with solid density or percent solids. The selection of percent solids is based on some factors including capital and operational cost (technology). The implementation of conventional technology thickener (see Fig.2) produces tailings with very low
yield stress and this condition generates large percentage release of transported water and increases decant water into TSF (Fourie, 2012). Therefore, the optimum solid density or percent solids should be determined to achieve the effective and efficient tailings transportation.

Two common tests to determine the mechanical or physical behaviour of tailings are through cone or rheology test. This test describes flow behaviour of tailings in the pipe during transported that can be used by engineer to design the TSF and tailings transportation system (Paterson et al., 2002, Boger et al., 2012, Boger, 2000).

The availability of various options on tailings disposal strategy requires the mine site to choose the strategy that suits with the characteristic of mine and has sustainable perspectives. Furthermore, the advantages and disadvantages related to different tailings disposal strategies could potentially be determined using a framework that comprehensively considers sustainable aspects.

3. A review of the existing frameworks
The review of current frameworks focuses on the above-mentioned MCMPR (2003) and DITR (2007) frameworks. The following elements were considered in the framework review: contexts, approaches, and framework flows.

3.1 Context of the current frameworks
Each of the documents has a slightly different context to the discussion of tailings management. MCMPR (2003) is more concerned with tailings management in the mine operational context while DITR (2007) considers tailings management across the various phases of the mine cycle, including
planning and design, construction, operation and monitoring, decommission and closure, and post-closure.

The MCMPR (2003) divides its framework into five main key principles: stewardship, stakeholder engagement, risk management, implementation, and closure (MCMPR and MCA, 2003). Each of these principles, shown in Fig. 3, focuses on specific areas, as follows:

1. **Stewardship** is focused on best practices of implementation, tailings minimization, continual improvement of processes and practices, technological innovation, and benchmarking with other sites.
2. **Stakeholder engagement** is aimed at identifying community and other stakeholders’ concerns. The success of stakeholder engagement may increase stakeholders’ acceptance of a project.
3. **Risk management** involves risk assessment, risk mitigation, and emergency response. The implementation of risk management is aimed at minimizing potential risks associated with tailings storage and transportation.
4. **Implementation** is focused on developing an effective tailings management system and involves variables such as company policy and commitment, planning, procedures and resources, monitoring progress, and reporting.
5. **Closure** is aimed at ensuring effective long-term stability of TSF and will be followed by a monitoring program to ensure that success criteria have been achieved.

![Fig.3. MCMPR strategic framework for tailings management](image-url)

As noted, the DITR framework was developed under the LPSDP program and encompasses key issues affecting sustainable development in the mining industry, including tailings management. Tailings management, as discussed in the LPSDP, highlights the importance of tailings and sustainable development and includes examples of the implementation of tailings technologies. The relationship
between tailings and sustainable development is bundled in the terminology of “Enduring value principles for tailings management” (DITR, 2007). These enduring value principles are: implementing the environmental management system, providing safe storage and disposal, rehabilitating disturbed land, and consulting and informing related stakeholders regarding risks and impacts. In addition, according to the DITR, a tailings management system should be implemented throughout the life of a TSF, from planning and design to construction, operation, and closure planning (Fig. 4).

![Fig.4. Tailings management system life cycle – adapted from (DITR, 2007)](image)

The proper implementation of a tailings management system will ensure effective closure, provide a TSF that is stable and safe to the environment and humans, as well as reduce financial expenses for the mine.

### 3.2 Approaches chosen by the current frameworks

Before describing the MCMPR and DITR approaches, it is necessary to define the significant safety, health, environment, and financial hazards or risks associated with TSF operation (DITR, 2007, MCMPR and MCA, 2003, MAC, 2011). These hazards or risks can lead to, or be a trigger for, TSF failure. There are many possible causes of TSF failure (Rico et al., 2008); however, it can be concluded that the most effective way to avoid such failure incidents is through effective risk management. It is also important to understand the basic principles of risk management and their relation to tailings management.

![Table 3](image)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Potential risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation</td>
<td>Leaking of tailings slurry pipeline</td>
</tr>
<tr>
<td></td>
<td>Geotechnical failure</td>
</tr>
</tbody>
</table>

It is first necessary to define risk, prior to describing the basic principles of risk management. Risk can simply be defined as the effects of something on objectives; such effects might be positive or negative and may be multidimensional, incorporating aspects such as health and safety, environment, finances, and social elements (ISO, 2009, Heikkinen et al., 2008). It could also define as the potential loss in health and safety, environment, economic associated with an event or activity. Potential risks associated with mine tailings are detailed in Table 3. The geochemical risks are beyond of this study and included in the decision analysis process as shown in Fig.7 and section 4.2.3.
These risks should be managed and monitored to prevent or eliminate the hazards that may occur. Managing and monitoring risks is one of the steps outlined in risk management principles. Risk management can be streamlined into seven stages: problem definition, data and information collection, risk identification, causes and controls, assessment and analysis, planning and action, and monitoring and review (Fig. 5). This cycle is a continual improvement process where the monitoring and review stages act to produce further improvement initiatives.

Both MCMPR (2003) and DITR (2007) argue that the application of risk management will provide advantages for tailings management. These advantages are as follows:

1. Minimize tailings incidents associated with tailings transportation and storage.
2. Minimize the likelihood of environmental, health, safety, and business risks.
3. Minimize the risks associated from the initial mine tailings step, planning and design, through to the final step of post-closure.
4. Prioritization of having an action plan associated with hazards or risks in place.
Besides using the same risk-based approach in tailings management, there are a number of similar considerations between the MCMPR (2003) and DITR (2007) frameworks. These are the aspects relating to stakeholder engagement, closure, and operations. Stakeholder engagement focuses on the importance of involving all stakeholders at the design and planning, operation, monitoring, and closure phases. Closure is aimed at ensuring the stability of TSF and meeting the closure success criteria. Lastly, operation is intended to ensure safety and cost effectiveness of TSF.

3.3 Flow of current frameworks
The strategic framework developed by the MCMPR “is not a detailed set of guidelines for tailings management” (MCMPR and MCA, 2003). The framework gives a brief description of the essential components to be considered when managing tailings. Five main components are considered: stewardship, stakeholder engagement, risk management, implementation, and closure, as described in Fig. 3. It seems that each component of this framework plays its own independent role, as there is no discussion on how to integrate those components. The framework developed by the DITR is more comprehensive and provides some examples of tailings containment, disposal, and rehabilitation, and of prospective technologies for tailings management, through case studies. In addition, DITR (2007) also provides a structured overview of steps to develop a conceptual tailings management system (Fig. 6).

The DITR’s tailings management concept starts by defining operational parameters. Two types of data are involved - technical and non-technical. The technical data required includes topography, hydrology, catchment area, rainfall, evaporation, tailings volume and characteristics, and seismic data. Non-technical data includes regulations and community concerns. After all operating parameters have been defined, tailings storage sites should be determined by considering factors such as site rehabilitation and the potency of environmental impacts. The determination of tailings storage sites will be followed by the calculation of site water balance. During this stage, the impacts of different tailings storage options and disposal methods will be evaluated using water supply and rainfalls as the main variables. The next stage of the tailings management concept developed by the
DITR is analysing dewatering options. These options include conventional options, high rate and paste thickener, vacuum and pressure filters, centrifuges, and cyclones. The DITR (2007) uses two main parameters as initial screening tools to sort available dewatering options - the site water balance and tailings density target. These dewatering and storage options are then assessed from a financial point of view by calculating the net present cost and value of each option. The cost elements calculated are associated with the geographic position of the dewatering equipment and storage site, tailings transportation choices (pumping, hauling, and conveying), and price-sensitivity of reagents and water. The final step is referred to as final assessment. This step combines all results from the previous steps and generates the most preferred option by using ranking analysis for tailings dewatering, transportation, and storage. In addition, DITR (2007) notes that non-numerical parameters such as community concerns should also be considered during this final stage.

A third tailings management framework has been developed by the Mining Association of Canada (MAC, 2011). This framework has been designed according to continual improvement principles, as commonly applied by ISO standards. The steps of this framework adopt the ISO cycles, starting from policy and commitment, followed by planning, plan implementation, checking and corrective actions, and concluded through a management review. This framework is a closed cycle framework where the management review step will generate actions for continual improvement, with these actions then implemented in other steps. Based on implementation of the ISO concept, it can be concluded that the focus of this framework is on the operational stage of tailings management. This framework is thus not as detailed as the framework presented by the DITR (2007).

3.4 Gaps and weaknesses in current frameworks
The three tailings management frameworks (MCMPR (2003), DITR (2007) and MAC (2011)) place emphasis on tailings management as a tool during the operational phase of TSF mine cycles, even if
the DITR (2007) framework also describes the importance of considering all life-cycle stages of a TSF. As mentioned by MCMPR (2003) that their framework is not detailed guideline and it can be seen from how this framework discusses the tailings management. The authors see this framework as an management system of tailings because it consists of some main management system elements such as continual improvement, innovation, operational control, compliance, and reporting. The same principle is seen on a framework developed by MAC (2007) in which the continuous improvement plan through management system close cycle process is applied. These two frameworks might be fit with the audit process but not suitable for the planning and design process. It is the authors’ view that the tailings management framework introduced by the DITR (2007) is more rigorous compared with the other two frameworks. This is because it considers all mine phases and provides case studies, enabling an illustration to the reader of differences between conventional and DITR concepts.

However, the DITR (2007) framework seems very descriptive and qualitative and thus too general to be used during the implementation phase. This framework could be used as a guideline at the conceptualisation stage but not at the implementation level. A specific framework that provides detailed guidelines on how to determine mine tailings management options is thus currently required. The lack of such detailed steps is a main gap and weakness identified in current frameworks. Detailed steps will enable the mine site to choose an appropriate tailings management method in a sustainable management context. In addition, while current frameworks are using risk-based approaches as their main approach, the ‘beyond sustainability management’ approach should also be included to ensure that a social licence to operate and close is granted by stakeholders.

4. Results and Discussion

The application of mine tailings disposal strategies including direct disposal (riverine and submarine tailings disposal) and indirect disposal (tailings dam, thickened tailings, and paste tailings) provides an illustration that mining operation has some choices in dispose their tailings. Selection of appropriate mine tailings disposal will provide benefits for mining not only short-term but also long-term benefits particularly associated with social licence to operate. The sustainable development components including water, energy, cost, technology, and environmental impact should be used as a reference to determine the appropriate mine tailings disposal strategy for a mine site.

However, the interaction between key tailings components (water, energy, cost, technology, and environmental impact) has not yet been fully addressed by current research or existing frameworks. The lack of a comprehensive framework is also mentioned by McLellan et al. (2009); the integration of these components into a framework that also includes social and regulation aspects is therefore urgently needed.

4.1 Proposed alternative framework

The proposed framework aims to generate a detailed step to determine a preferred mine tailings management method from a sustainable development perspective. This framework would complement and fill the gaps as described on section 3.4 of the existing MCMPR (2003) and DITR (2007) frameworks. In addition, the proposed framework consists of laboratory analysis, computational assessment, cost analysis, regulation review, and decision-making process. All of these elements are combined into sustainable-based frameworks as shown in Fig.7.
The authors propose to divide the proposed framework into 8 steps:

Step 1. Geochemical characterisation is supposedly already done and the tailings will not release any contaminant.

Step 2. Identify and analyse tailings characteristics and behaviour through laboratory analysis, including rheology and pumping tests.

Step 3. Analyse laboratory data and determine the relationship between water and energy consumption. Identify potential technologies for mine tailings management options.

Step 4. Calculate the cost of each option by considering main components (i.e., OPEX, CAPEX, and closure).

Step 5. Identify and calculate the potential environmental impacts of each option.

Step 6. Identify the relevant regulations in place.

Step 7. Involve relevant stakeholders through decision analysis processes.

Step 8. Conduct a final assessment to consider all outcomes from previous steps.

In our approach, laboratory work (step 1-2) plays an important role as a data provider to other steps. The data produced by laboratory testing includes tailings characteristics, rheology, and pumping energy. The tailings characteristics data will give an overview of the components inside the tailings and this information is important to find out how to handle mine tailings effectively (Boger et al., 2012). The subsequent steps in the framework depend on good characterisation of the physicochemical properties of the tailings which includes rheology. Assessing the potential impacts, technologies, cost etc. is highly case-specific depending on the properties of the tailings, which is

Fig.7. Proposed framework for mine tailings management
where the frameworks literature fail; and hence why good characterisation of the physical properties of the tailings is needed as a first step of a robust analysis.

The laboratory data will then be analysed to identify the list of technologies that can potentially provide high contributions to water and energy synergies or trade-offs. One of the tools used to determine the relationship between water and energy is the Hierarchical System Model (HSM). HSM is a computer model that represents the interaction between water use, energy use, and emissions in mining applications (Woodley et al., 2013, Keir and Woodley, 2013). The typical application of the HSM is in developing simplified systems-level models of mine site water and energy networks, in which the complex topology of a mine water network is simplified to a level which is more easily comprehensible for management purposes, but retains most of the behaviour of the real water system. More detail on the HSM is provided in section 4.2.1. The following steps (4-5) assess the list of potential technologies in terms of economic and environmental impacts. The economic aspect should take into account mine closure costs as well as Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). The NPV calculation of these three monetary components is generated at this stage. The economic calculation will then be compared with the environmental impacts aspect. With regard to the latter, LCA is considered to be a comprehensive tool to assess potential environmental impacts of each technology proposed or applied. LCA is comprised of four methodological phases: goal and scope definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Life Cycle Interpretation (Udo de Haes et al., 2005, Heijungs and Guinee, 2012). Data from the laboratory tests such as water and energy consumption will feed into the LCI phase. However, in order to establish a comprehensive inventory for the LCI phase, it will be necessary to supply additional data obtained from mine sites, with this including the volume of ore and tailings, mine tailings process handling, TSF mine closure processes, and chemicals used.

The stakeholder engagement phase (step 7-8) represents the importance of the role of stakeholders in tailings management decision-making. The stakeholders should consist of internal and external parties that represent different interests, such as community, experts, and mining company representatives. There are some essential steps to implement decision-making phase such as identify the sustainability issues, weight the issues by considering the mine, communities, stakeholder expectations, and corporate values, assess the relative performance of each alternative, and compare the alternative performance of weighted issues. One of the decision-making tools commonly used is Analytical Hierarchy Process (AHP) and according to Saaty (2008) is “a theory of measurement through pairwise comparisons and relies on the judgement of experts to drive priority scales”. The inconsistency of expert judgment and how to improve judgment are two main considerations that need to be considered when applying AHP as a decision-making tool (Saaty and Vargas, 2006, Saaty, 2008). The involvement of various stakeholders in the decision-making process is a crucial aspect allowing a mine site to get the social licence to operate and to close.

The detailed steps including appropriate analysing tools and the sustainable-based approach make this proposed framework more comprehensive and complete compared to other three frameworks presented earlier. Therefore, this framework could be used as a complementing and filling the gaps of other frameworks.

4.2 Framework application
The following is one hypothetical situation in a mine site to show how the framework works. After completing physicochemical analyses to determine the characteristic of tailings including density,
yield stress, and chemical properties, a HSM, shown in Fig. 8.1, is developed to demonstrate connections between components in mining operations including tailings dam. Two scenarios are assessed: conventional tailings with 30% solids and thickened tailings with 50% solids.

4.2.1 Hierarchical system model (HSM)
The HSM is a graphical, user-friendly software tool that allows users to build so called ‘systems models’ of mine site water, energy, and emissions networks at arbitrary levels of detail. The essential feature of the systems modelling approach previously adopted is that the main uses of water and energy on mine sites may be grouped in several broad categories: (i) extraction of material, including drilling, blasting, digging and ventilation; (ii) transport of material, particularly between the point of extraction and the point of processing, including use of trucks and conveyors, and associated dust suppression; and (iii) processing of material, which involves separating salable product from waste, including activities such as crushing, grinding and separation.

The HSM represents water and energy interactions using six basic components: (i) water inlets that represent water entering the system; (ii) water outlets that represent water leaving the system; (iii) energy / emissions inlets that represent energy and / or emissions entering the system; (iv) energy / emissions outlets that represent energy and / or emissions exiting the system; (v) stores that represent where water is held within the system; and (vi) tasks that represent where water and / or energy are used within the system.

A detailed description of the technical operation of the model is beyond the scope of this paper: the basic premise is as follows. In general, stores and tasks can receive multiple inlets of water (e.g. catchment runoff, rainfall, external water allocations, water entrained in mining material etc.); while tasks can also receive multiple inputs of energy (e.g. network electricity inputs, use of fuels such as diesel, use of explosives etc.), and emissions (e.g. emissions associated with the production or supply of energy sources). Stores and tasks can supply water to outlets (e.g. evaporation, discharge to the environment, supply of water to external agents etc.) or to other tasks; while tasks can also provide multiple outlets of energy (e.g. energy produced on-site to the wider electricity network) and emissions (e.g. atmospheric emissions, either from on-site consumption of energy, or from processes such as fugitive emissions from coal seams).

Tasks request water from stores or inlets with both the flow rate required and the maximum inlet concentration (salinity) permissible. Tasks can draw water from multiple sources, and intelligently ‘mix’ these sources to achieve maximum water reuse while respecting individual task concentration limits. Tasks can also modify the quality of water passing through them, to reflect processes such as coal washing.

Tasks also request energy based mainly on mine production rate, using correlations derived from US industry data (BCSIncorporated, 2007); as well as producing emissions, considering the energy sources used to supply that particular task. Pumping energy requirements (and subsequent emissions) are also modelled using representative pipe lengths, elevation changes, and pump efficiencies; as well as some simple heuristics designed to approximate the behaviour of engineered pumping systems. However, only fairly rudimentary methods are used for calculating energy use due to the pumping of tailings, where a representative specific pumping energy is specified for the life of the simulation. In reality, specific pumping energy requirements for tailings streams will change over
the mine life due to both short and long term variations in the mineralogical characteristics of tailings.

Using the HSM, a typical model of mine site operations can be constructed as shown in Fig.8.1. Similarly to previous mine water systems modelling approaches e.g. (Cote et al., 2007), (Cote et al., 2010), the water / energy network is considerably simplified, as follows. The various water storages on site are aggregated into two large storages (the Raw Store and Mixed Store) based on whether they contain ‘raw’ water only (that which is ‘new’ to site); or some combination or raw water and ‘worked’ water (that which has been involved in some mining process) The many activities that occur on site are also represented by three aggregated tasks (Mining, Transport, and Processing), as per the groupings of water and energy use discussed previously. A specialised ‘Tailings Dam’ component as shown in Fig.8.2 is also included to represent the dual functionality of the tailings dam in disposing of waste, as well as storing some water (a portion of which can be recovered for reuse). The model is then typically run for a long time period (years or decades), driven by daily timestep climate and production data.
Fig. 8.1. The baseline mine
The framework is used to assess two tailings disposal strategies (conventional and thickened) for a hypothetical 11,600 tonne per day (tpd) run of mine production rate (ROM). The conventional disposal scenario is flocculated tailings pumped in 30% solids (slurry). Thickened tailings use additional treatment such as super flocculation or thickener cones to produce 50% solids. To implement thickened tailings some changes are required to the conventional scenario including the specific gravity of the tailings increased from 1.55 to 2.1 and the pumping requirements automatically increased from 0.127 kWh/t/day to 0.387 kWh/t/d (Paterson, 2004). Besides the pumping test, an estimation of pumping energy can be obtained from rheology data (Boger et al., 2012, Boger, 2013).

The correlations between energy and water based on HSM are shown in Table 4 and it shows that the application of thickened tailings will reduce water use around 50%. However, the energy requirement increases more than 300% from 3 TJ/y to 10 TJ/y.

![Fig.8.2. The tailings dam](image)

**Table 4**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Task</th>
<th>Mining</th>
<th>Processing</th>
<th>Transport</th>
<th>Tailings Dam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional (30% solids)</td>
<td>Water use (ML/γ)</td>
<td>0</td>
<td>2,409</td>
<td>639</td>
<td>1,791</td>
</tr>
<tr>
<td></td>
<td>Energy use (TJ/γ)</td>
<td>123</td>
<td>277</td>
<td>215</td>
<td>3</td>
</tr>
<tr>
<td>Thickened (50% solids)</td>
<td>Water use (ML/γ)</td>
<td>0</td>
<td>2,409</td>
<td>639</td>
<td>901</td>
</tr>
<tr>
<td></td>
<td>Energy use (TJ/γ)</td>
<td>123</td>
<td>284</td>
<td>215</td>
<td>10</td>
</tr>
</tbody>
</table>
4.2.2 Cost and Environmental Analyses

In order to obtain a comprehensive decision on sustainable tailings disposal method some other aspects should also be considered including cost, environmental impacts, and regulations. In terms of cost, generally, there are two main costs are covered capital and operating cost. An example of disposal method cost items for coal mine are presented on table 5 below and the characteristic of mine and processing method applied are two main factors that influence the cost items significantly.

<table>
<thead>
<tr>
<th>COST in ($)</th>
<th>SCENARIOS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline - conventional</td>
<td>Thickened Tailings</td>
</tr>
<tr>
<td>TOTAL Capital Cost:</td>
<td>35,063,129</td>
<td>62,537,411</td>
</tr>
<tr>
<td>Thickener, thickener underflow pumps, tailings disposal pumps and pipelines, flocculant plant and piping, civil works, tailings dams, return water system and seepage control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL Operating Cost:</td>
<td>806,948</td>
<td>6,384,114</td>
</tr>
<tr>
<td>Water, flocculant, power – energy, maintenance, labour</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: QCC Resources (QCC, 2013)

Some others comparison between capital and operating cost of tailings disposal strategy varies depend on mine sites including life of mine (LOM) as follows (Fourie, 2012, Johnson et al., 2013):

- Osisko Hammond Reef mine, Canada: thickened tailings showed a 40% savings in dam construction, and 19% savings in reclaim water pumping.
- Quebrado Honda Facility, Peru: operational cost for thickened tailings was 19% lower than conventional method.
- Century mine, Australia: the thickened tailings operation generated 33% savings compared to conventional operation.

The cost analysis of each scenario is combined with environmental impact analysis to give a clear picture of available scenarios. Three end-points in LCA are used to determine the impacts of each scenario, these are resources, ecosystem quality, and human health (PreConsultants, 2010).

4.2.3 Decision-making process

All the data generated from previous steps are provided to stakeholders in decision-making process. stakeholders including experts, communities, and company representatives should screen the mine tailings management factors through several round of scoring, and then the selected factors are presented in Fig.9.
Fig. 9. Mine tailings management evaluation

An Analytical Hierarchy Process (AHP) is chosen to analyse the stakeholders judgment on those issues above. The fundamental scale of absolute number introduced by Saaty was used (Saaty, 2008) to establish the judgment matrix of each layer (B, C, and Scenario). The normalize of eigenvectors should be done to get all the weights of each issue, as shown in Table 6.

Table 6

<table>
<thead>
<tr>
<th>Issues</th>
<th>C11</th>
<th>C12</th>
<th>C13</th>
<th>C14</th>
<th>C15</th>
<th>C16</th>
<th>C17</th>
<th>C18</th>
<th>C19</th>
<th>C20</th>
<th>C21</th>
<th>C22</th>
<th>C23</th>
<th>C24</th>
<th>C25</th>
<th>C26</th>
<th>C27</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>0.005</td>
<td>0.076</td>
<td>0.068</td>
<td>0.02</td>
<td>0.015</td>
<td>0.001</td>
<td>0.014</td>
<td>0.011</td>
<td>0.004</td>
<td>0.006</td>
<td>0.039</td>
<td>0.019</td>
<td>0.146</td>
<td>0.029</td>
<td>0.099</td>
<td>0.364</td>
<td>0.073</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SCENARIOS</th>
<th>CT (%)</th>
<th>TT (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT (%)</td>
<td>66.67</td>
<td>33.33</td>
</tr>
<tr>
<td>TT (%)</td>
<td>33.33</td>
<td>66.67</td>
</tr>
</tbody>
</table>
Table 7

Ranked listing of alternatives

<table>
<thead>
<tr>
<th>Preference</th>
<th>Alternative</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Conventional tailings</td>
<td>45.90</td>
</tr>
<tr>
<td>2</td>
<td>Thickened tailings</td>
<td>54.10</td>
</tr>
</tbody>
</table>

For this hypothetical situation, the best choice of mine tailings disposal strategy is by using thickened tailings, as shown in Table 7. On the other word, the thickened tailings is 1.2 times more preferable than the conventional tailings method.

5. Conclusions

Mine tailings pose a high potential risk in mining operations. Statistical data shows that, on average, there were two mine tailings incidents recorded each year between 2000 and 2009. Recorded mine tailings incidents have resulted from poor water management, failure of the tailings disposal method applied, dam failure, and natural disasters. Poor water management is the most influential factor in mine tailings incidents and considerable focus has been directed toward the development of technologies that reduce the percentage of water content in mine tailings. Examples of such technologies include tailings paste, thickened tailings, and belt press filtration. These technologies are believed to also increase the efficiency of water use and recycling in the mining industry. In addition, the cost incurred for the implementation of these technologies is relatively competitive compared with the application of conventional technologies if mine closure cost is also considered. Furthermore, the determination of appropriate technologies that consider sustainable development is currently a challenge for the mining industry. A guiding framework is therefore required. The currently available frameworks associated with mine tailings management are limited and their discussion too general. Mine tailings management also requires specific steps to determine the most appropriate disposal option. The alternative framework proposed in this paper is thus essential.

This alternative framework presented will fill a current gap associated with mine tailings management, particularly by providing detailed steps to determine a mine tailings disposal option. The stages of this framework assess the sustainability of mine tailings disposal options. The steps used to develop this framework are laboratory work, field survey, computational assessment, a review of regulations, and stakeholder involvement. It is recommended that future research elaborate on the potential for reuse of mine tailings in other industries based on the industrial symbiosis concept. This will not only reduce the volume of tailings generated by mining but will also serve to expand the scope of the alternative framework proposed.

Acknowledgements

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Figure captions

Figure 1 Mine tailings: worldwide direct disposal
Figure 2 Description of Paste and Thickened Tailings – adapted from (Fourie, 2012)
Figure 3 MCMPR strategic framework for tailings management
Figure 4 Tailings management system life cycle – adapted from (DITR, 2007)
Figure 5 The risk management cycle - modified from (ISO, 2009, Verma, 2013)
Figure 6 DITR’s conceptual tailings management system (DITR, 2007)
Figure 7 Proposed framework for mine tailings management
Figure 8.1 The baseline mine
Figure 8.2 The tailings dam
Figure 9 Mine tailings management evaluation

Highlights

- Existing frameworks for mine tailings management have significant weaknesses.
- Mine tailings management needs to better factor in sustainability considerations.
- The proposed framework provides guidance for the selection of tailings management options.
- The framework could be further expanded by considering industrial symbiosis.