School of Civil and Mechanical Engineering
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A Life Cycle Assessment of Mine Tailings Management

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of
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Declaration

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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Abstract

The mining industry provides many significant economic benefits, but also creates some environmental challenges. Sustainable mining management and practices are increasingly seen as important factors in achieving a social license to operate for mining companies.

Wastes, including tailings waste, are key environmental issues that must be managed by mine sites. Tailings are a by-product of mineral processing and are managed through direct or indirect disposal methods. Globally, only 1% of mines apply direct tailings disposal methods including riverine and submarine tailings disposal, while the remainder utilise indirect methods. The global mining industry produced around 14 billion tonnes of tailings in 2010 (Jones and Boger, 2012). Tailings characteristics depend on the type of minerals mined and include problematic heavy metals. This heavy metals content, when accompanied with large volumes of tailings can cause irreversible environmental impact.

Mining is also a water and energy intensive industry, and reducing water and energy consumption are two important issues in the quest for more sustainable production. In addition, water and energy also directly affect mine production costs. The tailings storage facility (TSF) is typically a mine sites largest water use and water sink, and receives water from runoff, rainfall, and entrained tailings. The interaction between water and energy in tailings management occurs during processing, transporting, and tailings depositions. Examining the nexus or trade-off between water and energy use could substantially improve the sustainability performance of tailings management. Some mine sites have introduced Alternative Tailings Disposal methods (ATD) into their tailings management strategy to improve tailings management. ATD methods include thickened tailings, paste tailings, and filtered tailings (cake), which all reduce water consumption by increasing the mass percent solids in the tailings slurry. However, ATD tailings as a result of their higher mass percent solids require more energy consumption in the pumping of the tailings to the tailings dam. An integrated assessment of the water and energy use nexus is required to determine the trade-off between water and energy use in order to provide more sustainable Options for mine tailings management. In this thesis, an Australian open pit coal mine is taken as a case study in sustainable tailings management.

The following objectives are addressed in this research:

1. The development of a comprehensive mine tailings sustainability assessment framework for mine tailings management.
2. Determining the trade-off between water use and energy consumption for a variety of coal mine tailings disposal strategies/methods.
3. Comparing the environmental performance/impact of different mine tailings management strategies.
4. Evaluate the magnitude of the land-use change impact from various coal tailings management strategies.
5. Estimate the life cycle costing and environmental valuation of these strategies.
6. Determine the most sustainable coal mine tailings strategy in terms of cost, environmental benefit and environmental impact reduction.

A sustainability assessment framework was developed in this thesis to assess tailings disposal strategies using water and energy use modelling, life cycle assessment and life cycle costing. This framework was developed in order to improve upon the very broad risk based assessment frameworks currently used in the mining industry to assess tailings management. Following the development of the sustainability assessment framework, three typical scenarios of coal mine tailings management were evaluated, thickened tailings, paste tailings, and filtered tailings. The introduction of different flotation technologies and renewable energy Options were included in order to provide strategies for improving the sustainability performance of these disposal strategies. The rheological parameters were used as an input to estimate the pumping energy requirements and to predict tailings behaviour during the transport process. The Hierarchical System Model (HSM), examined the water and energy requirements for the tailings management strategies investigated using the rheological data obtained in the laboratory analysis. This modelling examined the water-energy trade-off for the various tailings management scenarios investigated. The data obtained from the HSM model was then utilised in the LCA assessment of the tailings strategies. These results were then combined with a life cycle costing and environmental valuation assessment for each strategy in order to develop a Net Present Value for the Benefit Cost Analysis of the tailings scenarios investigated.

This research is unique in combining rheological analysis, HSM computer simulations, and environmental and economic analyses of various coal mine tailings management strategies, in order to determine the most sustainable tailings management options. The results highlighted that Option 1C (belt press scenario with stack cell flotation and 10% wind energy) was found to be the most sustainable scenario generating benefit values of 0.01% to 54% higher and LCC values of -0.1% to 221% lower compared to the other Options.

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List of publications[*]

Peer-reviewed Journal:

Paper 1:

Adiansyah, J.S., Rosano, M., Vink, S., Keir, G., 2015. A Framework for a sustainable approach to mine tailings management: disposal strategies. *Journal of Cleaner Production*, 108, 1050-1062.

Paper 2:

Adiansyah, J.S., Rosano, M., Vink, S., Keir, G., Stokes, J.R., 2016. Synergising water and energy requirements to improve sustainability performance in mine tailings management. *Journal of Cleaner Production*, 133, 5-17.

Paper 3:

Adiansyah, J.S., Haque, N., Rosano, M., Biswas, W., 2017. Application of a life cycle assessment to compare environmental performance in coal mine tailings management. *Journal of Environmental Management, 199, 181-191.*

Paper 4:

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Conference - Paper 5:

Adiansyah, J.S., Rosano, M., Biswas, W., 2016. Comparing the carbon footprint of two different technologies in mine tailings management: a life cycle assessment perspective. 6th Brunei International Conference on Engineering and Technology (BICET), 12 – 14 November 2016, Universiti Teknologi Brunei.

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Industry Article:

Adiansyah, J.S., 2017. Alternative tailings disposals: are they improving mine tailings management performance?. *Australian Resources & Investment, 11, 40-41.*

Abbreviations

ATD	Alternative Tailings Disposal
BCA	Benefit Cost Analysis
BTM	Benefit Transfer Method
CAPEX	Capital Expenditure
CC	Capital Cost
CHPP	Coal Handling and Preparation Plant
DITR	Department of Industry, Tourism and Resources
DR	Discounted Rate
EVRI	Environmental Valuation Reference Inventory
FV	Future Value
GHG	Greenhouse Gas
GRI	Global Reporting Initiative
HSM	Hierarchical System Model
ICMM	International Council of Mining and Metals
ISO	International Organisation for Standardisation
IRR	Internal Rate of Return
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCC	Life Cycle Costing
LPSDP	Leading Practice Sustainable Development Program
MAC	Mining Association of Canada
MCA	Minerals Council of Australia
MCMPR	Ministerial Council on Mineral and Petroleum Resources
MIBC	Methyl Isobutyl Carbinol
MMSD	Mining, Minerals and Sustainable Development Project
MWND	Mine Water Network Design

NPV	Net Present Value
NPVB	Net Present Value Benefit
NPVC	Net Present Value Cost
OC	Operational Cost
OPEX	Operational Expenditure
PV	Present Value
ROM	Run of Mine
RTD	Riverine Tailings Disposal
SRW	Store Raw Water
STD	Submarine Tailings Disposal
SWW	Store Worked Water
TP	Tailings Paste
TSF	Tailings Storage Facility
TT	Thickened Tailings

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CHAPTER 1 Introduction

1.1 Background

The mining industry plays a crucial role in economic development worldwide. The industry globally contributed between 4 and 16% of total Gross Domestic Product (GDP) in 2010 from the top 20 minerals producer including Australia, Chile and China (ICMM, 2012a, Li et al., 2012). The percentage of mining contributions to the economic sector depends on the industrial maturity of each country (ICMM, 2012a), where more advanced industrial economies generate higher GDP contributions through their economic multiplier effects. Mining related industrial maturity can be categorized as emerging and advanced economies, as shown in Figure 1.1.

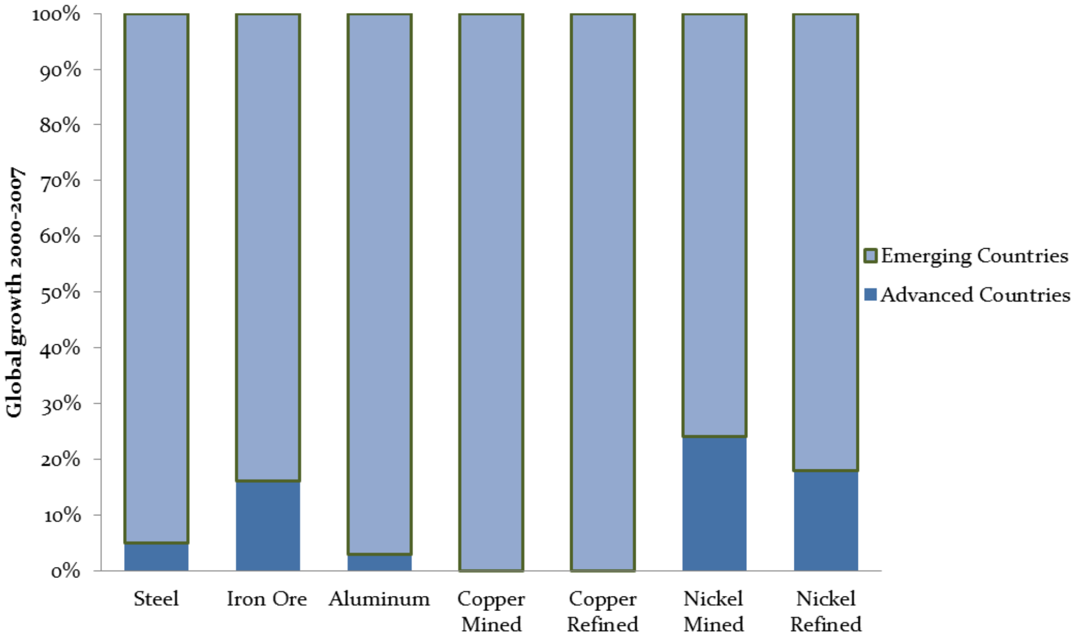

Figure 1.1 Global growth of mining production 2000 – 2007 (Humphreys, 2009)

Figure 1.1 indicates that emerging economies generate a higher output of metal commodities compared with advanced economies. The monetary revenue produced by this output could accelerate economic growth in emerging economies. ICMM (2012a) revealed that international metal mining production was dominated by iron ore (39%), gold (16%), and copper (13%). Total percentages of these three metals were 68% of the total world metal produced in 2011, with a total value of approximately US$ 854 billion (ICMM, 2012b).

The mining industry needs to address global sustainability challenges. Some sustainability aspects that are potentially influenced by mining industries include employment, household income, infrastructure development, and environmental degradation. In terms of employment, the ICMM recorded that more than 2.5 million people worldwide work in the formal mining industry and half of these are employed by global senior mining companies (ICMM, 2012b). Typically, mining operations positively impact the triple bottom line of sustainable development (social, economic, and environment outcomes). However, sustainable management in the mining sector remains challenging. A study by Lins and Horwitz (2007) revealed that the typical achievement of sustainability outcome indicators (environmental, social, and economic/governance) of five large mining companies was only around 55%. Furthermore, the three lowest scores were for water management, supply chain management, and transparency and accountability.

Mining operations generally involves five main activities as shown in Figure 1.2. The exploration phase discovers mineral reserves. In this phase, the environmental disturbance is limited, because the activity is conducted mainly through drilling and core sampling. The next phase is a feasibility study (FS). According to Laurence et al. (2011), an FS is a thorough assessment of a potential mine project in terms of its economic, environmental, and social impacts.

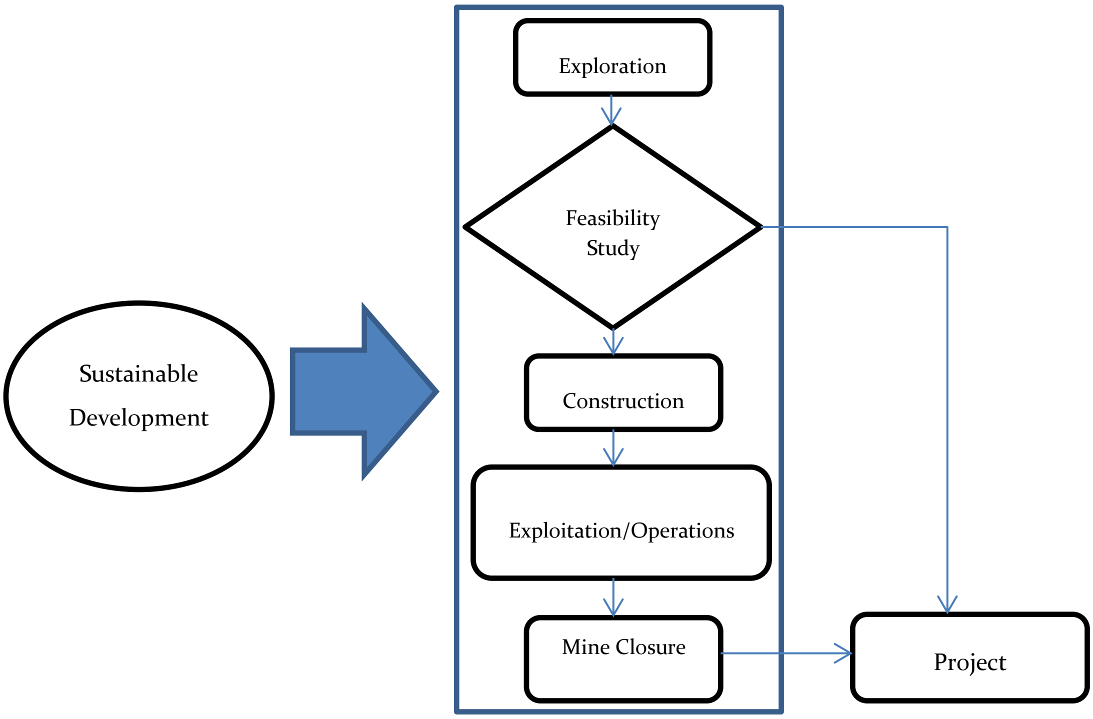

Figure 1.2 Mine life-cycle, modified from Laurence et al. (2011)

After the FS is concluded and the mining project is considered commercially viable, the construction phase begins. In this phase, activities include land clearing, demobilization and mobilization, and construction. Some potential environmental impacts can occur, such as habitat and biodiversity loss, increased dust, as well as land, water, and air pollution. The completion of the construction stage is followed by the exploitation phase. The potential environmental impacts associated with this stage are more complex compared to other phases. Therefore, the implementation of environmental management, monitoring, and compliance protocols are essential during the exploitation phase. One critical issue in this phase is related to waste management, namely that of mine tailings disposal. Tailings management is often mandatory at mine sites, because of its severe impact on the environment. According to Rico et al. (2008), In the years up to 2007, 147 cases worldwide of mine tailings accident/catastrophic were recorded. Finally, the last phase of mining is the mine closure stage. This stage comprises decommissioning and rehabilitation activities, including the decommissioning of tailings dams (Laurence et al., 2011).

Three common issues emerge in mining operations: water, energy, and tailings management. The mining industry is a "water and energy-intensive" industry. Studies have revealed that 260,000 tons of water and 200,000 gigajoules of energy are required to produce one ton of gold (Norgate and Haque, 2012, Prosser et al., 2011). The World Resources Institute (WRI) noted that freshwater use globally for agriculture, industry (including mining), and domestic usage was 70%, 22%, and 8% respectively (WRI, 2013). It can be concluded that mining projects could put pressure on water availability, especially in arid or semi-arid regions across Australia. Further studies have identified a correlation between energy and water use in mining (Gunson et al., 2010, Norgate and Haque, 2012, Nguyen et al., 2014). Tailings management is one activity that describes the important relationship between water and energy use in mining. Tailings are usually transported to the Tailings Storage Facility (TSF) in a slurry form, and energy is required to transport the slurry. Typically, TSF is identified as the largest water sink in most mine sites (Gunson et al., 2012). This condition creates risks for mine tailings management such as dam failure and water contamination. Examples of tailing dam incidents have occurred in Europe and have been described by Rico et al. (2008); for example, major incidents were recorded at the Baia Mare tailing dam in Romania (March 2000) and the Aitik Mine in Sweden (September 2000). The irreversible impacts caused by the failure of tailings dams prioritized this issue in a meeting of the Mining, Minerals, and Sustainable Development (MMSD) Commission in 2002. Reducing the volume of water in tailings slurry is a possible strategy to reduce the risks associated with tailings management. This strategy could also reduce the water managed by the TSF. Current applications of tailings dewatering technologies (Alternative Tailings Disposal) at some mine sites have initially indicated the feasibility of these strategies (Fourie, 2012, Jones and Boger, 2012). However, other studies question the effectiveness of these strategies for several reasons including their high energy consumption (Watson, 2012). The optimization of water and energy use, greenhouse gas emission (GHG), energy cost, and potential environmental impacts should be considered in order to improve the sustainability of tailings management. Currently, some studies focus on the trade-offs between mine water and energy consumption at local and regional mining scales (Greg and Woodley, 2013, Nguyen et al., 2014, Woodley et al., 2013). These studies focus only on the water and energy nexus and do not discuss other aspects of sustainability such as environmental impacts, environmental benefits, and the economic feasibility of environmentally friendly options. Furthermore, these studies exclude important rheology considerations in their analyses. Additional research on these aspects could provide an improved understanding of the potential for more sustainable tailings management. It is the intention of this thesis to investigate these issues further.

1.2 Research aims and objectives

The purpose of this thesis research is to assess the sustainability performance of various mine tailings methodologies in terms of water and energy use through rheology analyses, LCA, LCC, BCA and environmental valuation. In summary, the primary objectives of this research are:

1. The development of a new sustainability assessment framework for mine tailings management.
2. Modelling of the water and energy nexus (trade-off) for various coal mine tailings strategies.
3. A life cycle assessment of different technologies in coal mine tailings management.
4. Evaluating the magnitude of land-use change impact for various coal mine tailings management.

5. A life cycle cost assessment of different technologies in coal mine tailings management.
6. Joint optimisation of BCA, LCC and environmental valuation to determine the most sustainable tailings management strategy.

1.3 Scope and research questions to be addressed by this study

Coal mining generates two types of waste, namely 'coal rejects' and 'fine coal rejects'. The fine rejects known as tailings are commonly stored in a TSF. This study focuses on the fine coal rejects generated by a coal mine site in Australia. Three main strategies in coal mine tailings management are assessed from technical, environmental and economic perspectives. These three strategies include thickened tailings, tailings paste, and filtered tailings.

To achieve the research objectives outlined in Section 1.2, the following research questions were addressed:

1. How comprehensive is the current mine tailings assessment framework?

A comprehensive framework is required to enhance the sustainability performance of mine tailings management. The framework considered technological, economic, and environmental objectives of sustainability assessment. Social aspects of sustainability were not considered in this research. This research utilised two Australian mine tailings frameworks: 'The Strategic framework for tailings management (MCMPR and MCA, 2003)' and 'The LPSD: tailings management (DITR, 2007)'. Using these frameworks as a basis for the development of the more comprehensive framework presented in this thesis.

2. What is the relationship between water and energy requirements in tailings transport for different mass percent solids concentrations?

Water and energy are two critical variables associated with mine tailings management. Synergising water and energy use tradeoffs are required to improve mine tailings performance. This research conducted a rheology test of the mine tailings flow behaviour to determine the viscosity, shear stress and shear rates associated with various slurry concentrations. Data obtained from rheology laboratory analysis was incorporated into a Hierarchical System Model (HSM) to determine the water and energy nexus for various mine tailings solids concentration scenarios.

3. Which mine tailings strategies generate the lowest environmental impact?

Life Cycle Assessment (LCA) tool has been applied to determine the most environmental friendly method of coal mine tailings management. LCAs of three coal mine tailings method: thickened tailings, paste tailings, and filtered tailings have been conducted following ISO 14040-44:2006. The system boundary of these LCAs consisted of three stages: segregation of fine coal, mechanical dewatering, and tailings transportation. Data including equipment maintenance and transportation, labour, revegetation, and tailings disposal site monitoring and inspections were excluded from the system boundary due to a lack of available data.

4. What is the relative land-use impact of three typical mine tailings management methods?

Mining requires a large amount of land in operation including for tailings disposal. Variables that impact land use in mining include the production, processing technology, and percentage of tailings mass solids used. This study has considered three key variables: Area (A), Time (t), and Quality (Q) for in assessing land occupation impact (LOI) associated with various tailings strategies.

5. Which mine tailings management strategy produces the lowest cost and greatest environmental benefit?

Life Cycle Costing (LCC) and environmental valuation have been used to determine the most sustainable mine tailings options from the scenarios analysed. In term of cost, the inputs considered are capital and operational costs of a flotation tank, thickener and paste thickener, belt press, disposal methods, chemicals, and maintenance. This analysis has also taken into account three key environmental benefits associated with improved performance of mine tailings management: cost saving in water and energy conservation, and carbon credits associated with mine tailings sustainability management improvements.

6. Which tailings strategy provides the best sustainability benefits in terms of cost/benefit and environmental impact reduciton?

The most sustainable scenario for tailings management was then determined by normalizing the LCC, BCA, and GHG emissions results.

1.4 Integration of published articles

This thesis is presented as a hybrid thesis consisting of four papers that have been published for publication in international peer-reviewed journals and one conference paper that will be published in the IET digital library. The integration of these published papers (Appendix B-F) presents the relationship between the mine tailings management framework, the mine tailings energy and water nexus, LCA, and LCC (Figure 1.3).

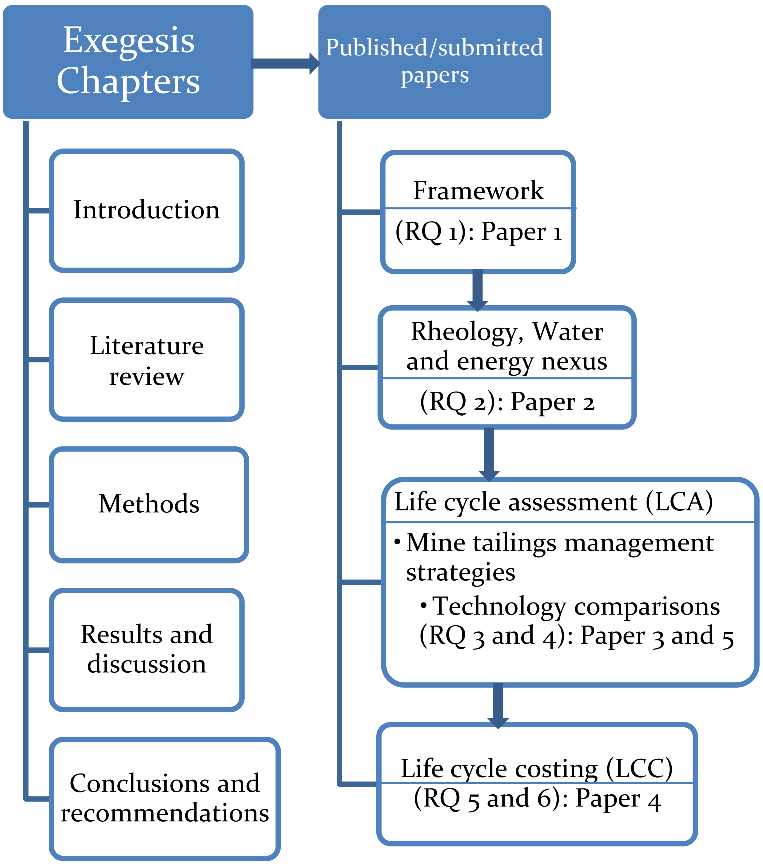

Figure 1.3 Hybrid thesis flow chart

The linkage between theses publication papers noted in Figure 1.3 is now briefly summarised below:

Paper 1 (published, see Appendix B) is in the outcome of Chapter 4 that focused on the development of a new sustainability framework for mine tailings management. Two current Australian tailings management frameworks are discussed and compared. Results showed that the current two frameworks need to be significantly enhanced from a sustainability management perspective. A new framework was proposed in this chapter to improve the sustainability performance of mine tailings management. As a result of this revised framework, eight steps including geochemical characterisation, tailings flow behaviour (rheology), water and energy use nexus, environmental impact assessment, and economic analysis were included to improve the sustainability performance of mine tailings management. This framework was used as a guiding sustainability assessment framework in the subsequent Chapters.

Chapter 5 (Paper 2, published, see Appendix C) discusses coal tailings flow behaviour, and the trade-off between water and energy consumption. Five different mine tailings slurry concentrations were selected to assess tailings flow behaviour and their impact on the important water-energy nexus. The tailings rheology parameters, obtained from rheological laboratory testing, were then used as an input into a computer-based model (HSM). These parameters also contributed to the estimation of the pumping energy. The three main variables, namely rheology, water use and energy use, play an important role in determining the optimum scenario for coal mine tailings management in terms of water saving, water management, and energy consumption. This Chapter also contributes to the development of life cycle inventory (LCI), by incorporating energy pumping data which is then utilised in Chapter 6 (Paper 3) for LCA analysis.

The LCI analysis compiles the material and energy inputs into and out of the mine tailings management system boundaries. This step is a pre-requisite to conduct an LCA assessment as discussed in Chapter 6 (Paper 3, published, see Appendix D). The mine tailings management scenarios proposed in Chapter 6 are then compared and assessed to predict the environmental performance of each scenario. Important land-use impacts were also estimated for each scenario. The comparison of different mine tailings technologies was also presented as an invited talk at the 6th Brunei International Conference on Engineering and Technology (see Paper 5 in Appendix E).

The life cycle assessment impacts, discussed in Chapter 6, was then compared with the the results obtained from life cycle costing analysis in Chapter 7 (Paper 4). Two methods: LCC and environmental valuation were applied to estimate the total costs and benefits of the mine tailings management strategies . These economic variables (costs and benefits) were calculated by using NPV and BCA formula (see Appendix F and J).

1.5 Significance

The research in this thesis is significant for a number of reasons. Firstly, it develops a comprehensive mine tailings management framework that is more robust than that which currently exists (MCMPR and MCA 2003, DITR 2007) and includes sustainable development indicators. Secondly, it determines the current water and energy consumption of existing methodologies and alternative tailings disposal (ATD) systems for a specific Australian coal mine case study. Thirdly, it generates new information on potentially more sustainable strategies for coal tailings management in Australia.

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CHAPTER 2 Literature review

2.1 Introduction

This chapter comprises six sections. The first section discusses mine tailings management frameworks by focusing on the current frameworks applied in countries such as Australia and Canada. The second section presents typical mine tailings management methods applied worldwide including tailings discharge systems and tailings disposal methods. Sustainability context in mine tailings management is also discussed in this section. The third section describes the role of rheology in determining tailing slurry flow behaviour associated with pumping energy requirements. The fourth section explains the correlation between water and energy consumption in transporting tailings from a generating area to the tailings disposal area. The Hierarchical System Model (HSM) and some other models assessing water and energy use in mine operations are also discussed. The fifth section defines an environmental system analysis tool (LCA) used to analyse the environmental impacts of different coal mine tailings management methodologies. In the last section, issues related to life cycle costing and environmental valuation are discussed by presenting two case studies in mining industry (copper and open cut lignite mine).

2.2 Mine tailings management

Mine waste, summarised in Table 2.1, is commonly classified based on three parameters: physical properties, chemical properties, and source (Lottermoser, 2010). Extracting minerals from the earth's crust, which is the primary activity of mines, generates two types of waste, namely overburden/waste rock and tailings. The overburden consists of soil and waste rock in the surface layer of the mineral reserves. This overburden must be removed to access the ore or coal seams. Overburden is stockpiled on land near to the mine site and is often reclaimed in the closure period. Mine tailings (a by-product of the processing plant) contain fine-grained materials, and chemical residues which are then transported to tailings disposal areas through pipelines.

Table 2.1 Types of mine wastes

Activities	Waste sources	Types of mine waste
Open pit, underground mining	Mining	Waste rocks, overburden, spoils, mining water, atmospheric emissions
Mineral processing, coal washing, mineral fuel processing	Processing	Tailings, sludge, mill water, atmospheric emissions
Pyrometallurgy, hydrometallurgy, electrometallurgy	Metallurgy	Slags, roasted ores, flue dust, ashes, leached ores, process water, atmospheric emissions

Source: Lottermoser (2010)

The large volume of tailings generated by the mining industry in 2010 around 14 billion tonnes (Jones and Boger, 2012) has created much environmental pollution. In total, 237 tailings accident cases worldwide have been recorded since 1917 (ICOLD, 2001, Lottermoser, 2010, Rico et al., 2008). The last two recorded mine tailings accidents were the Fundao tailings dam failure (November 2015) at Samarco iron ore mine in Minais Gerais Brazil, and the Mount Polley TSF breach (August 2014) at Mount Polley copper/gold mine in British Columbia Canada (British Columbia, 2015, Morgenstern et.al, 2016). These accidents affect environmental performance and have economic and social impacts on mining production (Franks et al., 2011). As a result, effective mine tailings management is required to avoid or minimize the often irreversible impacts of tailings accidents.

2.2.1 Mine tailings management methods

The two most common mine tailings discharge systems applied by approximately 2,500 mines worldwide are the direct disposal and indirect disposal methods. Most mine sites (99.3%) apply indirect tailings disposal, where tailings are transported to storage facilities (Vogt, 2012). Indirect tailings disposal follows either conventional or alternative approaches, which are differentiated by slurry mass percent solids. The conventional method consists of 25 - 30% of solids (DITR, 2007, Fourie, 2012), and the mass percent solids of alternative tailings disposal methods vary depending on parameters including chemical and physical properties, topography, and the types of dewatering technologies (mine tailings strategies) being utilised (Boger et al., 2012, Boger, 2009, Moolman and Vietti, 2012, Nguyen and Boger, 1998, Sofra et al., 2015). The increased use of alternative tailings disposal methods can potentially improve the environmental standards associated with tailings management (Fourie, 2012).

The benefits from each method shown in Table 2.2 provide at least three aspects for consideration, namely cost, environmental impact, and safety. The conventional method is often superior in terms of cost, because of the lower consumption of chemicals and electricity. On the other hand, alternative tailings disposal (ATD) provide lower risks in relation to safety and environmental impacts. Some studies have also revealed that the implementation of ATD results in higher total savings in operational and capital costs compared with conventional methods particularly when mine closure costs are included for example as in the Osisko Hammond Reef in Canada, Quebrada Honda Facility in Peru, and Century mine in Australia (Fourie, 2012, Johnson et al., 2013). The Osisko Hammond Reef mine, which employs the thickened tailings strategy, demonstrated 40% total savings in capital and operational costs in dam construction, and 19% savings in water pumping. However, capital and operational cost are not the only considerations when determining a suitable mine tailings management strategy. Other sustainability parameters including environmental impacts and environmental benefits should also be addressed to generate a more comprehensive framework for decision makers in selecting appropriate tailings disposal strategies.

Table 2.2 Indirect tailings disposal method

Disposal Method	Type	Advantages	Disadvantages
Indirect disposal	Conventional (Slurry)	Easy application and low cost, low reagent consumption	Potential for overtopping, pipe leakages, dam failures, contamination of groundwater, high TSF footprint, high cost of mine closure, long-term monitoring of post-mine closure, high water consumption
	Thickened/Paste	Low TSF footprint, reduced risk of dam failure, reduced mine closure cost, high water and reagent recovery, low water use, reduced potential for groundwater contamination	High cost, high energy consumption, high level of difficulty during on-site application

Adapted from Boger (2013), DITR (2007), IMO (2012), Jones and Boger (2012)

Coal mines have two different types of categorised waste: coarse coal processing waste (CCPW) and fine coal processing waste (FCPW). The CCPW is usually dumped in impoundment area for structural purposes due to the size which larger than 150 micron. The FCPW called tailings is typically transported to the slurry ponds. The two wastes should be managed properly to avoid the negative impacts that may occurred including generation of acid-drainage and elevation of sulphate concentration in surface water (Chugh and Behum, 2014).

The common type of coal mine tailings management is by constructing impoundment or dam that will accommodate tailings during the life of mine. Furthermore, the mine site has some options in tailings dewatering technology that can be applied i.e. Caval Ridge coal mine in Australia uses thickener method and combined with belt press filter (BMA, 2009) , and Central Appalachia coal mine in the United States of America operates paste thickening (Patil et.al, 2007).

2.2.2 Sustainability context in mine tailings management

Sustainability issues are a priority for most mining and minerals companies, because of their requirement to maintain a ‘social license to operate.' As soon as the Brundtland Report was published in 1987 and followed by the UN Conference on Environment and Development in 1992, the minerals industry conducted a series of meetings to adopt the spirit of sustainable development in their operations. These meetings were organised as regular consultation forums and include the Global Mining Initiative from 1999 to 2002, and the World Bank’s Extractive Industry Review from 1999 to 2002. A mining sustainability standards final agreement was achieved upon the establishment of the International Council on Mining and Metals (ICMM) in 2001. This agreement demonstrates the willingness of the mining and minerals industry to actively contribute to the sustainable development agenda.

The definition of sustainable development in the mining and minerals industry reflects a combination of environment, economy, and social indicators (Azapagic, 2004, Hilson and Murck, 2000, Humphreys, 2001, Oana et al.). Other studies include workplace safety and energy efficiency efforts as part of their sustainability management practices (Dubiński, 2013, Laurence, 2011). These indicators create the challenge for the industry to sustainably manage its operations. Good sustainability management generates better relationships with stakeholders, which directly affects the process of obtaining a social license to operate by mine operations. The limitations of available sustainability frameworks and guidelines were highlighted by Hilson and Basu (2003) and Laurence (2011) as one of the barriers in realising sustainable mining practice.

Sustainable mining practice is affected by waste management programs implemented at mine sites. The tailings management program handles tailings from the generator to the disposal area, and is a critical step in improving the mine's sustainability performance. Currently, the Government of Australia has issued two mine tailings management frameworks. The collaboration between the Ministerial Council on Mineral and Petroleum Resources (MCMPR) and the Minerals Council of Australia (MCA) produced a guideline entitled "A Strategic framework for tailings management" in 2003. Four years later, the Department of Industry, Tourism, and Resources (DITR) delivered the "Leading Practice Sustainable Development Program" for the Mining Industry (LPSDP).

The MCMPR and MCA (2003) guidelines focused on five specific areas, namely stewardship, stakeholder engagement, risk management, implementation, and closure. These guidelines cover the pre-operation, operation, and post-operation stages of mine tailings management. In pre-operation, the selection of mine tailings strategy that could minimise the environmental impacts and promote innovation is a characteristic of responsible stewardship principles. In the operation phase, engaging with stakeholders, applying risk management principles, and implementing appropriate operational controls are important principles amongst others. In the post-operation stage, effective monitoring of the tailings disposal area ensures the safety of humans and the environment. However, these guidelines fail to focus on sustainability management in their principles.

The DITR (2007) framework suggested the life cycle of a tailings storage facility comprising the planning and design, construction, operation, decommissioning, and post-operation of the TSF as the basic elements needed when assessing sustainable mine tailings management. The importance of considering life cycle in a sustainable development framework for the mining and minerals industry was also noted by Azapagic (2004). He included design, operation, decommissioning, and rehabilitation as the primary stage in the life cycle of mine operations. Incorporating a life cycle perspective into the analysis could assist in identifying sustainability issues in each stage. The DITR (2007) framework promotes this life cycle perspective when assessing mine tailings management options in the planning and design stages. The sustainable development parameters include the environment, water resources, social and economic values. The environment mainly concerns impacts such as mine acid drainage and salinity generation. A site water balance should be carried out to estimate the water requirements for mine tailings disposal that might also affect local water resources. Communication with stakeholders to identify their concerns is the main objective of the social analysis. The economic analysis of various mine tailings management disposal methods ensures that this framework is more rigorous than the one developed by the MCMPR and MCA (2003). However, the DITR (2007) framework is still very general and excludes energy consumption as one of the primary parameters in mine tailings operation and sustainability assessment.

2.3 Role of rheology in tailings transportation

As water is a significant part of various mineral extraction processes, tailings are conventionally disposed of as a slurry and then confined to large tailing dams. Tailings consist of fine particles commonly distributed from the processing plant to the tailings storage facility through a pressurized pipe, where low velocity helps to avoid pipe blockages during the transport process. Knowledge of tailings behaviour (rheology) is therefore essential in eliminating problems during tailings distribution.

2.3.1 Rheology in the mining and minerals industry

Boger (2013) revealed that resource industries are the largest generators of waste. He noted that the mining industry generated approximately 51 billion tonnes of overburden and 14 billion tonnes of tailings in 2010. Along with the increasing volume of low ore grade processed, the large volumes of waste including tailings will continue to be a problem into the future. As a consequence, increasing areas will be required for tailings disposal facilities into the future. Understanding the role of rheology is therefore necessary in reducing tailings volumes produced and stored, and in order to decrease the land footprint involved. The application of rheology in resource industries has provided an opportunity to use ATD methodologies, which include thickened tailings, paste tailings, and filtered (cake) tailings. Some mine sites are applying these methods to increase water recovery and reduce environmental impacts (Boger, 2013, Fourie, 2012, Moolman and Vietti, 2012, Scola and Landriault, 2007, Shuttleworth et al., 2005, Theriault et al., 2003, Verburg, 2001).

Lord et al. (2015) describe 12 mine sites worldwide as case studies that currently apply the ATD method. These sites located in South Africa, Australia, Canada, Iran, Indonesia, and Chile apply paste and thickened tailings that are disposed of using either surface or underground (backfilling) systems. An example of these case studies is the application of ATD method in the Osborne copper mine in Queensland, Australia. As illustrated in Figure 2.1, there are two sources of tailings generation: nest cyclone underflow, and thickener underflow. These two tailings sources are then collected in a sump area before being pumped to the TSF for final deposition.

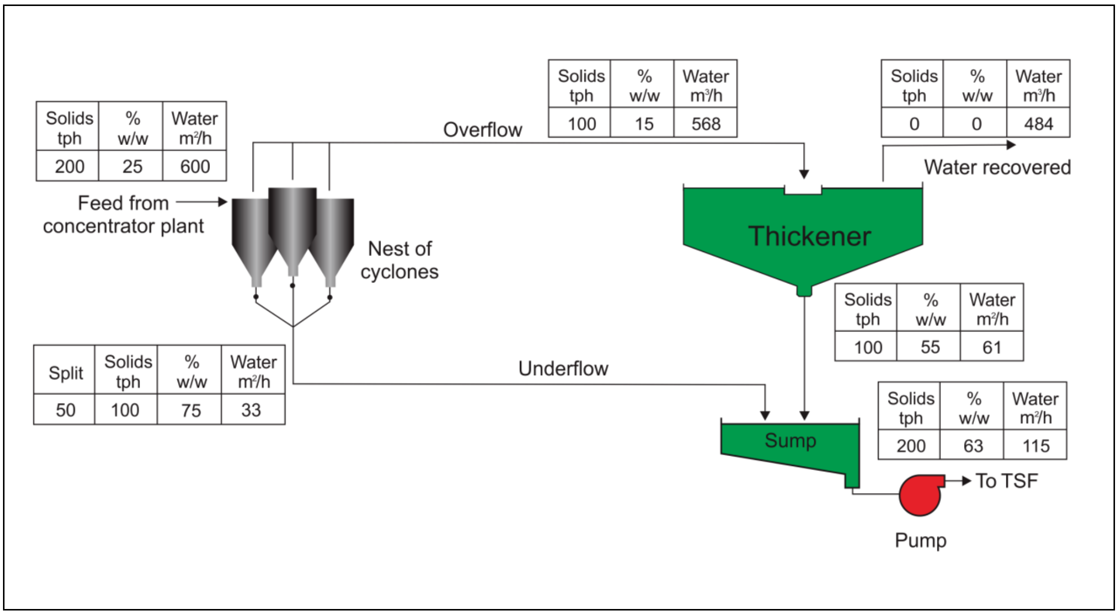

Figure 2.1 Flow diagram of the Osborne thickening plant (Lord et al., 2015)

The application of thickener technology in the Osborne copper mine increased the mass percent solids to 76% and reclaimed water by 484 m^3/h. The advantages of ATD applications are evident, however, Watson (2012) claimed that ATD also has some limitations including high energy demand and cost. Furthermore, Watson (2012) noted that an effective ATD application for high volume production mines is still being questioned. Bascetin et al. (2016) highlight two disadvantages in applying surface paste disposal: firstly it creates additional costs, and secondly operational difficulties. He concludes that the unit cost of surface paste disposal in a Pb-Zn mine is 0.04 $/ton higher compared to conventional tailings disposal. Therefore, an analysis in terms of environmental impact, and the cost-benefit value of current mine tailings management applications are essential in reviewing these two competing elements of water and energy use.

2.3.2 Correlation between rheology and tailings transportation

Defining the flow behaviour of tailings during the transport process is a key point in avoiding operational problems during tailings distribution including pipeline blockages. Determining the behaviour of fluids commonly depends on rheology testing, which is known as the study of deformation and material flow (Barnes et al., 1989, Boger et al., 2012, Morrison, 2001). Studies on transporting minerals concentrate including tailings slurry are well-established. The flow behaviour of various minerals and types of mineral waste have been investigated including coal clay tailings, manganese tailings, nickel tailings, red mud tailings, copper tailings, kaolinite paste, kimberlite tailings, fly ash and limestone slurry (Boger, 2013, Kwak et al., 2005, Naik et al., 2011, Paterson, 2012, Paterson and Vietti, 1999). Generally, the results indicate that conventional tailings slurry exhibits Newtonian behaviour while ATD slurries commonly demonstrate non-Newtonian behaviour (Boger, 2009, Nguyen and Boger, 1998).

Two examples (red mud and coal clay) of tailings distribution in a semi-dry disposal method were presented by Nguyen and Boger (1998). The red mud flow curve shows the shear thinning characteristic, where viscosity (η) decreases as the shear rate ($\dot{\gamma}$) increases. In addition, the yield stress (τ_y) parameter which plays a major role in pipeline transport creates a high yield stress that allows tailings slurry to be pumped in laminar flow with less risk in terms of solids deposition (Nguyen and Boger, 1998). Similar results were found with coal clay slurry, where the shear thinning behaviour exhibited an increased in yield stress (τ_y) strongly correlated with mass percent solids. These rheology results indicate that the flow behaviour of tailings slurry determines the most appropriate transport method that might be used such as pumping, conveyor, or trucking. Rheological properties also determine the pumping energy requirements during transport of the tailings slurry from the processing plant to the tailings disposal area (Nguyen and Boger, 1998).

2.4 Water and energy nexus in tailings management

Water and energy are the two main resource components associated with tailings management. These two variables play a significant role in the sustainability performance of mine tailings management. Furthermore, water and energy consumption were also identified as operational risks, specifically with regard to a social license to operate (EY, 2015, WBCSD, 2009). These risks not only affect a company's reputation and financial flow, but can also impact community wellbeing with local water shortages and land degradation. The ultimate impact of these risks might interrupt production, increase environmental costs, and even close down a mining operation.

2.4.1 Water and energy use

The importance of water and energy use in mining operations including tailings management has increased the number of initiatives by mining companies to reduce water and energy usage at mine sites. Water conservation initiatives have been implemented by many mine companies worldwide including Minera Esperanza in Chile, Olympic Dam BHP Billiton and Argyle Diamond in Australia. These mine sites have reduced their water use through strategies such as thickening tailings method, wastewater usage, and capturing and recycling seepage from tailings (ICMM, 2012). Minera Esperanza in Chile, BHP Billiton and Rio Tinto in Australia have also applied energy reduction initiatives at their mine sites. These initiatives include grinding improvements in the processing plant, installing variable frequency drives, and implementing plant information systems (Bascur and Soudek, 2014, Buckingham et al., 2011, Durocher and Putnam, 2013).

One mine site in Western Australia, Kalgoorlie Consolidated Gold Mines (KCGM), requires around 12.5 gigalitres of water per annum and local water resources supply 33% of their total water consumption (KCGM, 2015). Water requirements in mining vary depending on many parameters including production rates and processing technologies. Bleiwas (2012) noted the water use in copper porphyry mining processes of around 17.5 megatonnes of ore per annum when using conventional flotation technology. The volume of processed water required to process copper ore is about 44 megatonnes, and 30% of the total process water is transferred to TSF along with tailings slurry (50% mass solids). Sustainable tailings water management is therefore required to reduce the adverse impacts of water usage including water shortage, social and environmental impact.

High water demand in mining operations including tailings has encouraged some mining companies to apply alternative (non-conventional) tailings management (ATD) methods such as thickened tailings, and tailings paste methods to reduce the volume of water transported to the TSF. However, the implementation of ATD does increase the energy demand during the tailings transportation process. Moolman and Vietti (2012) revealed that the conversion of a platinum tailings distribution method from low-density tailings (50% mass solids) to medium-density tailings (60% mass solids) increased energy consumption by 14%. In coal mine tailings, increasing mass percent solids from 50% to 60% led to an increase in power consumption by a factor of 15 (Adiansyah et al., 2016a). These two cases show that tailings water reduction strategies result in conflicting energy management practices. Therefore, determining the nexus of water and energy use as the optimum ratio of these two parameters should be understood in order to improve tailings management overall sustainability. This research conducted a rheology test to determine the optimum ratio of energy and water in order to specifically assess the economic and environmental feasibility of tailings management methods for a case study coal mine in Queensland, Australia.

2.4.2 Modelling water and energy consumption

Modelling the water and energy nexus in tailings management is essential in mining operations wishing to enhance both energy and water efficiency. In the last decade, two studies associated with mine water and energy models have been published. The first model is the Mine Water Network Design (MWND), which describes the relationship between water sources and consumers (Gunson et al., 2010). The main aim of the MWND was linking these two parameters to ensure more efficient energy consumption. To achieve this objective, understanding the water balance, identifying water sources and consumers, constructing power consumption matrices, and analysing water and energy interaction are the main steps in applying the MWND. Water inputs and outputs from mine and mineral processing plants were used as a reference to describe the site's overall water balance. The site water balance provides information on the water flows and water quality discharged within the mine system boundaries (Cote et al., 2013, SMI, 2012). Water balance was also used by Cote et al. (2010) when they developed a mine water management model for seven coal sites in the northern Bowen Basin, Queensland, Australia. Once the water balance is finalized, all potential water sources (supplier) and water users (consumers) within the mine system boundary are then quantified. The water quality generated by the water provider and required by consumers is also specified. Water distribution from the supplier to consumers in a mining system commonly requires energy for pumping, treatment, cooling and heating. The construction of energy matrices is then prepared to identify the water and energy networks. As a final step, the MWND model uses linear programming to generate the scenarios with the least energy requirements.

The second water and energy model is the Hierarchical System Model (HSM). Here, three variables water, energy, and GHG emissions are interconnected across various mining boundaries: sub-site, site, and at regional scale (Nguyen et al., 2014, Greg and Woodley, 2013). The sub-site scale represents the interaction of variables in the internal task unit, such as mining, transport, or processing tasks. For example, for the mining task, the subsite scale core component includes blasting, dust suppression, and underground mining and each of these functional components is linked to construct a model, and optimization analysis. At the site level, HSM describes the interface of mining, transport, and processing tasks within a mine site. At the site level, all basic components of the subsite are included. While at the regional scale, the HSM focuses on the interaction between a mine site and neighbouring areas. An example of a regional scale analysis was presented by Greg and Woodley (2013) when developing three main scenarios for mine water treatment plants (WTP) at three different mine sites as presented in Figure 2.2. These scenarios included a decentralised and centralised scenario. Decentralised treatment options require each mine to build a small WTP on their site and prepare a contingency plan for extracting water from the local dam when the site water volume drops below 40%. The centralised treatment option requires these mine sites to construct one larger WTP that supplies the water demanded by each mine location. The same rules apply when the regional dam supplying water to these mine sites if the internal water volume drops below 40%. This research has considered the application of the HSM model in assessing the water and energy nexus as a part of a more sustainable mine tailings management framework.

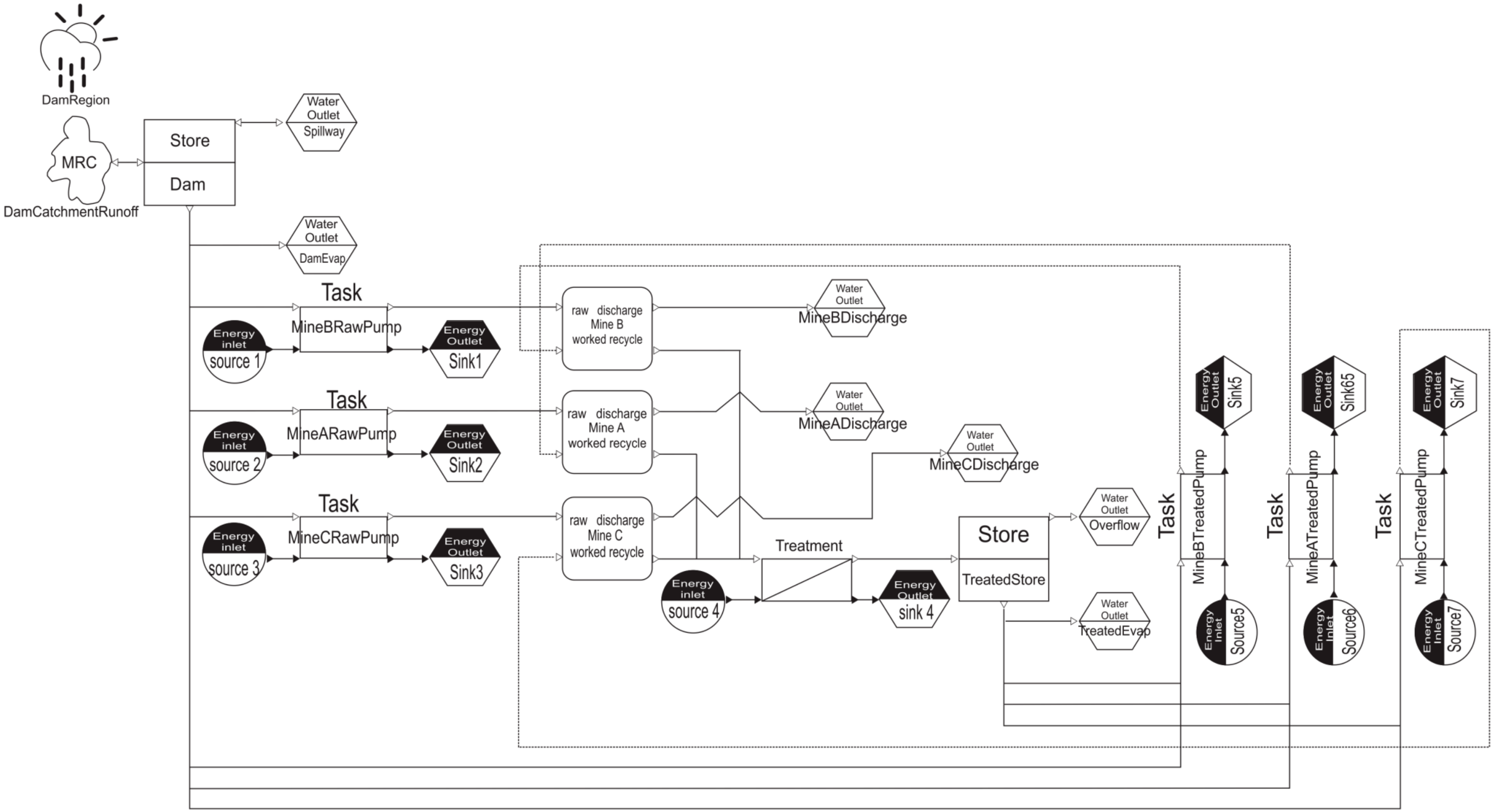

Figure 2.2 The HSM at the regional scale (Greg and Woodley, 2013)

The interaction between water and energy in the HSM is represented through six components: water inlets, water outlets, energy inlets, energy outlets, emissions outlets, stores, and tasks (Woodley et al., 2013). Generally, an inputs and outputs concept is applied in the HSM by building a network between the operational mine site components where detailed information is credited to each element including water quantity, water quality information, and energy consumption. The final outputs of the HSM are water and energy use, as well as GHG emissions emitted at either the mine site or at a regional level (Nguyen et al., 2014).

Both the MWND and the HSM have a similar approach, where using input and output concepts in the development of the model. However, the underlying difference between both models lies in their application as the MWND model is only applicable at the design stage (Nguyen et al., 2014).

2.5 Environmental impact assessment in the mining Industry

Environmental impact assessment (EIA) is a critical step in the approval process for mining projects. All possible environmental impacts are discussed and listed in the EIA. Three main objectives are achieved by the EIA including identifying the various activities and impacts, determining the level of impacts and preparing the tools/methodologies to minimize or eliminate the impacts. For example, an Environmental Impact Statement (EIS), developed by a coal mine site in Queensland, covered environmental indicators including geochemical, surface water, groundwater, ecology, and air quality (BMA, 2009).

Additional analytical tools can also be used together with the EIA such as the LCA, life cycle costing (LCC), and environmental valuation (Ahlroth et al., 2011, Finnveden et al., 2003, McLellan et al., 2009). Ahlroth et al. (2011) claim that these tools assist in the comparison of the environmental impacts associated with different operating scenarios. In addition, Finnveden et al. (2003) note that using these additional tools provides two different overviews both qualitative and quantitative. However, a different view was presented by McLellan et al. (2009) who found that these tools were not effective in guiding the mineral industry towards a higher level of sustainability management. They argued that these tools should be embeded within mining sustainability frameworks including triple bottom line concepts (economic, environmental and social).

The application of environmental assessment is a mandatory obligation in the minerals industry, and one tool that is commonly used in assessing environmental impacts is life cycle assessment (LCA). LCA is a comprehensive environmental management tool for quantifying and interpreting the environmental impacts of a product or service throughout its lifecycle considering three main factors: the environment, human health, and resources used (ISO, 2006). The application of LCA in the mining industry is not as popular as in other fields (Blengini et al., 2012), Awuah-Offei and Adekpedjou (2010) recorded that less than 10% of published LCA papers reviewed the mining industry. The limited study of LCA in mining can possibly be attributed to the significant input and output data required that is often not publicly available (Haque and Norgate, 2015, Norgate et al., 2007). Most mining LCA studies have focused on mining operations including material handling (Erkayaoğlu and Demirel, 2016), minerals production (Ferreira and Leite, 2015, Haque and Norgate, 2015, Memary et al., 2012, Norgate and Haque, 2012), and tailings management (Fernandez-Iglesias et al., 2013, Reid et al., 2009). LCA in coal mine operations was also discussed by Ditsele and Awuah-Offei (2012), and Burchart-Korol et al. (2016). However, current mining LCA research in the literature has not included all dimensions of mining sustainability such as land use impacts, or a review of coal mine tailings strategies including enviornmental valuation.

Bovea et al. (2007) examined red clay mine operations from cradle to the customer's gate and covered three main activities including clay excavation, clay processing to generate a product, and product distribution to the customers. Fuel consumption during excavation, loading and the transport process were the largest 'hotspots' in terms of environmental impact (emissions). In addition, Memary et al. (2012) presented carbon footprint trends from 1940 to 2008 generated by copper mining in Australia. They also noted an opportunity to use the LCA as a tool to examine technology and energy alternatives in the mineral sector. Norgate and Haque (2012) focused their LCA study on profiling gold production impacts associated with energy, water, and solid waste. The ore grade processed was the main environmental footprint factor in gold production and was seen to be higher than some other metals. Ferreira and Leite (2015) and Haque and Norgate (2015) reviewed iron ore mining in Brazil and Australia. These studies similarly assessed the energy consumption required to produce one ton of iron ore and estimated the environmental impacts. Overall, these studies indicate that fuel/energy consumption and water use are the two most significant inputs in mining operations.

2.5.1 Life cycle assessment of coal mining operations

Coal mining, with 860 billion tonnes in reserve, supplies 29% of the world's energy demand (Thomas, 2013). In Australia, coal-fired power plants dominate the electricity market with more than 64% of total electricity production. Coal consumption worldwide is also predicted to increase at an average rate of 0.6% per annum between 2012 to 2040 (EIA, 2016). These figures reflect the significant contribution of a coal mining to energy production.

In general, the three main stages in coal mining are mining, processing, and transporting. Coal extraction (mining) can be conducted using either surface mining or underground methods, depending on the depth of the coal seam. The case study in this research focuses on surface coal mine tailings management. Sanders (2007) described 11 steps in coal mining production and is presented in Figure 2.3.

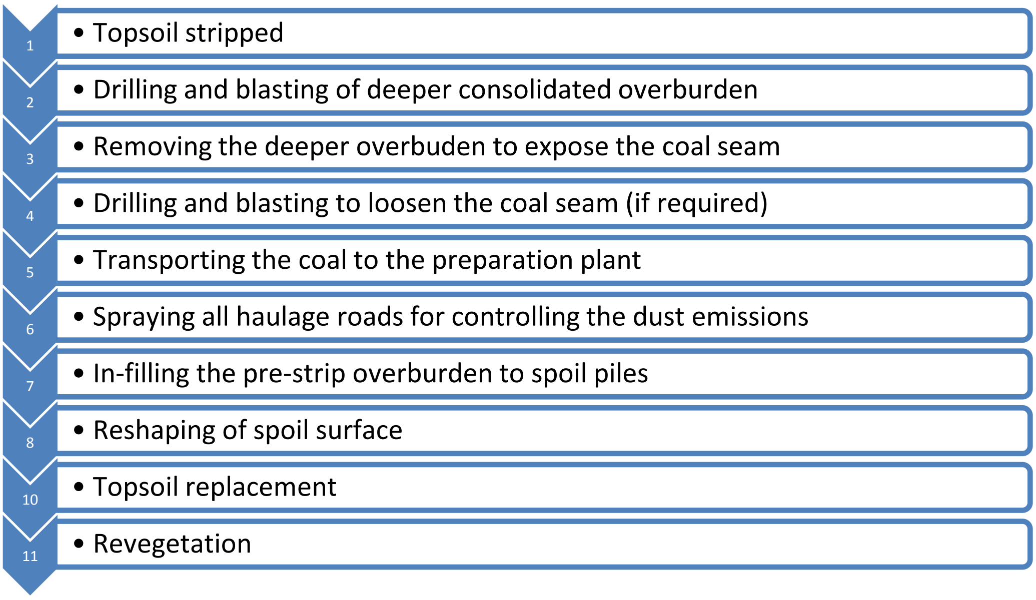

Figure 2.3 Strip sequence in the surface coal mine (Sanders, 2007)

Coal generated from the pit is commonly known as run-of-mine (ROM) coal. ROM coal is a mixed material in terms of particle size, and composition (Sanders, 2007). ROM coal is further processed in the coal handling and preparation plant (CHPP) through four stages of washing, cleaning, processing, and beneficiation, during which two products are generated, namely coal as a product and tailings as a by-product (Gluskoter, 2009). The transportation process of these two products is the final stage of coal mine production. Coal is transported to buyers and tailings are disposed of in the tailings storage facility (TSF), as shown in Figure 2.4.

The stages illustrated in Figure 2.4 show mining/processing boundaries can be identified by the "cradle to gate" principle and the combination of the mining/processing boundary, and utilization boundary can be classified as the "cradle to grave" principle. These two principles are commonly used in identifying the life cycle of mining projects including coal production (Bovea et al., 2007, Durucan et al., 2006, Mistry et al., 2016, Steward et al., 2012, Suppen et al., 2006). During the life cycle flow, various material inputs and outputs include electricity, fuel, water, land occupation, and GHG emissions.

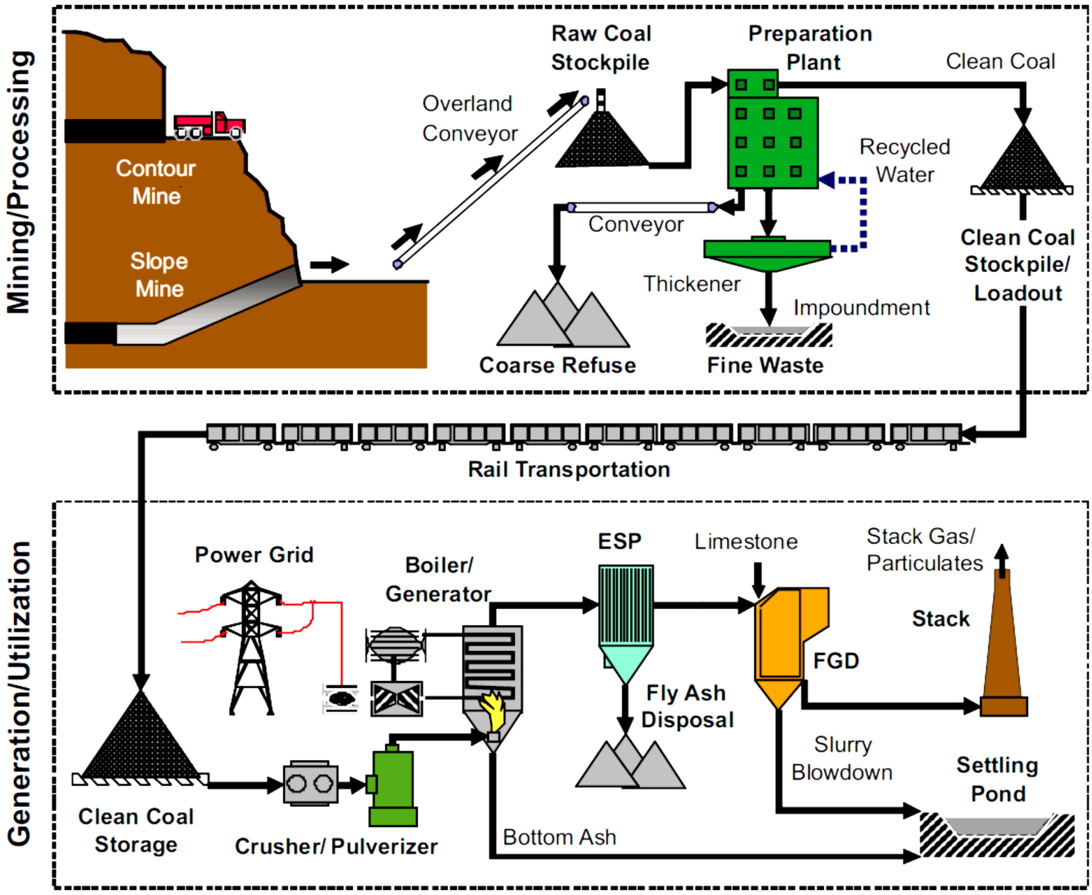

Figure 2.4 The coal mine life cycle adapted from Gluskoter (2009)

A few current studies describe mining LCA (see Section 2.4); however, Burchart-Korol et al. (2016) claim that the LCA of coal mines is not comprehensive enough to describe the actual environmental impacts incurred from coal mining operations. Most current LCAs focus on mining and processing activities, with only two studies associated with tailings management specifically: Fernandez-Iglesias et al. (2013) and Reid et al. (2009). No other research is currently available on LCA in coal mine tailings management.

2.5.2 Life cycle assessment of coal mine tailings management

Mine tailings management is a critical activity in mining operations. The proper management of mine tailings can prevent the mine site from incurring high environmental costs, and loss of human life due to a tailings incident. An example of a tailings incident occurred in Surigao del Norte in the Philippines when 0.7 million tonnes of cyanide-bearing tailings spilled from the tailings pipeline, buried 17 homes and degraded over 51 ha of land (Lottermoser, 2010).

LCA is an assessment tool that can be used to analyse the impacts of mine tailings management. Using mine tailings disposal options that suit mine site characteristics reduces not only the risks of the tailings operation, but also increases the sustainability performance of the tailings operation. Currently, there are limited LCA studies on mine tailings management, two of these studies include an LCA on copper-zinc tailings in Canada (Reid et al., 2009) and an LCA of iron ore tailings in Brazil (Fernandez-Iglesias et al., 2013). The first study, conducted by Reid et al. (2009), assessed tailings management in a closed copper-zinc underground mine. Three scenarios were developed for the operational stage as follows: 1) tailings dam operation with 100% of the tailings submerged, 2) tailings dam operation with 48% of the tailings submerged, and 3) backfill plant operation with 52% of the tailings processed. Scenario 1 and 2 each have three alternative tailings options for the closure phase including tailings submerged (A), partial desulphurization (B), and cover with capillary barrier effects (CCBE). The second study by Fernandez-Iglesias et al. (2013) compared the two tailings management systems, namely conventional tailings with 20% mass solids in tailings slurry (Scenario 1) and thickened tailings with 60% mass solids in tailings slurry (Scenario 2). Both studies agreed that land-use impacts should be considered when assessing the lifecycle of mine tailings management. These studies also showed that the characteristics of mine sites including the final products, processing technology, and location were significant factors influencing the inventory process. Mine characteristics also contribute in defining the appropriate functional unit to represent the relevant systems boundaries.

2.6 Cost analysis of tailings management disposal methods

Economic considerations are crucial factors in mining due to the significant financial capital involved. For example, the Boddington Gold Mine (BGM) in Western Australia costs US$ 2.4 billion to operate, the Caval Ridge coal mine in Central Queensland Australia needs approximately US$ 3.4 billion for initial project costs and the Vale mining company provided US$ 2.48 billion in 2007 to expand their Carajas Iron Ore mine in Brazil (MT, 2016a, 2016b, 2016c). Financial considerations can also be a barrier or driver for mining companies when implementing a program such as for energy efficiency (Levesque et al., 2014). Therefore, a tool for economic analysis is also required to provide a cost effective evaluation of the various tailings management options available. LCC and environmental valuation are two common tools used to compare alternative operating scenarios and assists stakeholders in making decisions (Curran and Steen, 2005, Finnveden and Moberg, 2005, Höjer et al., 2008) that could improve sustainability performance.

LCC is defined as a process to determine all costs to support activities from the planning stages to the end of project life (AS/NZS, 2014, Curran et al., 2005, Woodward, 1997). The three main objectives of LCC according to AS/NZS (2014) are calculating the expenses of a product or service, providing economic considerations to stakeholders, and identifying the cost drivers of product or services. AS/NZS (2014) and Woodward (1997) agree that two important inputs of LCC are the cost element and cost structure. All costs incurred during the life cycle should be categorised as a cost element, while project division activities including planning, construction, and operation are considered as cost structure items.

Environmental valuation also considers cost in its main analysis focusing on environmental cost elements. In classifying the environmental elements, Damigos (2006) and Damigos et al. (2016) proposed the concept of total economic value (TEV), which comprises use values and non-use values. Use value is associated with resource utilization, ecosystem function, and future resource value, while the non-use value is related to people's willingness to pay to maintain or preserve an asset or resource. The comparison between benefit and costs, known as BCA, is employed in this research as a final tool to describe the magnitude of sustainability benefits (economic and environmental) of the project components analysed.

2.6.1 Joint implementation of life cycle costing and environmental valuation

LCC and environmental valuation in tailings management assessment are not as common place in the mining industry as in other fields, such as building and forestry. However, some studies focusing on LCC and environmental valuation have been done for mining industry case studies. For example, Curran et al. (2005) examined the implementation of LCC in the Polish mining industry through a case study of a Polish non-ferrous copper producer, KGHM Polska Miedz SA. The volume of solid waste generated including tailings, dust, and slag created environmental issues for the mine site. LCC and NPV methods were used to analyse the economic possibility of different technologies to reduce the volume of solid waste. The combination of LCC and NPV (LCNPV) resulted in the most economically feasible scenario that could be applied to reduce environmental impacts. Furthermore, Curran et al. (2005) concluded that LCC should be integrated with LCA and other environmental management tools to provide a more comprehensive analysis to support the decision-making process. Danthurebandara et al. (2015) integrated LCA and LCC to evaluate the valorisation of thermal treatment residues in enhanced landfill mining. They identified three materials that contributed the most to potential global warming and the NPV, namely sodium silicate, sodium hydroxide, and cement. Combining environmental impacts and economic values provides an opportunity to model these two parameters simultaneously to help determine scenarios with the lowest environmental impact and greatest economic value.

Environmental valuation analysis can play a significant role in the decision-making process (Damigos, 2006). Conducting an environmental valuation can create a consensus for a mining company to prioritise the option that generates the greatest environmental benefits (Damigos and Kaliampakos, 1999, Damigos and Kaliampakos, 2003). Some case studies highlight an environmental valuation to determine the most appropriate operational scenario. For example, Larondelle and Haase (2012) conducted one such study to develop three post-mining landscape scenarios for land-use in an open cut lignite mine: tourism (alternative-A), agricultural production (alternative-B), and reforestation (alternative-C). Environmental valuation was used to evaluate the environmental services of each scenario provided.

The limited studies of LCC and environmental valuation are also found in mine tailings management issues. Previous studies have not conducted an LCC and environmental valuation of mine tailings management. As a result, a framework for assessing both the economic and environmental implications of mine tailings methods has been developed and is presented in Chapter 4.

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CHAPTER 3 Methodology

3.1 Introduction

This Chapter focuses on the triangulation research methodology (Jack and Raturi, 2006) used in this thesis to assess the sustainability performance of various mine tailings disposal strategies. The triangulation method used includes a literature review and case study analysis, a 3 month laboratory rheology analysis of coal tailings samples, and a computational assessment of coal tailings input and output modelling in HSM (water and energy use analysis) and LCA (environmental impact assessment) software . The sources of data utilised in the computational analysis was obtained from laboratory work, company reports, open source, and industry experts. Data included rheology parameters, water and energy consumption, material and energy inputs, environmental values, and capital and operational costs.

3.2 Research Methods

The research methodology is presented in Figure 3.1.

A review of the current tailings management frameworks issued by two institutions in Australia in Chapter 2 (DITR, 2007, MCMPR and MCA, 2003) was conducted to highlight research gaps and research opportunities (Adiansyah et al., 2015). A proposed alternative mine tailings sustainability assessment framework was developed and is presented in Appendix B.

This alternative framework proposed eight steps which utilised rheological data, the Hierarchical System Model (HSM), Life Cycle Assessment (LCA), and a Life Cycle Costing (LCC) and an Environmental valuation. These methods are described in Section 3.2.1 - 3.2.3. An open pit coal mine in Australia with 20 million tonnes per annum (Mtpa) of ROM was selected as the base case study. Such a comprehensive economic and environmental analysis of coal tailings management has not been done before.

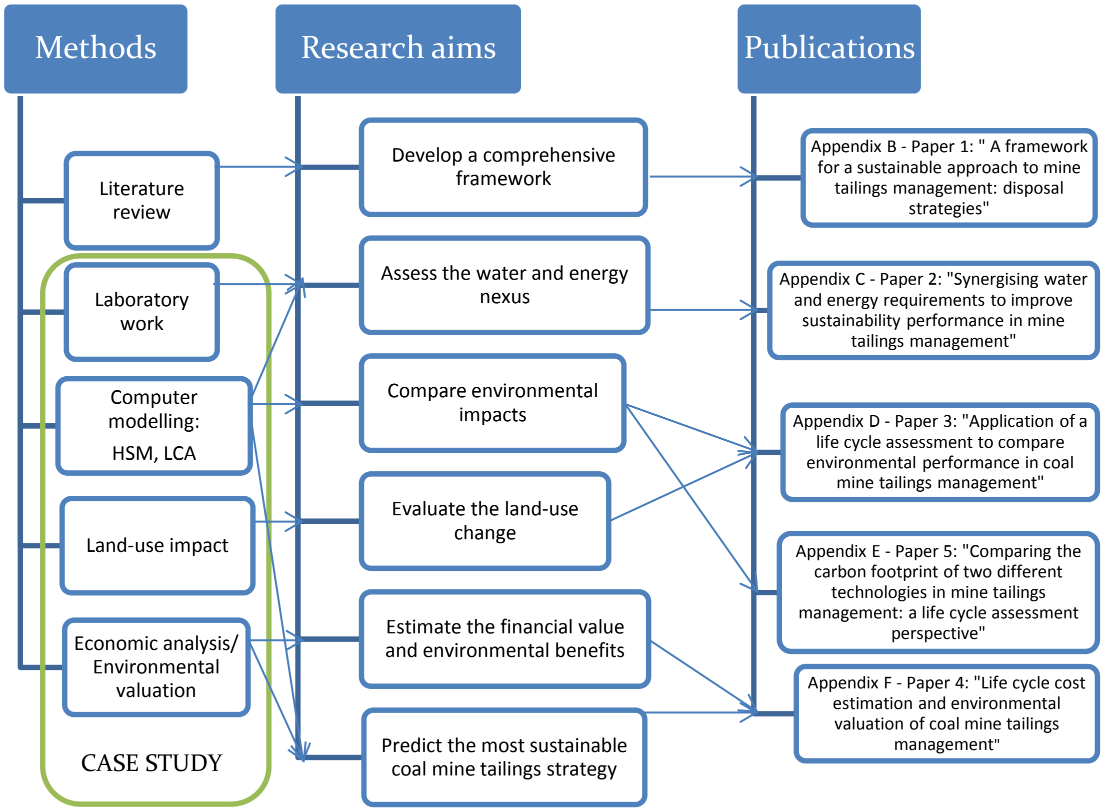

Figure 3.1 Research methodology

3.2.1 Rheology and Hierarchical System Model

Coal mine tailings with various mass percent solids (scenarios – see Table 3.1) were tested to determine the behavior of tailings slurries during the transport process. The rheological parameters were tested at the University of Queensland Chemical Engineering Laboratory (December 2014 to February 2015), including shear stress (τ), shear rate ($\dot{\gamma}$), viscosity (η), and yield stress (τ_y) (Adiansyah et al., 2016). Slurry rheology was measured using a rheometer AR-1500ex and shear stress test ranges from 0.01 to 1000 Pascal (Pa).

Table 3.1 Mass percent solids

Mass solids (%)				
Option 1	Option 2	Option 3	Option 4	Option 5
30	50	60	65	70

The outputs from the rheology tests were used to estimate pumping energy requirements and to update and modify the current input model of mine water and energy usage (the HSM). The estimation of the pumping energy required the Herschel-Bulkley model approach and pressure loss formula (Adiansyah et al., 2016a). The final steps for determination of the water and energy nexus involved incorporating the rheology results into the HSM computer-based systems model of mine water, energy, and emissions. The HSM is a graphical, user-friendly software tool that enables users to build models of mine site water, energy, and emissions networks at arbitrary levels of detail. 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 more easily comprehensible for management purposes, but which retains most of the characteristic behavior of the real water system. Furthermore, detail on the HSM can be found in the Appendix C and Appendix G.

This study does not investigate any geochemical or mineralogical characterizations of coal mine tailings as the thesis is focused on the water energy nexus in tailings management and other chemical/mineralogical considerations are largely very secondary in terms of any impact.

3.2.2 Life Cycle Analysis and land-use impact

An environmental management tool was then used to analyse the environmental impacts of various coal mine tailings management methods and scenarios analysed. LCA, which is categorised as an environmental management tool to assess the potential environmental impacts of a product, process, or service throughout their cycle (ISO, 2006).

The LCA, involved energy and material inputs, and was comprised of four phases as presented in Appendix H and I (Adiansyah et al., 2017a, Adiansyah et al., 2016b):

1. Goal and scope definition.

   Various coal mine tailings management scenarios were assessed, as presented in Table 3.2. The goal is to assess the environmental implications of coal mine tailings disposal associated with the production of fine coal concentrate. The functional unit (FU) is defined as one tonne of fine coal concentrate slurry generated by flotation cells.
2. Life Cycle Inventory (LCI).

   LCI provides series of data associated with energy and material inputs. These data include water, energy, and chemical consumption during fine coal segregation in a flotation tank, tailings dewatering, and tailings transport process. See Appendix H for detailed LCI data.
3. Life cycle impact assessment (LCIA).

   In this stage, the environmental impacts were determined through an inventory analysis. The input and output data in the LCI were then transferred into LCA software – SimaPro 8.0 (PreConsultants, 2010) to assess the environmental impacts of each mine tailings scenario. The assessment results are presented in Appendix D and E (Adiansyah et al., 2016a) and (Adiansyah et al., 2016b). Detailed LCA results can also be found in Appendix I.
4. Results interpretation.

   This stage evaluates the results of the LCI and LCIA to determine the most preferred strategy for coal mine tailings management in terms of least environmental impact. It also helps identify 'hotspots' requiring environmental mitigation strategies such as the use of renewable energy as a replacement for fossil fuel to generate electricity for tailings operation.

Table 3.2 Coal mine tailings management strategies

Scenario	Segregation	Mechanical dewatering	Tailings transport
1. Tailings with 65% solids 1.A Tailings with 65% solids – flotation technology improvement	Flotation column cells with additional of frother and collector.	#1. Thickener with additional of anionic flocculant; #2. Belt press with additional anionic and cationic flocculants.	Transported by truck to the tailings disposal area.
2. Tailings with 50% solids	Flotation column cells with additional of frother and collector.	#1.Thickener with additional of anionic flocculant; #2. Paste thickener with an additional anionic flocculant.	Pumping to the tailings disposal area.
3. Tailings with 30% solids	Flotation column cells with additional frother and collector.	Thickener with additional of anionic flocculant.	Pumping to the tailings disposal area.

Intensive land use by mining companies is one of the main important reasons to include land use impact assessment in any environmental assessment of mining activities. The total area, which is required for tailings disposal, depends on tailings volume and the mass percent solids of the tailings slurry. A method that employed in Lindeijer (2000) was selected to estimate the magnitude of the impact from mine tailings management. Three parameters were required, namely Area (A), Time (t), and Quality (Q) as presented in Appendix D (Adiansyah et al., 2017a).

3.2.3 Economic analysis

Life cycle costing (LCC) and environmental valuation were used to assess the costs and benefits of the different mine tailings management strategies investigated. Environmental benefit valuation has increasingly been considered an important tool in decision-making over the past decade (Damigos, 2006; Marre et al., 2016). The Benefit Transfer Method (BTM) was used to estimate the environmental benefits (dollar value) of various coal mine tailings management strategies. These data were then assessed using NPV.

An economic assessment was carried out to determine the highest benefit values and the most cost-effective mine tailings management methods. In this analysis, the parameters examined are capital and operational expenditure, and the benefit values of each assessed scenario (see Appendix J) include saleable coal, water and land conservation, and GHG reduction.

Data from each scenario was analysed based on the economic principles of net present value (NPV), internal rate of return (IRR), and discount rate (DR) as presented in Appendix F (Adiansyah et al., 2016c). Two economic values were compared during this assessment: cost value and environmental benefits. A benefit-cost analysis (BCA) was used to generate the option providing the highest benefit at the lowest cost (AG, 2016). The three environmental benefits considered are water conservation, land conservation, and GHG reduction (see Appendix J).

The normalization of three parameters, namely LCC, BCA, GHG, was then used to determine the most preferred scenario in terms of cost, benefit, and environmental impact.

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CHAPTER 4 A framework for a sustainable approach to mine tailings management: disposal strategies[*] (Paper 1)

4.1 Introduction

One of the challenges, faced by mining operations, is tailings management. Proper mine tailings management is required to minimize tailings accidents of which more than 200 accidents have occurred between 1917 to 2009 (Lottermoser, 2010, Rico et al., 2008). Mine tailings management should be integrated into mining plans, and therefore a robust framework is required.

4.1.1 Contribution and limitation

The application of appropriate mine tailings strategies that consider sustainable development outcomes is currently a challenge for the mining industry. A robust and detailed framework is needed by the mining industry in assisting them to enhance sustainability performance of mine tailings operations. Unfortunately, current frameworks only provide a very general assessment and do not include any focus on those elements of mine tailings management like water and energy use that significantly impact upon the sustainability performance of the tailings management strategy chosen. This water energy nexus is a crucial component in understanding the comparative sustainability performance of different tailings strategies. The two mine tailings management frameworks currently used internationally, the MCMPR and MCA (2003) and the DITR (2007), only use a risk management assessment approach in trying to minimize the environmental, health, safety, and business risks associated with the tailings strategy. A new sustainability assessment

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[*] This Chapter has been published as a research paper in Journal of Cleaner Production, 18, 1050-1062, 2015 (see Paper 1 in Appendix B)

framework is proposed to improve the sustainability performance of tailings strategies which here thereto has been ignored in currently available mine tailings assessment frameworks. Reducing the water flow into the TSF and estimating the optimum water and energy nexus (trade-off) is the key assessment component of the proposed framework, which is currently missing in conventional mine tailings assessment frameworks.

The limitation of this framework that could be elaborated further as a future research is associated with the mine tailings utilization option. By considering the potential reuse of mine tailings, the scope of the proposed framework will expand.

4.2 Publication resume

Three objectives were discussed in Paper 1:

1. An assessment of two current mine tailings management frameworks which were issued by two leading mining institutions in Australia.
2. A review of tailings disposal strategies typically applied by international mining companies.
3. A proposed new comprehensive sustainability framework for mine tailings management.

To achieve these objectives, the authors divided the discussion into three sections, namely the current application of tailings disposal strategies, a review of the existing frameworks, and alternative frameworks. Two common mine tailings disposal (direct and indirect disposal) were discussed in the first section. The direct disposal strategy where tailings are discharged directly into river, ocean and the lake bodies is applied by less than 1% of total mine sites worldwide. Indirect disposal tailings require an impoundment, cell, or dam as a storage area and internationally most of the mine sites are applying this method. Tailings slurry types include conventional tailings, tailings paste, thickened tailings, and tailings cake. The last three types are known as Alternative Tailings Disposal (ATD) methods. Some mine sites that apply ATD were also presented include Kidd Creek Mines in Canada, Alcoa Mines in Australia, and Esperanza Mines in Chile.

The second section in the paper assesses current mine tailings management frameworks focusing on two current Australian mine tailings management frameworks by The Ministerial Council on Mineral and Petroleum Resources (MCMPR) and the Mineral Council of Australia (MCMPR and MCA, 2003) and Department of Industry, Tourism, and Resources (DITR, 2007). Australia is the 4th largest producer of coal product in the world which further makes this assessment interesting. Another mine tailings management framework issued by the Mining Association of Canada was also discussed for comparison. There are many similar elements amongst these frameworks including stakeholder engagement, mine closure, and risk-based approach. However, the authors found that these frameworks tend to use qualitative methods of assessment and are too general to be used in mine implementation stages. These frameworks are reviewed and an additional eight steps are introduced to improve their sustainability management focus.

The third section discussed in this paper introduces a new sustainability framework as presented in Figure 4.1. The proposed sustainability assessment framework provides a detailed step by step approach on how to select a mine tailings management strategy from a sustainability management perspective. Eight steps were proposed including an analysis of tailings behaviour, assessing the relationship between water and energy use in tailings management, calculating the environmental impacts, and estimating the costs and benefits of each mine tailings management method.

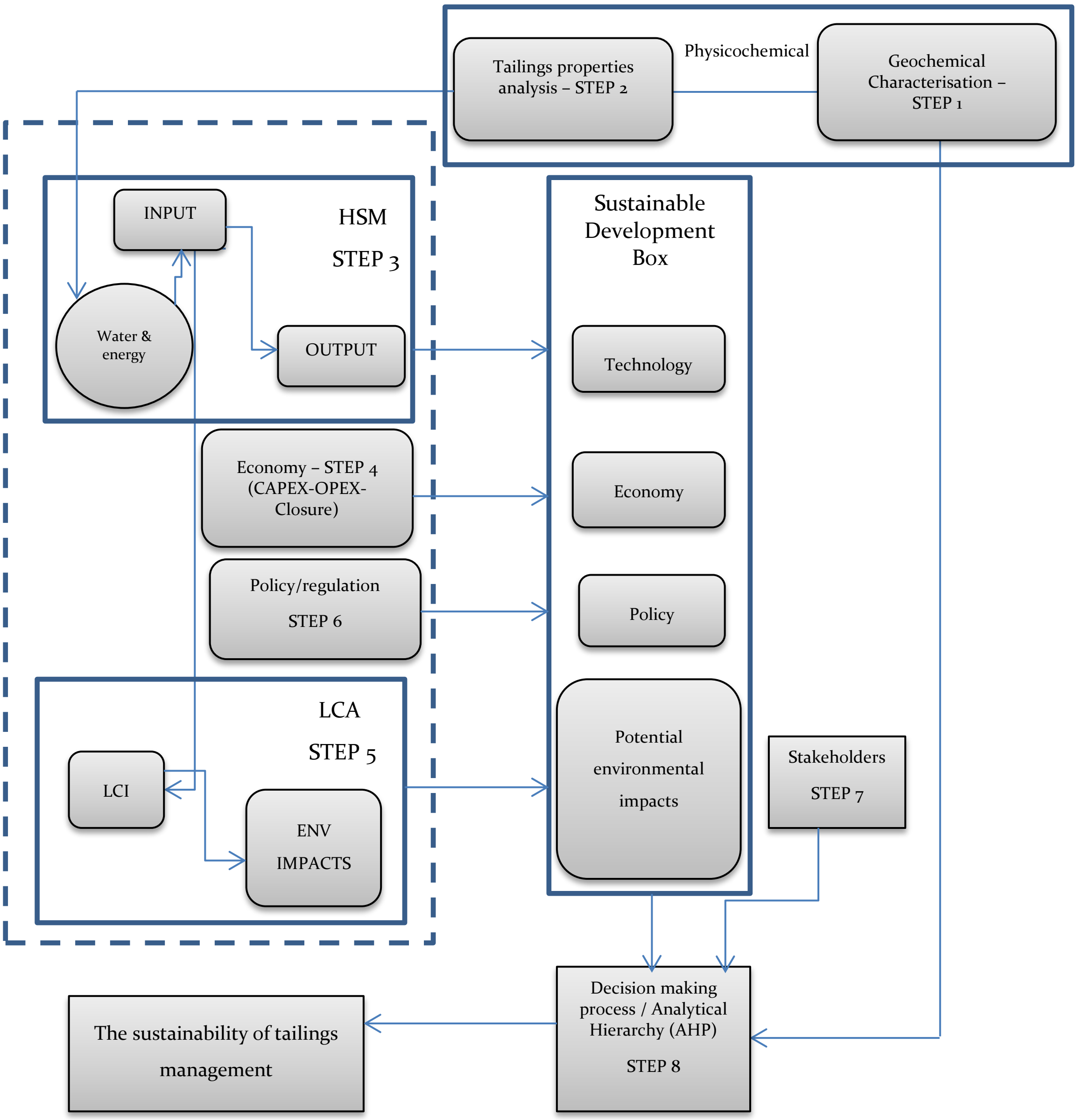

Figure 4.1 Proposed sustainability assessment framework for mine tailings management

Methodologies introduced in the proposed framework are then used to assess the coal mine tailings management scenarios presented in Chapter 5-7.

CHAPTER 5 Synergising water and energy requirements to improve sustainability performance in mine tailings management[*] (Paper 2)

5.1 Introduction

A new sustainability framework assessment of mine tailings management was presented in Chapter 4. Water and energy consumption play a significant role in determining appropriate mine tailings management methods. The nexus between these variables can be used as an initial indicator in assessing the sustainability performance of tailings management strategies.

5.1.1 Contribution and limitation

Rheology analysis is a common methodology in predicting fluid flow behaviour. As tailings slurries consist of both water and solids, a rheology analysis is required to assess specific tailings behaviour during pipeline transport. The rheology analysis undertaken confirmed that coal mine tailings exhibit non-newtonian flow behaviour and two particular characteristics of coal tailings slurry were also noted from the yield stress values generated in the laboratory analysis. These were pumpable and non-pumpable tailings mass percent solids results. This laboratory data helped in determining the appropriate strategy technology for tailings transport to the disposal area (TSF).

The yield stress data obtained from the rheology analysis was then used to modify current data in the HSM model. The current HSM model does not include rheological (yield stress) data input in estimating the pumping energy

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[*] This Chapter has been published as a research paper in Journal of Cleaner Production, 133, 5-17, 2016 (see Paper 2 in Appendix C)

requirements of the tailings slurry and relies on field data averaged for modelling estimation only. A strong trade-off relationship (nexus) was found between water and energy consumption in tailings management with a direct correlation with the percentage of mass solids in the coal tailings slurry. This nexus can be used to simulate the optimum percent solids in tailings slurry by looking at the trade-off between water and energy use.

The result of pumping energy estimation using rheology and mathematical analysis has some limitations. However, this approach was assumed to be most appropriate due to the equipment and time constraints.

5.2 Publication resume

The aim of Paper 2 was to assess the trade-off between water and energy usage in various tailings disposal methods in order to improve sustainability performance in mine tailings management.

To achieve these aims, samples from coal mine tailings generated by an open pit coal mine in Australia, were analysed as a case study. Rheology testing and water and energy modelling were used to estimate the water and energy requirements for each tailings disposal method. Five mine tailings scenarios/samples were prepared as shown in Table 5.1 and tested using a rheometer AR-1500ex. The test included shear stress test ranges from 0.01 to 1,000 Pa with one minute maximum time per point. Rheological test results together with other parameters including pipe diameter, velocity, and pipe length were used to calculate the pressure loss (ΔP). Two additional variables were required to estimate the pumping energy requirement, namely pressure loss (ΔP) and the slurry flow (Q).

Table 5.1 Scenario based on mass percent solids (Adiansyah et al., 2016a)

Mass solids (%)				
Option 1	Option 2	Option 3	Option 4	Option 5
30	50	60	65	70

The rheology results were then incorporated into a computer modelling (HSM) for synthesis and final analysis. HSM has six basic components, which interface with water and energy use within the system boundaries. These components include water inlet, water outlet, energy/emissions inlet, energy/emissions outlet, water stores, and tasks as presented in Figure 5.1.

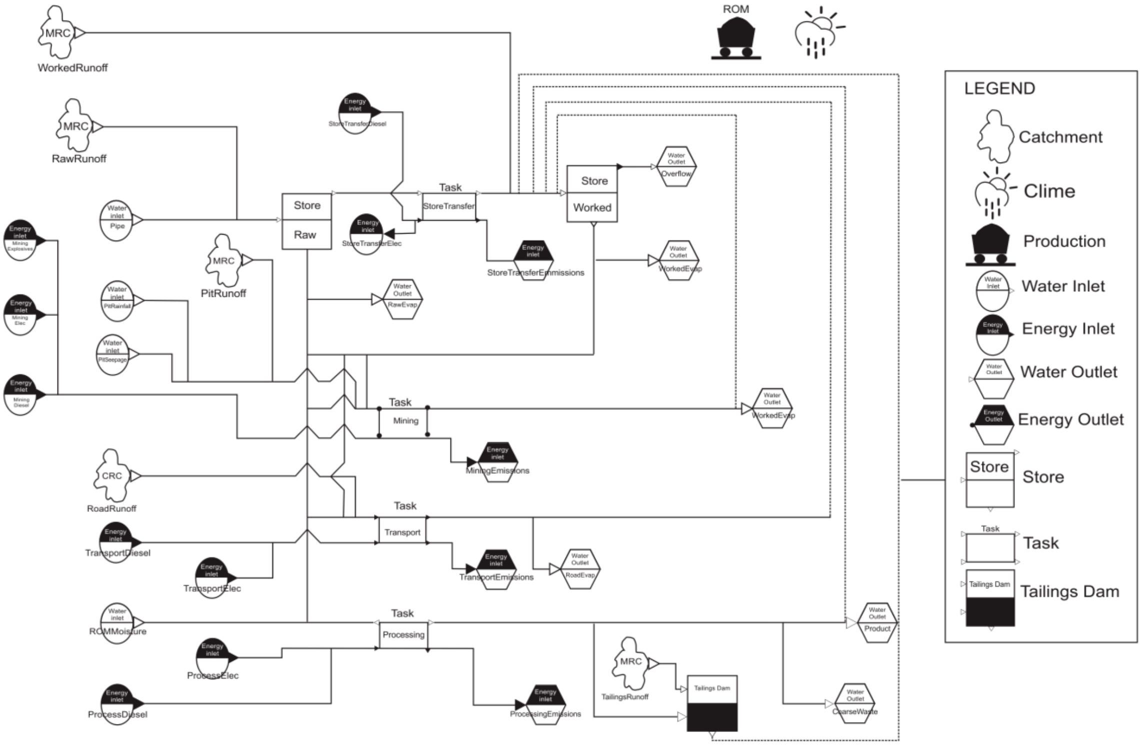

Figure 5.1 HSM basic components

The pumping energy, required for transporting tailings to the TSF, was then calculated by the HSM which indicated the higher the mass percent solids of the slurry the higher pumping energy required. The energy requirement in pumping is a data input into the LCA as discussed in Chapter 6. The ratio between the energy and water requirements, presented in this study, demonstrates the efficiency level of each mine tailings management method. The water conservation level indicated in the reuse water ratio could also be used to predict the overall flows of water to the TSF and the potential life time of a TSF.

The results from the HSM analysis of the energy and water use modelled have been utilised to develop a life cycle inventory (LCI) presented in Chapter 6.

CHAPTER 6 Application of life cycle assessment to compare environmental performance in coal mine tailings management* (Paper 3)

6.1 Introduction

Environmental impacts are important indicators in sustainable development assessment. A case study of an open pit coal mine in Australia was selected for this study to review the environmental performance (LCA) of typical coal mine tailings management.

6.1.1 Contribution and limitation

To more fully assess the sustainability performance of coal tailings management strategies, environmental impacts and land-use impacts were calculated and included for each scenario reviewed. These assessments are influenced by material inputs (i.e. energy use, chemicals, and water use) and the type of technology used (i.e. column flotation, stack cell flotation, paste thickener, and belt press). Two additional technologies were employed in order to reduce the environmental impacts associated with tailings management: firstly the inclusion of a stack cell flotation system and secondly the introduction of renewable energy as a power source. These additional technologies resulted in lowering both the environmental impacts by up to 97% and land use ratios by up to 20% compared to the conventional strategies used (i.e. column flotation and coal-fired electricity). The utilization of stack cell flotation for example reduced energy consumption by almost 50% compared with column flotation. Belt filter press strategies which use less land for tailings disposal but are higher energy consuming can be improved by

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* This Chapter has been published as a research paper in Journal of Environmental Management (Elsevier) – See Paper 3 in Appendix D and part of this Chapter has been presented as an invited talk in the 6th Brunei International Conference on Engineering and Technology (see Appendix E)

combining lower energy using stack cell flotation and renewable energy technology Options. Whilst this environmental impact assessment highlighted those scenarios with the lowest environmental impacts, each strategy needs to be also assessed from an economic perspective to ensure its operational feasibility. The application of LCA into coal mine tailings management provides an opportunity for improvement in mine operations. In addition, this study also attempts to enrich the LCA research in coal mine tailings that has not covered widely by the current studies.

The hybrid method (Australian and European) used in this study has its own limitation due to the differences in environmental impact context. In addition, the limited publicly data created a problem with the accuracy of results generated.

6.2 Publication resume

A total of eight mine tailings management scenarios, comprising three mine tailings methods (thickened tailings, tailings paste, and filtered tailing) and five improvement scenarios (by incorporating flotation technology and renewable energy), were assessed in Paper 3. The objectives of these assessments were to:

1. Compare the environmental impacts of a variety of typical mine coal tailings management methods.
2. Evaluate the land-use change impact associated with mine tailings management options.

The Functional Unit is one tonne of coal slurry produced by flotation cells. Three main steps within coal mine tailings management (life cycle) were analysed: segregation, mechanical dewatering, and tailings transport. The segregation process used flotation cells as the media to separate fine coal with tailings. In this study, three mechanical dewatering Options were assessed:

thickener, paste thickener, and belt-press. The dewatering process generated tailings with various mass percent solids (30%: thickened tailings, 50%: tailings paste, 65%: filtered tailings) and the final output was then transported to the tailings disposal area.

Figure 6.1 shows the flow diagram for each coal mine tailings management scenario. Flotation cells are fed with raw coal slurry originating from the de-sliming process in the CHPP, where raw coal particles smaller than 0.1 mm are separated. Two types of chemicals are utilized to separate coal from its impurities: methyl isobutyl carbinol (MIBC) as a frother and diesel oil as a collector. The segregation process generates two products, namely coal concentrate slurry and tailings slurry.

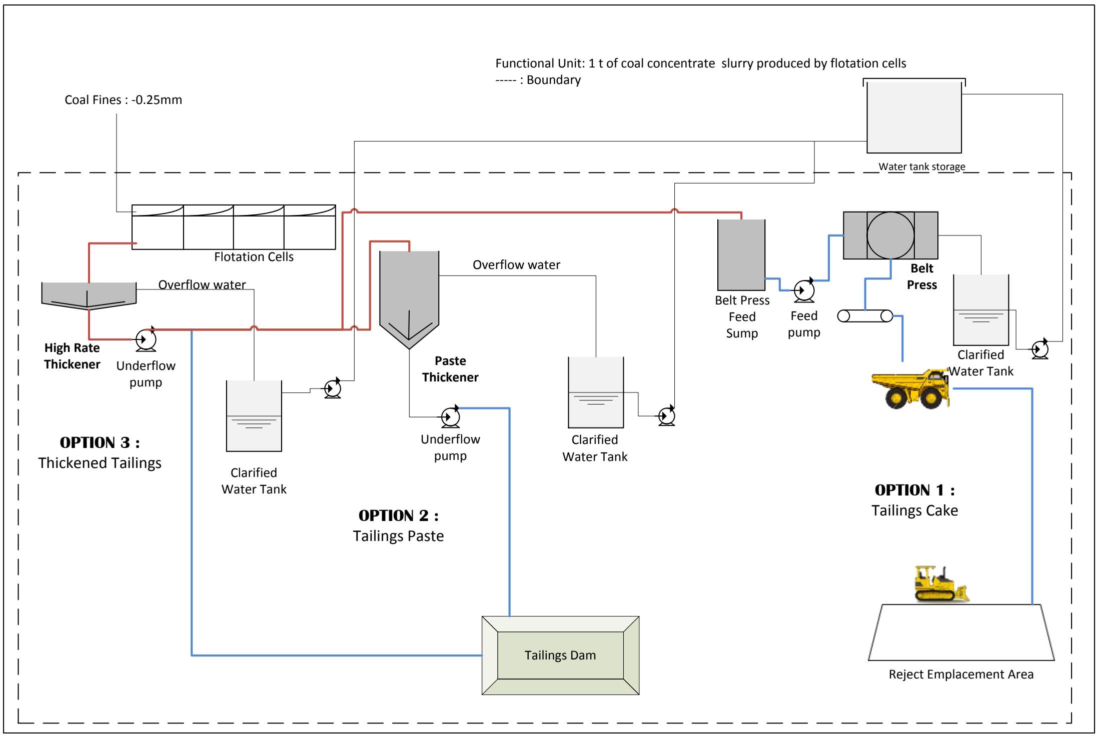

Figure 6.1 Flow diagram of mine tailings strategies

The underflow tailings slurry produced by the flotation cell flows by gravity to the next process as follows for each of the options investigated:

Option 1: A tailings thickener and anionic flocculant are added to the tailings thickener to assist in settling and aggregation. The thickener underflow with 30% solids is pumped into a belt press feed sump and then distributed to the belt press filter machine. During the flocculation stage, the fine coal tailings must be flocculated using two types of polymer: an anionic flocculant and a cationic coagulant. The free water in the flocculated slurry is drained by gravity through the drainage (lower) belt, leaving a mat of solids. Pressure is first applied in the wedge stage, squeezing the remaining water out of the tailings. Further dewatering occurs during the high-pressure stage when the tailings solids are compressed and sheared between belts and rollers. Tailings with 65% solids are discharged from the belt press filter and are transferred by conveyor to a transfer point, from where trucks transport the filtered tailings (cake) to a disposal area (reject emplacement).

Option 2: A tailings thickener and anionic flocculant are added to the tailings thickener to assist in the settling and aggregation of tailings. Underflow tailings from the thickener with 30% solids are then pumped into a paste thickener, as an extension of the normal thickening process. An anionic flocculant is added to the paste thickener to bind the fine particles together. Flocculated particles with 50% solids settled at the bottom of the paste thickener are then pumped and transported by pipeline into the tailings disposal area.

Option 3: A tailings thickener and anionic flocculant are added to the tailings thickener to assist in settling and aggregation. Underflow tailings with 30% solids from the thickener are pumped and transported by pipeline into the tailings dam.

Inventory analysis, which forms part of LCA process, indicated that the three main material inputs and outputs were electricity and water consumption, and chemical use (detailed LCI can be found in Appendix H). The combination of these materials was assessed by using SimaPro (LCA software) to generate the environmental impacts associated with each mine tailings management scenario.

Two mitigation Options i.e. flotation technology and renewable energy have been considered in scenario 1A-E to further reduce the environmental impacts associated with each scenario. These improvements involved the use of stack-cell flotation in the segregation process, and substitution of fossil fuel energy (10 - 100%) with renewable energy (see Appendix D and E).

Land-use is also an important issue in mine tailings management. Tailings slurry generated by mining operations require a significant disposal area (land) and this consequential land-use change creates environmental impact. This paper also evaluated land-use impacts by using the surface area occupation impact assessment which includes three variables: area (A), time (t), and quality (Q).

Environmental impacts and land-use change assessment help determine the lowest impact ratios for mine tailings management strategies. These variables can be used as guiding parameters in reviewing the feasibility of different tailings disposal methods to increase sustainability performance in mine tailings waste management.

Environmental impact assessment should be combined with economic analysis to enhance the sustainability performance of mine tailings management. The life cycle perspective, which discussed in this Chapter, is then compared with the life cycle costing in Chapter 7.

CHAPTER 7 Life cycle cost estimation and environmental valuation of coal mine tailings management* (Paper 4)

7.1 Introduction

Sustainability assessment typically considers cost elements in addition to environmental impacts. The combination of these two elements can improve the sustainability performance of a project/activity including mine tailings management.

7.1.1 Contribution and limitation

Life cycle costing (LCC) and environmental valuation both provide important sustainability information for decision-makers. LCC was used to analyse the Net Present Value (NPV) of the mine tailings management scenarios which was then combined together with the environmental valuation data to jointly determine the sustainability benefits and costs of each strategy.

The normalization of three parameters, LCC, BCA, GHG emissions (LCA) was used to determine the most sustainable scenario in terms of cost, environmental benefit and environmental impact. Normalization of the LCA (GHG), LCC and BCA results highlighted that the most sustainable Option was indicated as the one with the normalized value close to unity.

This study contributes to the body of knowledge of LCC and environmental valuation in coal mine tailings options that have not assessed by the current studies. Some assumptions were made for parameters including the percent recovery from flotation tanks, the rehabilitation period for each scenario, and maintenance cost due to the lack of available information. Therefore, the publicly accessed data is the common limitation for LCC studies.

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* This Chapter has been published as a research paper in Journal of Sustainable Mining (Elsevier) – See Paper 4 in Appendix F.

7.2 Publication resume

Paper 4 aims to estimate the financial value of different mine tailings disposal methods. A cost analysis is presented to compare the most sustainable options in terms of cost, benefit, and environmental impact. The estimation is based on two economic perspectives: life cycle costing (LCC) and environmental valuation. LCC represents life cycle flow of the product/process and depends on the functional unit as determined in the LCA while environmental valuation generates the cost and benefit of each disposal method during the lifetime of the mine.

To achieve the above objectives and to assess the material inputs and outputs during fine coal processing, a life cycle flow chart was created as shown in Figure 7.1. A desktop study was conducted to determine the economic value of the materials involved in the processing system.

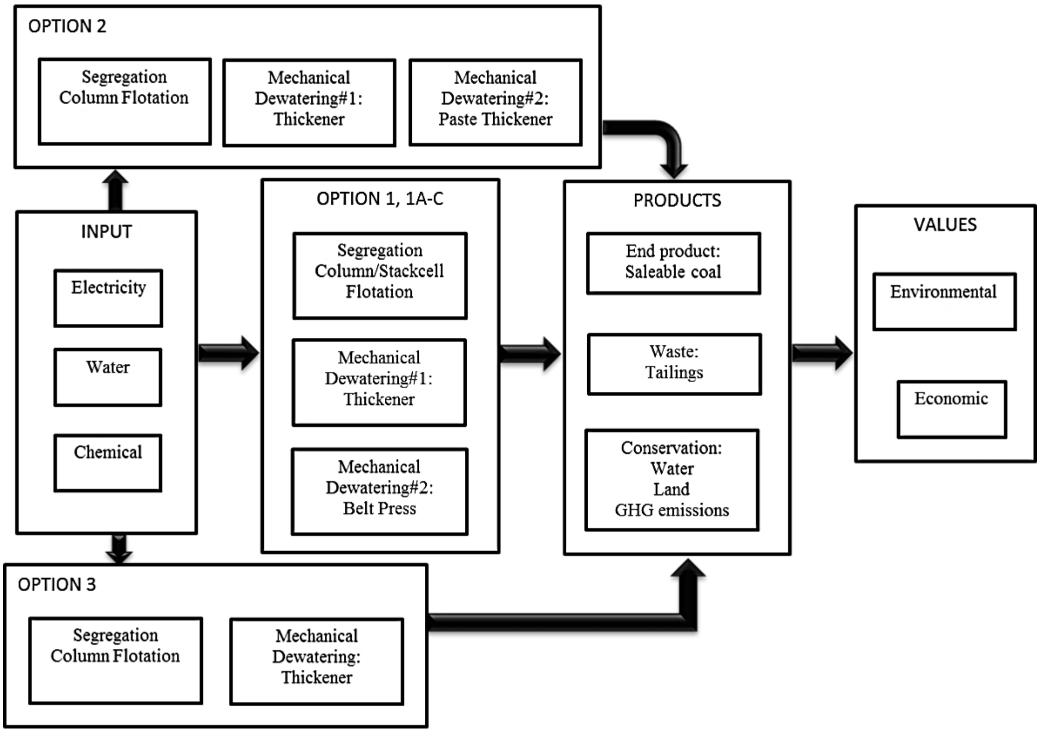

Figure 7.1 Process flow of mine tailings management strategies

This paper is divided into three sections. The first section provides a review of the previous studies on life cycle costing and environmental valuation of mining operations. The second section presents the methodologies used in the data analysis including data sensitivity using three different discount rates. The final section discusses the results of the net present value and benefit-cost analyses for each tailings management option investigated. Three main variables are involved in this analysis: capital costs, operational costs, and environmental values (see Appendix J). Water use, land use, and GHG emissions are the three environmental issues investigated as presented in Figure 7.1.

Three mine tailings management methods (thickened, paste, and filtered tailings) and three improvement scenarios (Option 1A-C) were assessed as presented in Table 7.1. These mine tailings management scenarios are identical to the scenarios discussed in the previous Chapters. The improvement technology scenarios previously presented with 100% renewable energy are as substituting fossil fuel energy with 100% renewable energy is not currently an economically viable Option for the mining industry given its typical geographic isolation.

Table 7.1 Scenario for tailings management Options

Tailings management	Characteristics
Option 1	Filtered tailings (cake) with belt press
Option 1A	Filtered tailings (cake) - belt press with technology improvement
Option 1B	Filtered tailings (cake) - belt press with technology improvement and 10% Solar RE
Option 1C	Filtered tailings (cake) - belt press with technology improvement and 10% Wind RE
Option 2	Tailings paste with paste thickener
Option 3	Thickened tailings with thickener

Option 1: this Option requires electricity, water, and chemicals to process the fine raw coal. Overflow from the flotation tank generates saleable coal in slurry form. The underflow slurry, categorized as tailings, requires further treatment in the thickener to increase its percent solids. This process in the thickener creates two material outputs: recycled water and tailings. The recycled water is pumped into water storage tanks, and underflow tailings are fed into the belt press to achieve the final percent solids portion of 65%. In this case study, a coal-fired power plant supplied 100% of the energy required. The authors also introduced technology improvements in Option 1A by replacing the type of flotation technology and incorporating 10% renewable energy (solar and wind power) for Options 1B and 1C as described in Table 7.1.

Option 2: the primary inputs required for Option 2 are similar to Option 1; the difference lies in the total amount of these materials used. The fine raw coal segregated in the flotation tank has two products: saleable coal as flotation overflow and underflow tailings. The tailings thickener receives the underflow tailings from the flotation tank and increases the percent solids of tailings by adding Sodium Acrylate ($C_3H_3NaO_2$). This acts as an anionic flocculant in the tailings slurry, and the process reclaims water, which is then distributed to the water storage tank. In order to attain a final percent solids level of 50%, a flocculant is added to the tailings in the paste thickener tank. Reclaimed water is generated by this process and pumped into the water storage tank. In this Option, 100% of electricity is supplied from the coal-fired power plant.

Option 3: this Option creates tailings with 30% solids and transports these tailings by a pipeline to the disposal area (tailings dam). The first two processes in Option 3 (segregation and thickened tailings) are similar with the other two Options. These processes generate recycled water pumped to the water storage tank. There is no renewable energy introduced in this Option.

The Net Present Value (NPV) method was used to analyse the cost variables of each mine tailings management scenario as presented in Figure 7.2. NPV was used to compare each Option and determine the most cost-effective strategy for the mine site. A NPV comparison of each coal mine tailings scenario is presented in Appendix F and J.

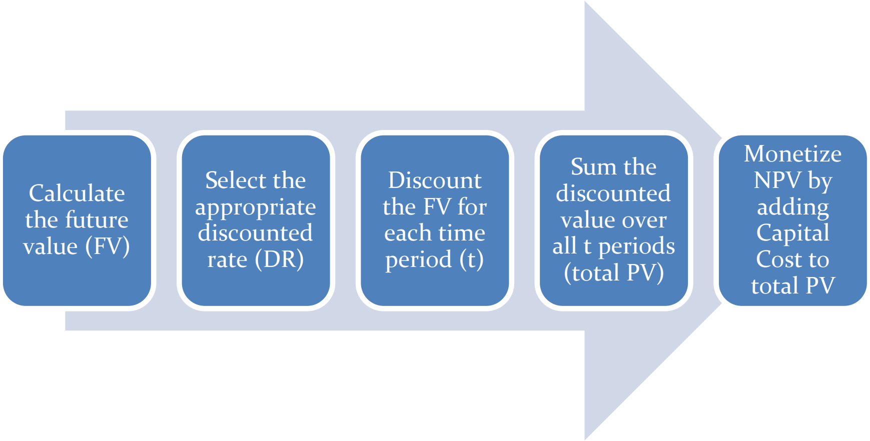

Figure 7.2 The application of NPV in LCC

The environmental valuation was conducted to provide a more comprehensive assessment of costs and benefits in present value dollar terms. Coal mine tailings management methods were then assessed from two perspectives: Benefit Value (saleable coal, water conservation, land conservation, and GHG reduction) and costs (capital and operational).

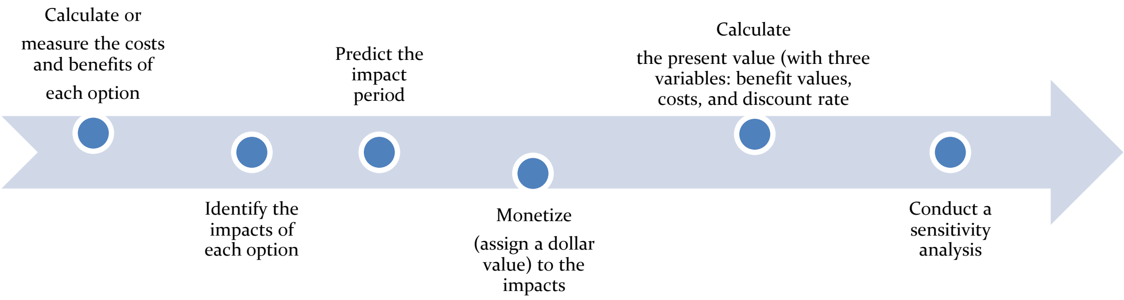

Figure 7.3 Benefit-cost analysis flow

The Benefit-cost analysis (BCA) presented in Figure 7.3, compares present value benefits (PVB) and present value costs (PVC) of the tailings scenarios investigated. If the (PVB-PVC) value for a particular Option is greater than zero, the choice is considered feasible. Sensitivity analysis is used the final stage of BCA and identifying the effect of variable changes (lifespan and discount rate) are discussed in Appendix F.

The most sustainable scenario of the six available Options for coal mine tailings management was then determined using a normalization approach where LCC, BCA, and GHG emissions as the main parameters are then normalized presented in Appendix F Section 4.4. A normalization approach was required due to the different scales of these three parameters.

CHAPTER 8 Results and discussion

8.1 Results summary

The HSM confirmed that the optimum Option in terms of water and energy conservation and water management is Option 2 with a tailings of 50% mass solids. This Option reduces water inflow to the TSF by 30% and therefore can also increase the capacity of the TSF affording additional land area conservation benefits.

Introducing technologies such as stack cell flotation and renewable energy resulted in lowering both the environmental impacts by up to 97% and land use ratios by up to 20% compared to the conventional strategies used (i.e. column flotation and coal-fired electricity)

In terms of LCC, the NPV indicated that the three most sustainable Options were Option 1A (belt press with stack cell flotation), Option 1 (belt press with column flotation), and Option 1C (belt press with stack cell and 10% wind energy) respectively. In addition, the environmental valuation (NPVB and NPVC) indicated that the three most sustainable Options were Option 1C (belt press with stack cell and 10% wind energy), Option 1B (belt press with stack cell and 10% solar energy), and Option 1A (belt press with stack cell flotation) noted as the sustainable Options.

The normalization of three elements, namely LCC, BCA, and GHG emissions resulted in the selection of Option 1C (Filtered tailings – belt press with stack cell flotation and 10% wind energy) as the most eco-efficient Option by offering environmental benefits in the most cost-effective way. Option 1C (Filtered tailings – belt press with stack cell flotation and 10% wind energy) generated benefit values of 0.01% to 54% higher and LCC values of -0.1% to 221% lower than the other Options investigated (see Appendix F).

8.2 Mine tailings management strategies

This Section synthesises the analyses provided in the preceding Chapters and connects the objectives of this research as noted in Chapter 1. The purpose of the research was to assess the sustainability performance of mine tailings management particularly in relation to water and energy use. The findings for research questions that have been addressed in Chapter 1 as follows:

1. How comprehensive is the current mine tailings assessment framework?

The current available frameworks associated with mine tailings management, in Australia, are limited and these assessments are mostly qualitative and quite generic with a focus on OHS and risk management. An alternative framework proposed in this study fills this gap by providing a more detailed operational analysis in determining sustainable mine tailings disposal options with a more specific focus on water and energy use and life cycle environmental impact assessment of the tailings process. The interaction between water and energy use in particular has not been previously assessed by existing frameworks.

The proposed framework, has eight steps including rheological analysis, environmental impact assessment, and life cycle cost estimation. The laboratory analysis focuses on tailings characterisation, flows behaviour, and pumping energy estimation. Environmental impact assessment provides the magnitude of impact of each mine tailings management scenario. Cost estimation, as the next step, compares the cost and benefits of each mine tailings management strategy. Two main cost components are operational expenditure (OPEX), and capital expenditure (CAPEX). Four benefit values are considered, namely the sale of the coal product, water reclaimed, land conservation, and GHG reduction.

2. What is the relationship between water and energy requirements in tailings transport for different mass percent solids concentrations?

Tailings transport is a critical component in mining operations that involves both significant water and energy consumption. Reducing water and energy consumption are two important issues in creating more sustainable tailings management methods.

Five mass percent solids scenarios were assessed using rheology testing to determine their flow behaviour as presented in Appendix C. These scenarios represent three types of ATD, namely thickened tailings (30% mass solids), tailings paste (50-60% mass solids), and filtered tailings (65-70% mass solids). The HSM, which requires rheology parameters as an input, was then used to analyse the relationship between water and energy use for the different mine tailings management options investigated. The rheology and HSM analysis indicate three major results as follows:

1. The optimum mine tailings management option in terms of water and energy conservation is the tailings with 50% mass solids (Option 2).
2. Pipeline systems cannot transport coal mine tailings with a mass percent solids above 65%.
3. The three main components, involved in the water and energy nexus (trade-off), are the pumping system, and the processing and dewatering technology used.

Examining the trade-off between water and energy use in tailings management is an important start in improving both the efficiency and sustainability performance of mine tailings management.

3. Which mine tailings method generates the lowest environmental impact?

Three coal tailings management methods were assessed: filtered tailings with 65% mass solids (Option 1), paste tailings with 50% mass solids (Option 2), and thickened tailings with 30% mass solids (Option 3). An additional scenario (Option 1A-E) was introduced by changing the flotation technology and replacing the coal-fired power plant energy with renewable energy. It was estimated that energy consumption declined by approximately 45% compared to Option 1 (belt press with column flotation) and 43% compared to Option 3 (tailings thickener).

LCA, which receives the input data from the life cycle inventory as presented in Appendix H, showed that thickened tailings generated the lowest environmental impact compared to the filtered tailings and paste tailings Options. However, the introduction of stack-cell flotation and renewable energy into Options 1A-E significantly reduces the overall environmental impacts associated with tailings management by up to 97% (Option 1C) when flotation technology improvement and renewable energy Options were combined. These scenarios generate lower environmental impact than both Option 2 (paste tailings) and Option 3 (thickened tailings) as shown in Paper 3 Appendix D.

4. What is the relative land-use impact of three different mine tailings methods?

The area of land disturbed varies depending on the strategy used for tailings management. Option 1 (Filtered tailings with belt press) results in the lowest land area affected and the implementation of Options 2 (Tailings paste with paste thickener) and 3 (Thickened tailings with thickener) increases the area of land occupied by tailings disposal by 41% and 61%, respectively. Results also indicate that the land-use magnitude impacts of using Option 3 (Thickened tailings with thickener) as a tailings management strategy are 2.3 and 1.6 times higher than when using Option 1 (Filtered tailings with belt press) and Option 2 (Tailings paste with paste thickener) – see Paper 3 Appendix D.

5. Which mine tailings management strategy produces the lowest cost and greatest environmental benefit?

The results revealed that Option 1A (belt press technology with stack cell flotation) was the first preference in terms of LCC while Option 1C (belt press technology with stack cell flotation and 10% wind energy) generated the highest benefits value (BCA) compared to the other Options (see Paper 4 in Appendix F).

6. Joint optimisation of BCA, LCC and environmental valuation to determine the most sustainable tailings management strategy.

The most sustainable scenario of the six Options (see Chapter 7) was assessed using a normalization approach where LCC, BCA, and GHG emissions were the main parameters. These parameters have different units (i.e. AU$, kilogram CO_2-e) and scales, which require normalization for comparative assessment.

CHAPTER 9 Conclusions and recommendations

9.1 Introduction

Research has indicated that mine tailings accidents are largely the result of poor water management, the failure of applied tailings disposal strategies, tailings dam failure, and the impact of natural disasters on tailings dams. Poor water management is considered the most influential factor in mine tailings incidents (Lottermoser, 2010). The Option for using alternative tailings disposal (ATD) technologies is a valuable strategy in reducing tailings slurry flow to the TSF. These technologies are believed to also increase the efficiency of water use and recycling, and reduce the land area required for slurry disposal. Examples of ATD technologies include, paste thickener, thickener, and belt press filtration. Utilization of these technologies should be able to contribute to important improvements in mining sustainability management and in particular in mine tailings management. However to date, very little research has been committed to a formal sustainability assessment of mine tailings management. This research focused on closing this research gap and in providing a detailed assessment of the rheological implications of different tailings management strategies, the water and energy efficiency nexus associated with each strategy and the associated carbon footprint and life cycle cost implications. Suggestions for further research are also made.

9.2 Conclusions

This research thesis focused on reducing the environmental impacts and improving the sustainability performance of various coal mine tailings management strategies. A very important consideration in tailings management is the trade-off, the nexus between water and energy use. Various methodologies have been used to achieve the research objectives. A multi-method research methodology was used in order to triangulate the results and cross-validate the research findings. This research is unique and provides research results and findings that have not been previously investigated. Firstly, a comprehensive literature review of current international mine tailings management was done. Next a significant rheology laboratory analysis was done on coal mine tailings samples at the University of Queensland. This laboratory analysis investigated the water and pumping energy requirements for the coal tailings samples investigated, in order to provide actual water and energy data for the computer modelling needed to investigate the important trade-off between water and energy use in transporting coal tailings to the tailings dam. This third stage involved using Hierarchical System Model (HSM), commonly utilised in determining the water and energy nexus of different mine tailings strategies. The fourth stage investigated the environmental impact of the coal tailings strategies assessed in stage three, using LCA and LCC to estimate their environmental impact and life cycle costs. Four published papers (Papers 1,2,3 and 4. Appendix B, C1, D, and F), one conference paper (Paper 5, Appendix E), and one industrial article (Appendix C2) were produced using these methodologies.

9.3 Recommendations

Whilst this research has not focused on ‘social’ elements in the sustainability management of coal tailings, it has considered the two dominant elements of environmental impact and cost benefit in improving the sustainability performance of coal tailings management. The mine tailings sustainability assessment framework developed can be used as a guideline for all mining companies in improving the sustainability performance of their tailings management. In addition, the water and energy balance generated research done both in the laboratory and in the HSM modelling, highlight the importance of understanding actual tailings rheology in preparing mine plan costs and efficiency programs for tailings management. The improvements in water management alone can offer very significant operational hazard and risk management benefits to mining companies requiring tailings management

The scope of this research was limited to coal mine tailings management. The tailings disposal to TSF is typically the last downstream process in mining and to date has not received much specific attention in terms of improving sustainability performance. Whilst this research excludes tailings waste recycling opportunities, further research could consider this in further reducing the environmental impacts associated with mining and mine tailings management. This strategy could also significntly reduce the area required for the disposal of mine wastes by converting these waste to resources.

Stakeholder involvement in the tailings management decision-making processes which is part of the framework of this research could also be incorporated into future research to improve the social life cycle assessment of tailings management and strengthen the social licence to operate for mining companies requiring tailings disposal operations. The reuse of tailings waste as resource by-product could also offer substantial long term social benefits.

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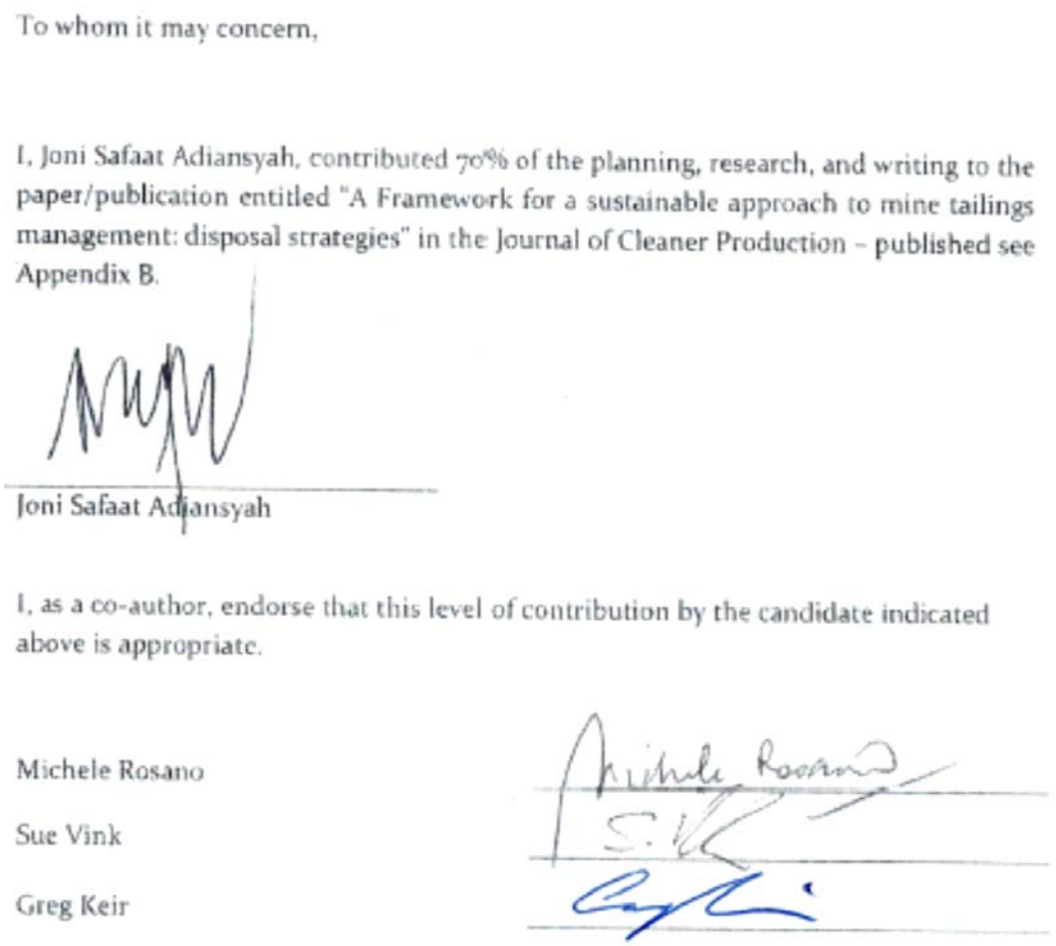


To whom it may concern,

I, Joni Safaat Adiansyah, contributed 70% of the planning, research, and writing to the paper/publication entitled "A Framework for a sustainable approach to mine tailings management: disposal strategies" in the Journal of Cleaner Production – published see Appendix B.

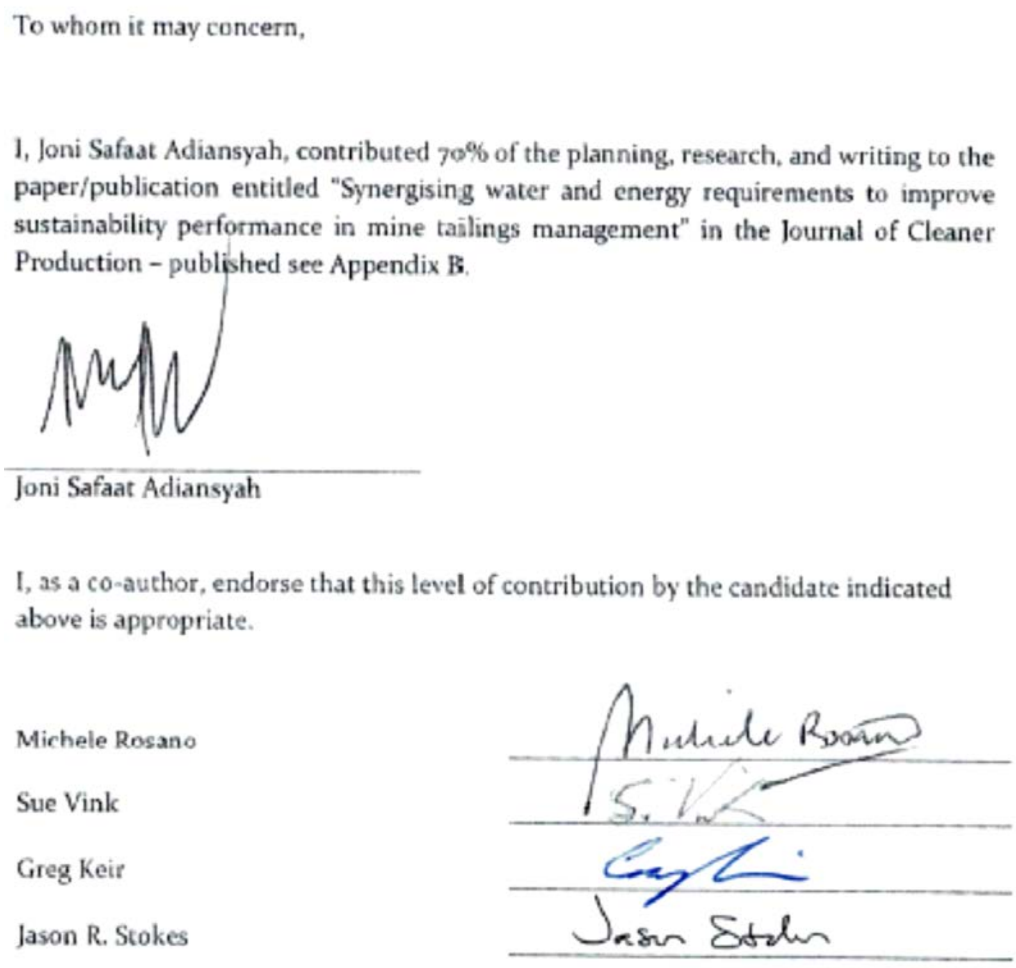
Joni Safaat Adiansyah

I, as a co-author, endorse that this level of contribution by the candidate indicated above is appropriate.

Michele Rosano Michele Rosano

Sue Vink S. V

Greg Keir



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I, as a co-author, endorse that this level of contribution by the candidate indicated above is appropriate.

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To whom it may concern,

I, Joni Safaat Adiansyah, contributed 70% of the planning, research, and writing to the paper/publication entitled "Application of a life cycle assessment to compare environmental performance in coal mine tailings management" in the Journal of Environmental Management – consideration for publication.

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To whom it may concern,

I, Joni Safaat Adiansyah, contributed 70% of the planning, research, and writing to the paper/publication entitled "Life cycle cost estimation and environmental valuation of coal mine tailings management" in the Journal of Sustainable Mining – published see Appendix F.

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I, as a co-author, endorse that this level of contribution by the candidate indicated above is appropriate.

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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.

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. 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

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Abbreviations: 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.

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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

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1. Introduction[1]

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. 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

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[1] 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

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

Environment	Economy	Social	Government (Regulation)
• Air and water pollution • Water resources depletion • Ecosystem	• Capital expenditure • Operating expenditure • Reagent loss	• Health issues • Safety issues for public (after closure) • Stakeholder	• Legal compliance

destruction • Ecosystem alteration • Land footprint • Emissions	• Energy cost • Closure cost	perception • Cultural impacts

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 and Vietti (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).

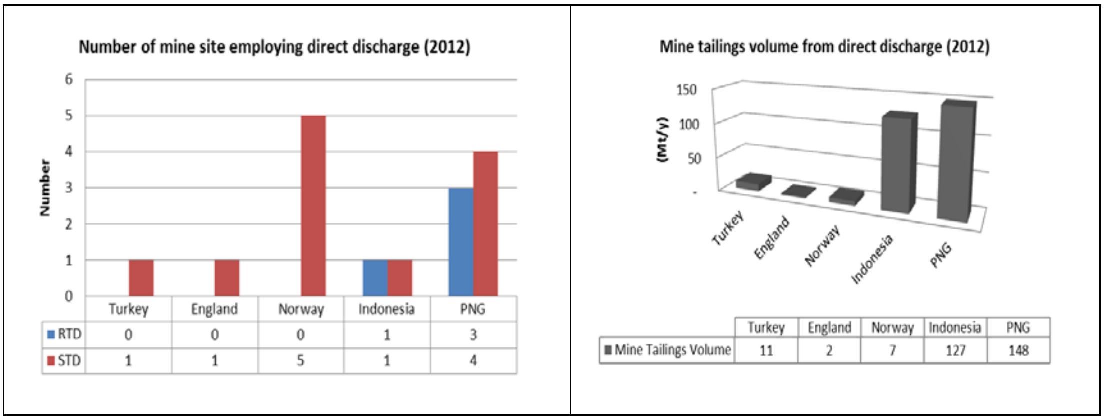

Fig.1. Mine tailings: worldwide direct disposal

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 2

Application of alternative tailings disposal

Mine site	Location	Type of mine	Production rate (Mt/y)	Tailings mass solids (%)	Disposal strategy
Kidd Creek Mine: copper-zinc	Canada	Surface	3.6	80.4	Thickened

Alcoa World: alumina	Australia	Surface	7.3	70	Dry stacking
Bulyanhulu Mine: gold	Tanzania	Underground	0.91	73	Paste backfill
Sunrise Dam: gold	Australia	Surface	1.5	77	Thickened
Esperanza Mine: copper-gold	Chile	Surface	29	67	Thickened
Boliden Garpenberg: lead-zinc	Sweden	Underground	2.5	70	Paste backfill

Source: (Robinsky et al., 2002, DITR, 2007, Moreno, 2011, MT, 2015, Walker, 2011)

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.

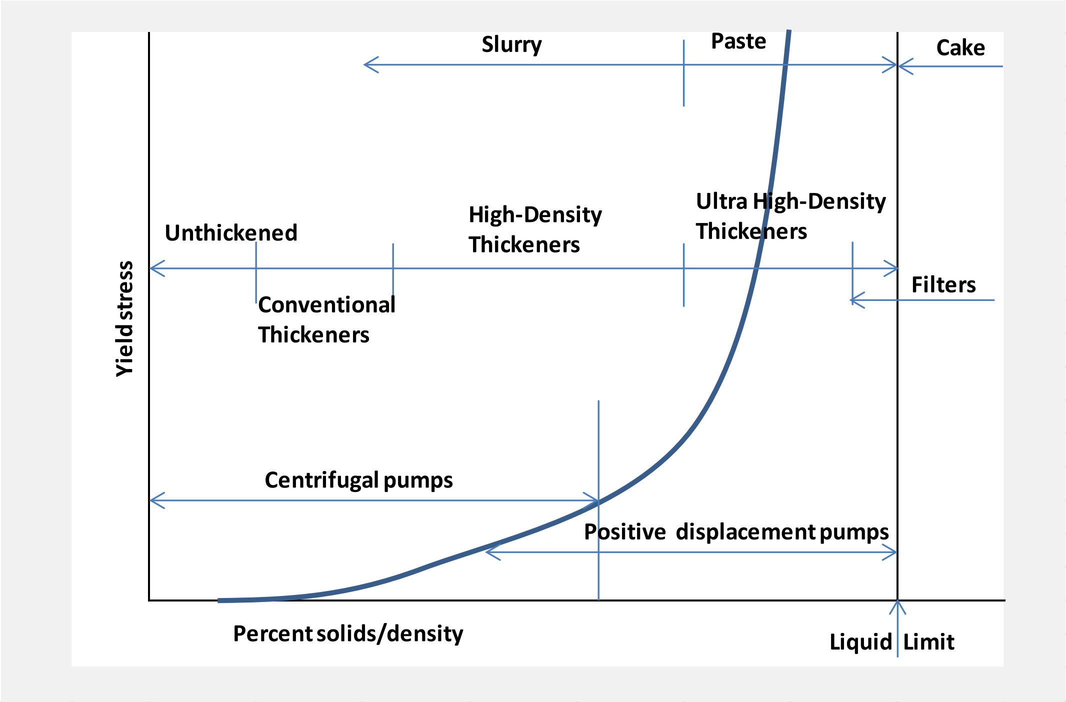

Fig.2. Description of Paste and Thickened Tailings - adapted from (Fourie, 2012)

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

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).

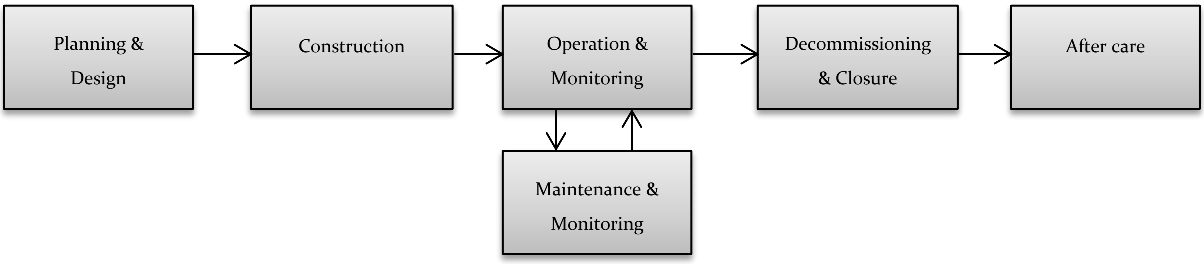

Fig.4. Tailings management system life cycle – adapted from (DITR, 2007)

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.

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.

Table 3

Potential risks associated with mine tailings

Phase	Potential risks
Operation	Leaking of tailings slurry pipeline Geotechnical failure TSF overflow Seepage through containment wall Seepage infiltration to ground water Particulate Matter (PM): dust or gas emissions Interaction of wildlife or livestock with tailings Mine acid pollution into the water: ground water and surface water
Closure	Erosion of containment wall Spillway failure Overtopping by rainfall run-off Failure of land cover system on tailings surface

Source: Adapted from (DITR, 2007, Laurance, 2003, Laurance, 2001)

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.

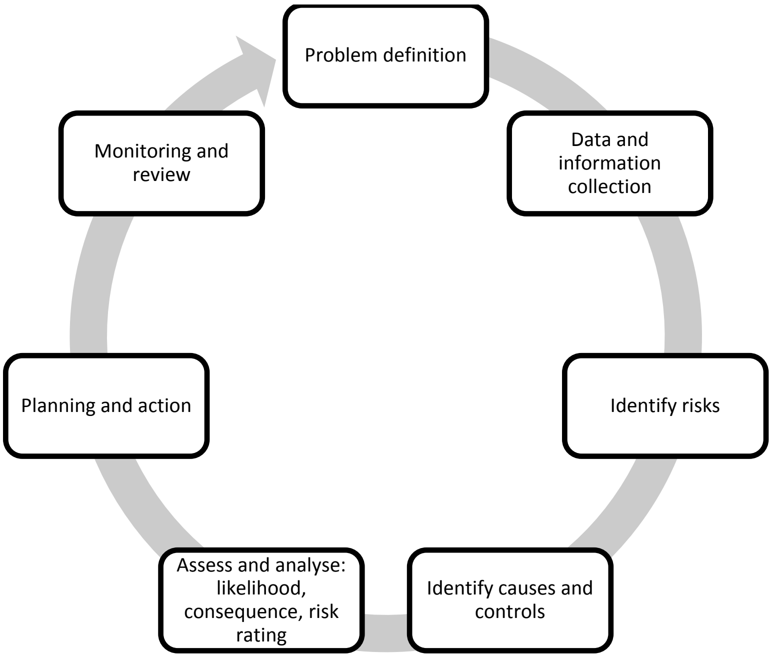

Fig.5. The risk management cycle - modified from (ISO, 2009, Verma, 2013)

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.

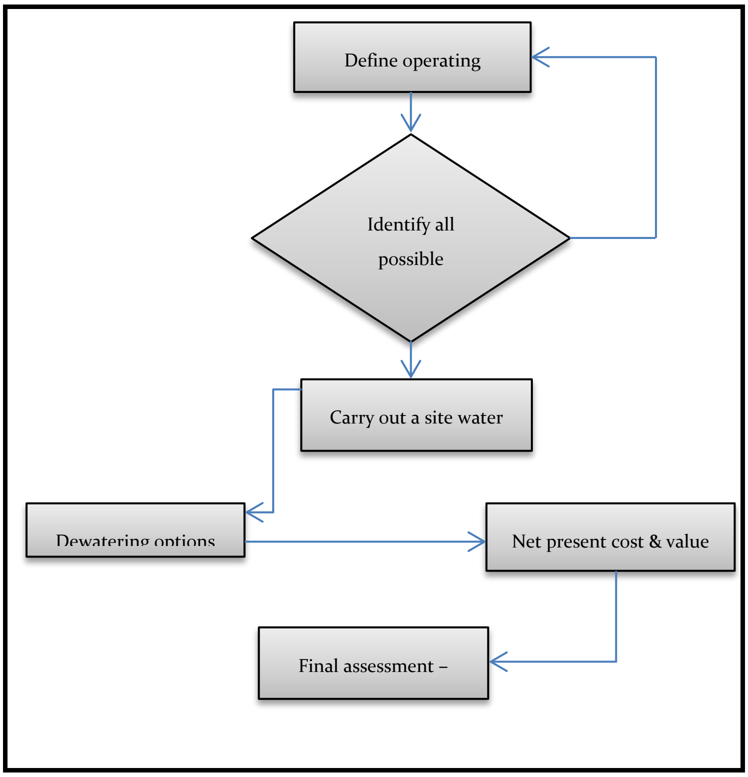

Fig.6. DITR's conceptual tailings management system (DITR, 2007)

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.

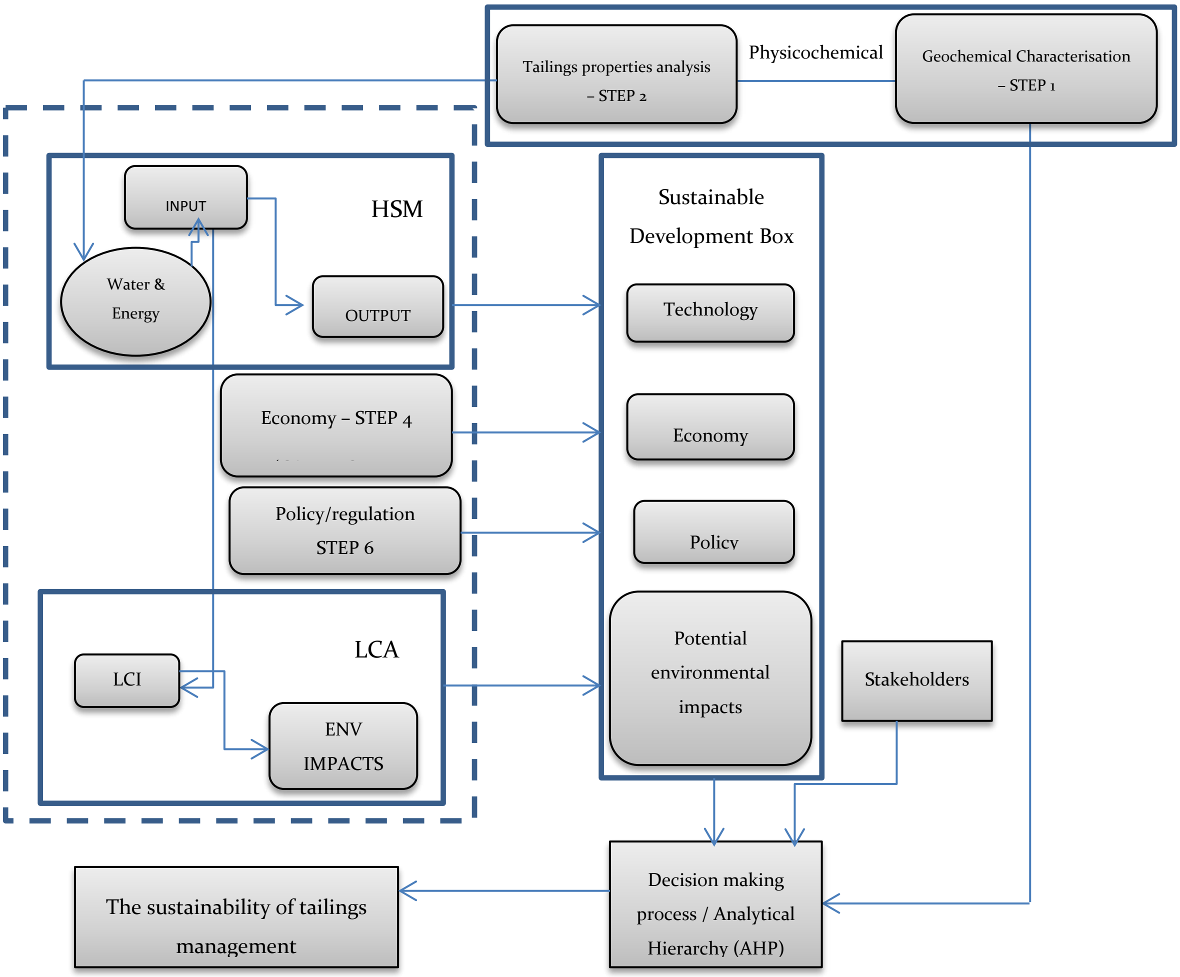

Fig.7. Proposed framework for mine tailings management

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 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 saleable 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.

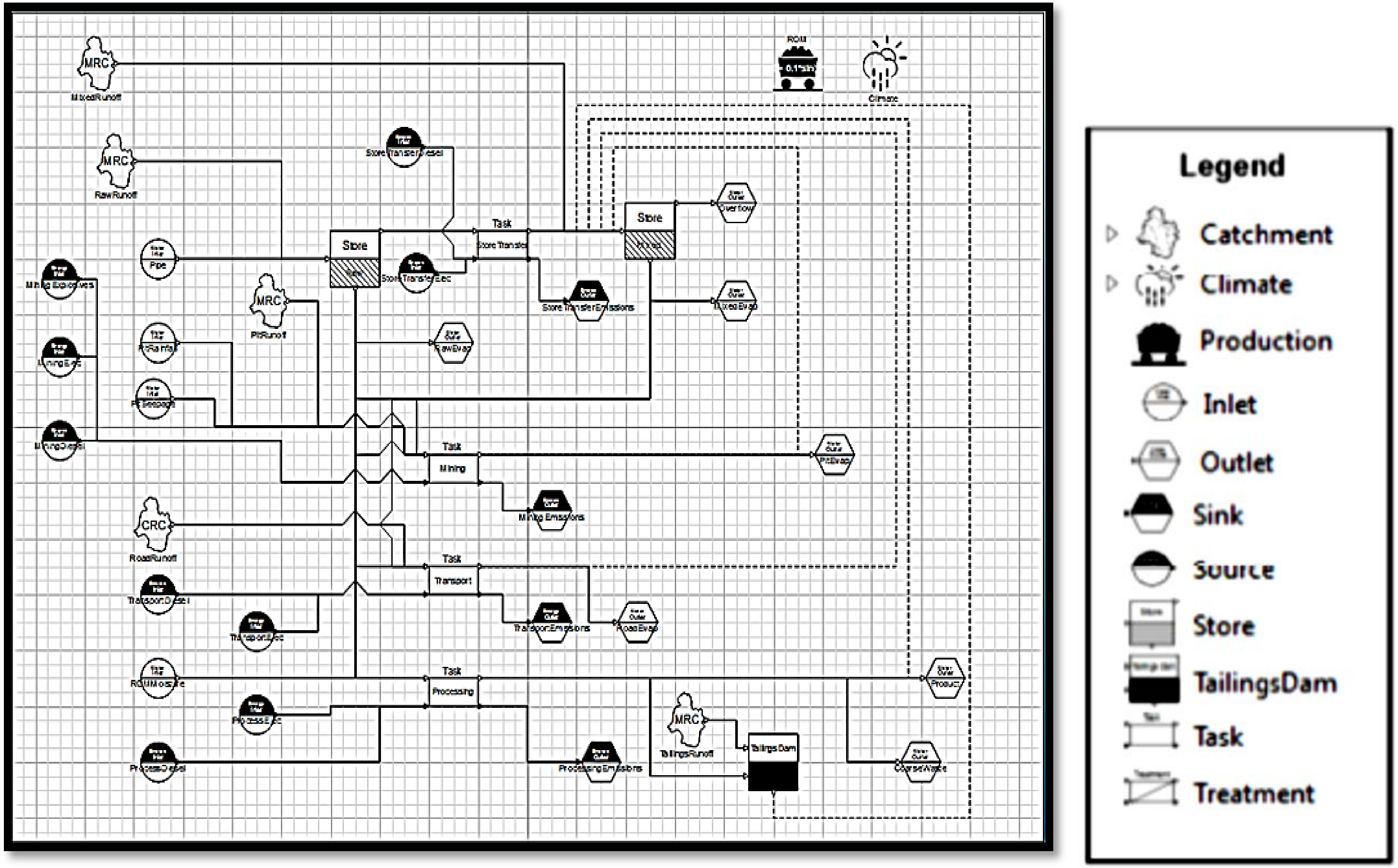

Fig.8.1. The baseline mine

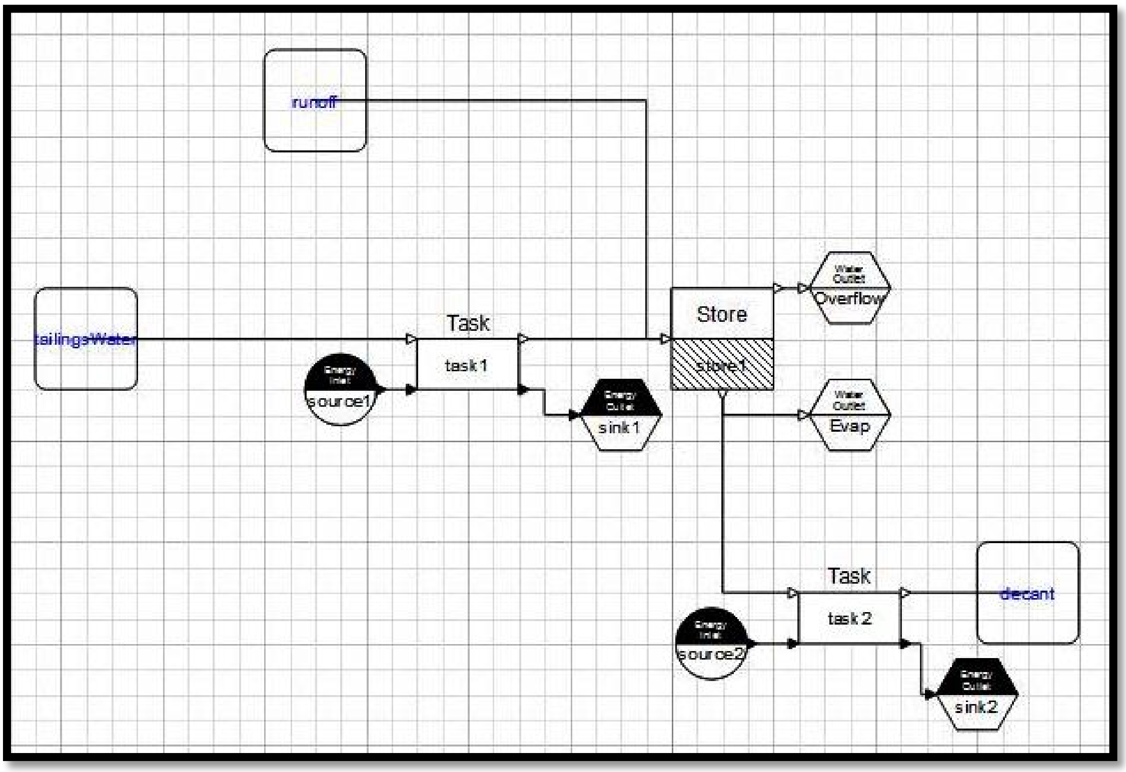

Fig.8.2. The tailings dam

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.

Table 4

Scenario comparisons

Scenario		Task			
		Mining	Processing	Transport	Tailings Dam
Conventional (30% solids)	Water use (ML/y)	0	2,409	639	1,791
	Energy use (TJ/y)	123	277	215	3
Thickened (50% solids)	Water use (ML/y)	0	2,409	639	901
	Energy use (TJ/y)	123	284	215	10

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 5

Capital and operating cost

COST in ($)	SCENARIOS	
	Baseline - conventional	Thickened Tailings
TOTAL Capital Cost:	35,063,129	62,537,411

Thickener, thickener underflow pumps, tailings disposal pumps and pipelines, flocculant plant and piping, civil works, tailings dams, return water system and seepage control		
TOTAL Operating Cost:	806,948	6,384,114
Water, flocculant, power – energy, maintenance, labour		

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.

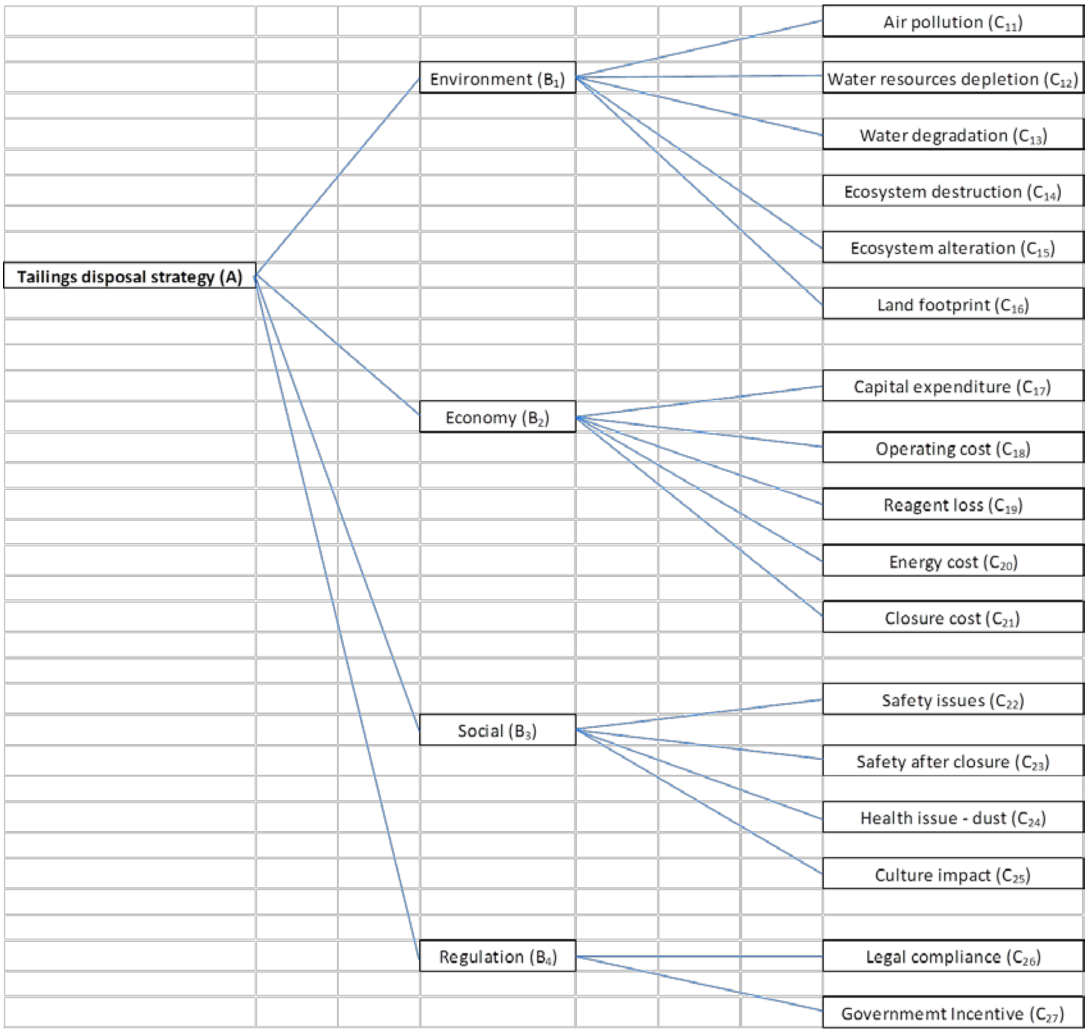

Fig.9. Mine tailings management evaluation

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

Comprehensive sorting of the index weights

Issues	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27
Weight	0.005	0.076	0.068	0.02	0.015	0.001	0.014	0.011	0.004	0.006	0.039	0.019	0.146	0.029	0.099	0.364	0.073
SCENARIOS																	
CT (%)	66.67	20	20	85.71	83.33	88.89	80	20	80	85.71	20	83.33	85.71	16.67	66.67	33.33	33.33
TT (%)	33.33	80	80	14.29	16.67	11.11	20	80	20	14.29	80	16.67	14.29	83.33	33.33	66.67	66.67

Table 7

Ranked listing of alternatives

Preference	Alternative	Percentage (%)
1	Conventional tailings	45.90
2	Thickened tailings	54.10

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.

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Synergising water and energy requirements to improve sustainability performance in mine tailings management

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ABSTRACT

Mining is a water and energy intensive industry, and reducing water and energy consumption are two important issues in the quest for more sustainable industrial production. The aim of this paper is to assess the correlation between water and energy requirements in various tailings disposal strategies (on a per cent solids-based analysis). Two main methods are used: rheology testing and a system modelling approach. A coal mine site in Australia was chosen as a case study to apply five tailings disposal options. These five options are differentiated by the percentage of solids in the tailings ranging from 30% to 70%. The rheology analysis indicated that the coal mine tailings with 65–70% solids are not pumpable and these two options are beyond the scope of this study. The results of the analyses show that the optimal scheme process in terms of water saving, water management, and energy consumption involved tailings with 50% mass solids. The implementation of this option resulted in both lower water transport (15,532 ML/y) and energy consumption (34.7 TJ/y). This option also reduced the overall flows of water to the Tailings Storage Facility by 30%.

1. Introduction[1]

1.1. Background

Mining operations cannot exist without sufficient and secure supplies of both water and energy; without these, problem may arise including production chain interruption, and increase to remediation costs (Nguyen et al., 2014). Water is typically used within a broad range of activities including haul road dust suppression, mineral processing, metal recovery, water cooling, tailings and concentrate transport, and worker requirements. These water demands are met by both surface water and groundwater sources. The volume of water withdrawn by mining operations across the globe was approximately 20.1 million m^3 per day in 2010 (Jain et al., 2016) with the ABS (2016) recording that mining in Australia consumed 141 GL of water between 2013 and 2014. Total water usage can vary depending on some factors including the size of the mine, the mining and processing methods used, and associated with water conservation practices. Gunson et al. (2012) provided a hypothetical analysis for water consumption based on the requirement of processing 50,000 ton per day (tpd) of low grade copper ore in an arid region (Table 1).

On a global scale, the mining industry is not the largest consumer of water; for example mining consumes about 1% of total freshwater withdrawals in the United States (Miranda and Sauer, 2010), and mine water consumption in Australia, Chile, and South Africa accounts for only 2–4.5% of national water demand (Gunson et al., 2012). However, on a local scale, mining operations can have a significant impact on the water supply of adjacent communities. Firstly, the primary source of direct water consumed by mining often comes from surface and groundwater. Secondly, mining operations often significantly affect the water quality of local resources, e.g., acid mine drainage, and heavy metal pollution of water resources in Southern Africa (Mccarthy, 2011; Ashton et al., 2001), Baia Mare, Romania (Bud et al., 2007), and Wadi Queh, Egypt (Abdalla and Khalifa, 2013).

In addition, the mining industry is considered to be one of the five largest consumers of global energy, with energy used not only for mining and processing but also ancillary services such as water treatment, wastewater management, and generating camp

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[1] TSF: Tailings Storage Facility, P&T: Paste and Thickened Tailings, HSM: Hierarchical Systems Model, ROM: Run-of-mine, CHPP: Coal Handling and Preparation Plant.

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Synergising water and energy requirements to improve sustainability performance in mine tailings management

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Abstract

Mining is a water and energy intensive industry, and reducing water and energy consumption are two important issues in the quest for more sustainable industrial production. The aim of this paper is to assess the correlation between water and energy requirements in various tailings disposal strategies (on a per cent solids-based analysis). Two main methods are used: rheology testing and a system modelling approach. A coal mine site in Australia was chosen as a case study to apply five tailings disposal options. These five options are differentiated by the percentage of solids in the tailings ranging from 30% to 70%. The rheology analysis indicated that the coal mine tailings with 65-70% solids are not pumpable and these two options are beyond the scope of this study. The results of the analyses show that the optimal scheme process in terms of water saving, water management, and energy consumption involved tailings with 50% mass solids. The implementation of this option resulted in both lower water transport (15,532 ML/y) and energy consumption (34.7 TJ/y). This option also reduced the overall flows of water to the Tailings Storage Facility by 30%.

Keywords: mine tailings management, rheology, hierarchical system model, water and energy consumption

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Mining operations cannot exist without sufficient and secure supplies of both water and energy; without these, problem may arise including production chain interruption, and increase to remediation costs (Nguyen et al., 2014). Water is typically used within a broad range of activities including haul road dust suppression, mineral processing, metal recovery, water cooling, tailings and concentrate transport, and worker requirements. These water demands are met by both surface water and groundwater sources. The volume of water withdrawn by mining operations across the globe was approximately 20.1 million m^3 per day in 2010 (Jain et al., 2016) with the ABS (2016) recording that mining in Australia consumed 141 GL of water between 2013-2014. Total water usage can vary depending on some factors including the size of the mine, the mining and processing methods used, and associated with water conservation practices. Gunson et al. (2012) provided a hypothetical analysis for water consumption based on the requirement of processing 50,000 ton per day (tpd) of low grade copper ore in an arid region (Table 1).

Table 1

Water usage in copper mining

Process	Usage (m^3/d)
Flotation with 30% mass solids	115,646
SAG Mill cooling	4,100
Ball Mill cooling	4,100

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[1] TSF : Tailings Storage Facility

P&T : Paste and Thickened Tailings

HSM : Hierarchical Systems Model

ROM : Run-of-mine

CHPP : Coal Handling and Preparation Plant

Compressor cooling	4,100
Road dust control	3,520
Froth wash	2,880
Pump glad seal water (GSW)	1,440
Reagent dilution	720
Dust control in primary crusher	358
Dust control in ore stockpile	121
Domestic water	58

Source: Gunson et al. (2012)

On a global scale, the mining industry is not the largest consumer of water; for example mining consumes about 1% of total freshwater withdrawals in the United States (Miranda and Sauer, 2010), and mine water consumption in Australia, Chile, and South Africa accounts for only 2-4.5% of national water demand (Gunson et al., 2012). However, on a local scale, mining operations can have a significant impact on the water supply of adjacent communities. Firstly, the primary source of direct water consumed by mining often comes from surface and ground water. Secondly, mining operations often significantly affect the water quality of local resources, e.g., acid mine drainage, and heavy metal pollutions of water resources in Southern Africa (McCarthy, 2011, Ashton et al., 2001), Baia Mare, Romania (Bud et al., 2007), and Wadi Queh, Egypt (Abdalla and Khalifa, 2013).

In addition, the mining industry is considered to be one of the five largest consumers of global energy, with energy used not only for mining and processing but also ancillary services such as water treatment, waste water management, and generating camp electricity. Mining utilized 20% of Chile’s total electricity consumption in 2013 (Simpson et al., 2014), 20% of South Africa’s total electricity generated in 2006 (Johnson and Fourie, 2012), and 9%

of Australia's net total energy consumed between 2012-2013 (BREE, 2014). Energy consumption is also a critical component in mining production costs and typically contributes between 14-30% of total production costs (Simpson et al., 2014, ABB, 2012). Energy consumption also generates greenhouse gas (GHG) emissions through both the purchase of energy and direct burning of fuel.

Consequently, water and energy should be appropriately managed to enhance the sustainability of mining operations. Initiatives presented in Table 2 have already been implemented by mining sites across the world in an effort to reduce water and energy consumption.

Table 2

Examples of water and energy reduction initiatives in the international mining industry

Mine site	Initiatives	Goals	Achievement
Minera Esperanza, Antofagasta, Chile	Implementing thickening tailings method; Using seawater.	Ensuring the usable water supply to mine operations; Optimizing water use.	Water use reduction up to 600 L/s.
BHP Billiton, Olympic Dam, Australia	Establishing water saving project; covering open site water storage, increasing the volume of wastewater usage.	Minimizing water use from the Great Artesian Basin (GAB).	Water use reduction approximately 450 ML/year.
Argyle Diamond Mine, Western Australia	Capturing and recycling water seepage from tailings; dewatering underground mine.	Reducing water use from surface water sources.	Reduction on water supply from Lake Argyle up to 300 ML
Barrick Gold Corp.	Grinding improvement by put some changes	Reducing energy, GHG, and Cost.	Reducing on 20% net grinding energy

	including change the profile of cone crusher liner, use gearless drive.		and 43,000 tonnes CO_2/year.
The Teck Coal Elkview, BC	Installing Variable Frequency Drive (VFD) on the dryer exhaust fan	Reducing energy consumption	Total electric saving $ 105,079/year
Anglo American Group, Platinum Mining	Energy conservation through some methods including the installation of compressors, ventilation fan, and optimization of smelter.	Saving energy and cost	In 2012 total saving approximately $75 Million
	Implementing the Plant Information (PI) system infrastructure	Reducing overall energy cost	15% reduction in power consumption by 2015

Sources: ICMM (2012), Buckingham et al. (2011), Durocher and Putnam (2013), Ryan (2014),Bascur and Soudek (2014)

Tailings transport is an important component of mining operations that involves both significant water and energy consumption. The largest water sink at most mining sites is the Tailings Storage Facility (TSF) (Gunson et al., 2012). In TSF operation, the relationship between water and energy is significant and determines the tailings management strategies. The Castle Valley flow as shown in Fig.1 describes an example of water and energy interaction in a coal mining. The thickener facility was built to process fine coal, where tailings generated from the underflow thickener consist of 30% solids. As an illustrated, the water required to transport these tailings equals 0.7 ton for 1 ton of tailing slurry.

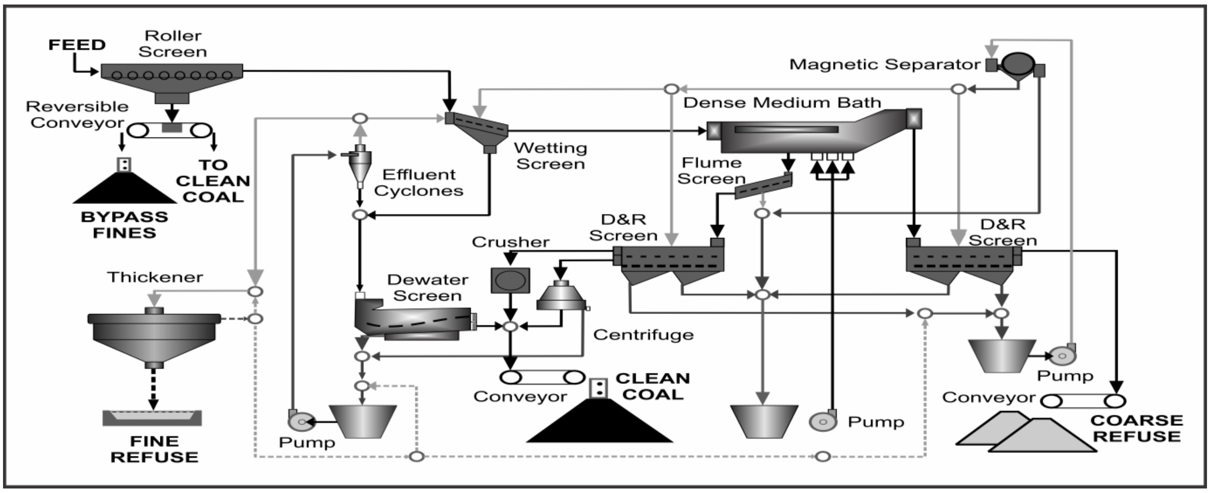

Fig.1. Castle Valley Plant (Bethell, 2012)

As a water sink, the TSF generally receives water from runoff, rainfall, and tailings entrained from the mine processing plant. The processing plant produces solid residue (tailings) which is generally transported to the TSF as slurry by a pipeline. This transport process requires energy and generates emissions. Energy is also needed when water is recycled from the TSF and pumped back to the processing plant's water supply. Therefore, the interconnection between water and energy consumption in terms of water reduction, energy efficiency, and associated environmental impacts becomes an important factor in sustainable tailings management.

1.2 Objectives

Research to date has assessed the relationship between water and energy use in mining operations including Gunson et al. (2010), Nguyen et al. (2014), and Moolman and Vietti (2012). A linear programing algorithm was used by Gunson et al. (2010) in comparing some possible options for supplying water to a copper mine and mill. In addition, Nguyen et al. (2014) discussed two types of water and energy relationships including potential synergies and trade-offs. The relationships were represented by two criteria: net water available volume and net operational demand. Three case studies from three different mine sites were discussed which included a copper mine (Chile), a coal mine (Australia), and a gold mine (Australia). Moolman and Vietti (2012) detailed the connection between water conservation and energy costs in tailings management for a platinum project in South Africa. The results of this study revealed that the thickened tailings option generated the lowest total cost per tonne of tailings discharged. Studies until now, however, have not considered rheology or water and energy trade-offs in different coal tailings management strategies. Therefore, this study attempts to fill the gaps and discover the novelty of synergising water and energy in coal mine tailings management.

The aim of this paper is to assess the nexus between water and energy requirements across various tailings disposal methods (using a percent mass solids-based analysis) that could further improve the sustainability of coal tailings management. Four research questions are being assessed:

- How much energy is required in pumping the tailings from the processing plant to the TSF after water and energy use for different concentrations?
- What is the water balance during tailings transport for various tailings mass solids concentrations?
- What is the relationship between water and energy consumption for different tailings disposal methods?
- What is the most suitable option for transporting coal mine tailings to the TSF in terms of the water and energy nexus?

In order to understand these questions, a rheology test for coal mine tailings samples was completed. In addition, a system modelling tool known as the Hierarchical Systems Model (HSM) (Keir and Woodley, 2013) was used to analyse the relationship between water and energy use for a coal mine site at the Bowen Basin in Central Queensland, Australia as presented in section 5.3. The following outlines current discussions relating to water and energy consumption in mining. Section 3 describes some basic rheology concepts and their relationship with mine tailings solid concentrations. Section 4 presents the material and methods used in the laboratory work and data analysis. Lastly, sections 5 and 6 present the laboratory results and analyses the interrelation of water and energy for each option.

2. Improving sustainability of mine water and energy use

Over the past two decades, mining operations have become more sustainable with initiatives being developed through the Mining, Minerals and Sustainable Development project (MMSD) starting in 2002. The MMSD project was initiated by nine of the world's largest mining companies as a two-year independent project of research and consultation; the International Institute for Environment and Development was selected as the project leader (MMSD, 2002). In addition, the establishment of the International Council of Mining and Metals (ICMM) in 2001 was seen as a commitment by the mining and minerals industry toward the development of more sustainable operations. This commitment was embodied in the ten principles of the ICMM sustainable development code (ICMM, 2003) as shown in Table 3. The ten principles are based on issues that emerged in the MMSD and are comparable to available international sustainable management standards including the Rio Declaration, Global Reporting Initiative, World Bank Operational Guidelines, the ILO Conventions, and the Voluntary Principles on Security and Human Rights (ICMM, 2003).

Table 3

Sustainable development principles of ICMM

The ten principles
1. Implement and maintain ethical business practices and sound system of corporate governance
2. Integrate sustainable development considerations within the corporate decision-making process

3. Uphold fundamental human rights and respect cultures, customs and values in dealings with employees and others who are affected by our activities
4. Implement risk management strategies based on valid data and sound science
5. Seek continual improvement of our health and safety performance
6. Seek continual improvement of our environmental performance
7. Contribute to conservation of biodiversity and integrated approaches to land use planning
8. Facilitate and encourage responsible product design, use, re-use, recycling and disposal of our products
9. Contribute to the social, economic and institutional development of the communities in which we operate
10. Implement effective and transparent engagement, communication and independently-verified reporting arrangement with our stakeholders

Source: ICMM website, 2003

These ten principles cover many issues related to sustainability including the spirit of equity and fairness (found in the ICMM sustainability codes) which shapes the interaction between mining, environment, and social outcomes. The ICMM has also developed position statements on mine closure, partnership for development, transparency on mineral resources, mercury risk management, indigenous people and mining, and protected areas and mining.

Continual improvement to environmental performance including re-use, recycling, and waste disposal is a key factor in mining sustainability. One reporting system, known as the Global Reporting Initiative (GRI), includes energy (EN3-EN7), water (EN8-EN10), emissions, effluent and waste (EN16-EN25) in their sustainability factors. Three of these aspects are described by Northey and Haque (2013) in their paper assessing the environmental footprint of copper mining activities in Australia, Chile, Peru, Laos, Papua New Guinea, South Africa, the USA, and Canada. This paper is based on the sustainability report published by each copper mine. The results show the rates of consumption of energy and water, and production of GHG emissions for each country. The average rates of these three components per ton of copper produced were as follows: 22.2 GJ of energy intensity, 2.6 ton CO_2-e of GHG emission production, and 70.4 kL of water used (Northey and Haque, 2013). Other studies revealed that 260,000 ton of water and 200,000 GJ of energy were required for every 1 ton of gold produced (Prosser et al., 2011, Norgate and Haque, 2012). In addition, Gunson et al. (2012) noted that conventional copper mines consumed water at approximately 0.34 to 2.07 m^3 per ton of ore processed. These figures indicate that water and energy are two critical components in mining operations. However, it is also important to considering how these two components interact to determine where the most efficient points of water/energy use are in terms of sustainability outcomes.

Several efforts have been made to assess the relationship between energy and water use in mining operations (Gunson et al., 2010, Norgate and Haque, 2012, Nguyen et al., 2014). Other studies have focused solely on mine water management without considering energy consumption (Cote et al., 2010, Gunson et al., 2012). The significance of water and energy consumption in mining operations is captured in some modelling systems such as the Mine Water Network Design (MWND) and the Hierarchical System Model (HSM) (Gunson et al., 2010, Nguyen et al., 2014). The MWND focuses on the estimation of energy consumed to supply water from specific water sources to consumers. Gunson et al. (2010) noted that there are five procedures that should be included to identify the energy/water nexus: 1) develop a site water balance; 2) identify all potential water sources; 3) identify all water consumers; 4) develop the energy demand matrices; and 5) utilize linear programming to minimise energy demand. However, the MWND has some limitations in analysing the existing mine water system and is only applicable for designing new mine water systems (Nguyen et al., 2014). There are many opportunities to improve energy and water efficiency in mining including more energy efficient processes, renewable energy use, water reuse and recycling, and increasing the percentage of solids in concentrates and tailings (Buckingham et al., 2011, Gunson et al., 2012, McLellan et al., 2012). Some companies, such as Newmont and BHP Billiton, have published their sustainability reports showing their commitment to improving their water and energy efficiency (Newmont, 2013, BHP-Billiton, 2014). However, only a few studies have investigated the interconnectedness between water and energy or the synergy in reducing water and energy consumption in tailings management. One study used an example from a platinum tailings management project conducted by Moolman and Vietti (2012). The two main parameters were the need for maximizing water recovery and minimizing power costs. Using a coal mine as its reference point or base, another study, used the Hierarchical Systems Model to assess this water/energy dynamic (Woodley et al., 2013), as discussed in section 4.2.3. The synergies of these two components can be used as a starting point in preparing water and energy strategic plans as discussed by Nguyen et al. (2014) which can help to prevent deleterious outcomes such as water and energy shortfalls.

Currently, there are three main methods for managing tailings: conventional tailings dams, paste and thickened tailings (P&T) , and direct disposal (Franks et al., 2011). The conventional tailings management system and direct disposal method require more water in transporting tailings to the TSF or final discharge compared with P&T tailings. This is due to the difference in the amount of mass solids contained in the tailings. Conventional tailings typically consist of 30% solids and P&T consists of up to 70% solids (Fourie, 2012). Some of the advantages of P&T tailings are identified by Jones and Boger (2012), and Boger (2013) including maximizing density of tailings in the TSF, minimising the TSF footprint and reclaiming water, processing reagents, and energy. However, further analysis is required to investigate the P&T tailings process and the nexus/trade-offs between water use, and energy consumption in tailings management.

3. Rheological concepts and their application to mine tailings management

Tailings management aims to protect the environment and society from the potential impacts that might be caused by mine waste (tailings). One of the biggest problems related to TSF management is the high volume of water used. Increasing the percentage solids of tailings is the most obvious way to reduce overall water use in tailings management (Boger, 2013). In terms of rheology as presented in Fig.2, Boger et al. (2012) consider various parameters for improvement to tailings management. These parameters include safety, environmental, and cost factors embedded in the selection, design, and testing stages. When determining disposal method in the selection stage, two questions should be considered: 1) the method appropriate to minimise environmental impacts; and 2) capital and operational costs. In addition, safety factors, such as the potential of dam failure and dam overtopping, present significant technical and design considerations. An understanding of the rheological characteristics of mine tailings is a key factor in determining tailings disposal systems. Boger et al. (2012) provides a flowchart (see Fig.2) on how rheology can be used as a tool to determine an appropriate disposal system in the planning phase of tailings management ("rheological-based decision").

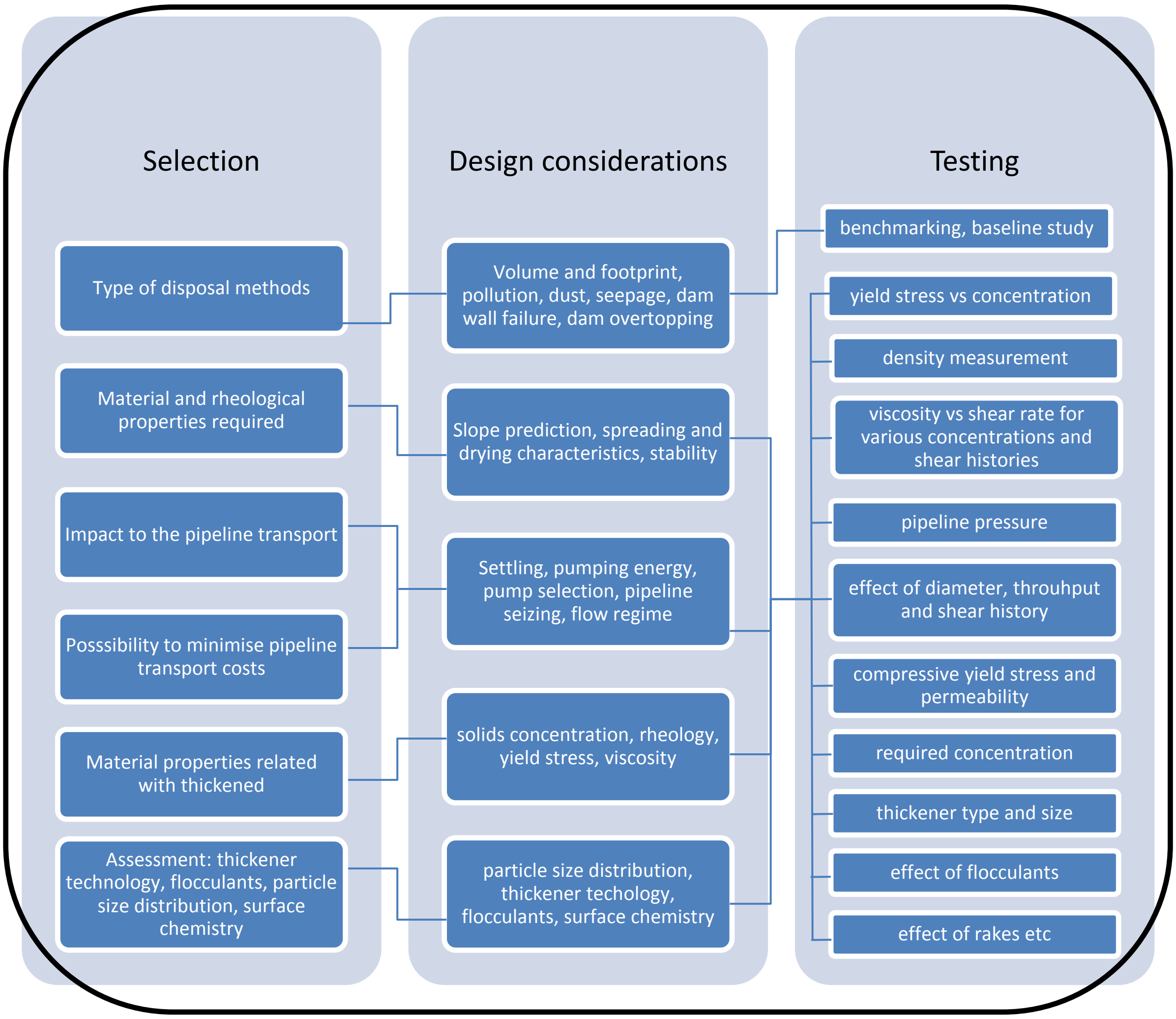

Fig.2. Rheology-based decision flow adapted from Boger et al. (2012)

Rheology plays a crucial role in designing mine tailings systems because it determines the flow behaviour of fluids during the transporting process and is known as a study of the deformation and flow of matter (Barnes et al., 1989, Morrison, 2001, Boger et al., 2012). The main parameter used to differentiate these two fluids is the viscosity (η). The resistance to flow (viscosity) is defined as the ratio of the shear stress (τ) to the shear rate ($\dot{\gamma}$) where the more resistant a fluid is to flow (viscous) the more pumping energy is required to transport it. The correlation between viscosity and shear stress (the force applied per unit area) shown in Fig.3 describes two behaviours of non-Newtonian fluids. These two behaviours are shear thinning (pseudoplastic) and shear thickening (dilatants). Pseudoplastic behaviour is shown when increasing the shear stress results in decreasing in the viscosity. Dilatant or shear thickening fluids are relatively rare in mineral suspensions and show an increased shear stress with increasing viscosity (Sofra et al., 2015, Goodwin and Hughes, 2008, Barnes et al., 1989).

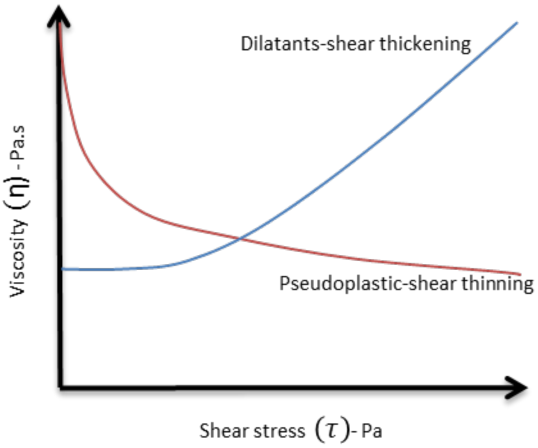

Fig.3 Non-Newtonian fluids behaviour

At sufficiently high solids levels, suspensions of mine tailings contain an apparent yield stress, which is the minimum shear stress required for flow to occur (Boger et al., 2012). These are commonly characterised by the Herschel-Bulkley Model shown in eq.1, where τ_y is the yield stress, K is the consistency index, and n the power-law index. Table 4 shows examples of yield stress values for different tailing suspensions, including alumina and lead-zinc tailings that have a yield stress ranging from 22 to 265 Pa (Boger et al., 2012, Sun et al., 2013).

$$\tau = \tau_y + K\dot{\gamma}^n \qquad \text{eq.1}$$

Table 4

Examples of yield stress values for mine tailings

Substance	Yield stress (Pa)
Thickened tailings disposal (alumina)	30-100
Tailings paste (lead-zinc) various solids concentration	22-265
Mine stope fill	250-800

The study of rheology in mine tailings management has brought many changes to the development of thickener technology (Schoenbrunn, 2011) and pumping systems (Paterson, 2012). Furthermore, it has created an opportunity to reduce the water content in tailings during transport to the TSF, helping to reduce the risk of tailings dam failure, minimise TSF footprints, and reclaim energy (Boger, 2013). Many mining operations apply rheological assessments to their mine tailings management systems including Alcoa bauxite production as presented in Adiansyah et al. (2015). Alcoa in Western Australia has been altering their disposal management system from wet to dry tailings. This enables Alcoa to reduce the total volume of waste and recycled water, and to recover caustic materials with total saving costs of approximately A$ 10 M/year (Cooling, 2007, Boger, 2009, Boger, 2013). Other examples of rheology benefits in mine tailings operations include Sunrise Dam, a gold mine in Western Australia which was able to reduce their mine tailings operational costs by approximately A$ 0.28 per ton when applying Thickened Tailings (TT) (Fourie, 2012). The Chihong mine in China was able to produce cemented paste backfill based on rheological experiments by increasing percent solids up to 80% (Yin et al., 2012), and the Sangan iron mine project in Iran recovered 0.87 Mm^3 of water when applying paste thickening technology (Rashidinejad and Naraghi, 2011).

4. Materials and methods

A rheological test was chosen to represent the behaviour of the coal tailings sample during the transporting process. The estimation of energy consumption during transport was based on generated rheology data. Different scenarios provided insight into the correlation between the water and energy used in tailings management. These scenarios were divided into five options including a conventional method (tailings slurry), and a non-conventional method (thickened and paste tailings).

A modelling analysis is also used to estimate the water and energy consumption in different tailings management scenarios. These two steps (rheology and modelling) were mentioned in Adiansyah et al. (2015) as part of a framework for achieving sustainable mine tailings management.

4.1 Materials

The tailings samples in this research were provided by the Centre for Mined Land Rehabilitation (CMLR) at The University of Queensland and were taken from a coal mine site in the Bowen Basin of Central Queensland, Australia.

Tailings samples were prepared into five different solids concentrations as presented in Table 5.

Table 5

Sample preparations – mass solids concentration

Mass solids (%)				
Option 1	Option 2	Option 3	Option 4	Option 5
30	50	60	65	70

Tailings were dried in the oven (50^0C) overnight and water was then added to meet the solids concentrations for each option (equation 2).

$$\% \text{ solids} = \frac{Ms}{MsL} . 100 \qquad \text{eq. 2}$$

where M_s = mass of solids in the sample and M_{sL}=mass of slurry in the sample

A rheometer type AR-1500ex was used in this study to evaluate the coal tailings behaviour in a variety of solid mass concentrations. This unit has a drag cup motor drive system with torque range from 0.1 μN.m to 150 mN.m, an air bearing mounting for the measurement system, and an optical encoder for measuring displacement (Semancik, 2014).

The vane geometry was chosen with the standard vane dimensions of 11.0 mm for stator inner radius, 22.50 mm for the outer rotate radius, and 15 mm for the cylinder immersed height. Utilization of a vane-in-cup device can eliminate the measurement slip and generate more precise measurements from a single-point determination (Nguyen and Boger, 1998, Boger, 2013).

4.2 Methods

The Bowen basin coal mine in Central Queensland, Australia was taken as the case study. This site has 6.05 Mt/year run-of-mine (ROM), the fine rejects from Coal Handling and Processing Plant (CHPP) are transported by pipe (diameter 0.45 m) to the TSF as 30% mass solids.

4.2.1 Rheological test

Tests were carried out on samples of coal tailings with solid content by mass from 30% to 70% w/w in order to investigate the behaviour of tailings during dewatering and transporting.

All the samples with different solids concentrations were tested using the rheometer AR-1500ex. The rheometer calibration with zero gaps approximately 11,000 μm. The container was then filled with the sample and the sensor was lowered until the vane was immersed. Steady state flow steps were applied to obtain the main parameters including shear rate, shear stress, and viscosity.

The test was set as a shear stress test with ranges from 0.01 to 1,000 Pa and the maximum time per point was one minute.

4.2.2 Energy estimation

The results obtained from the rheology test were used as the primary input to estimate the linear pumping energy required for transporting the tailings. The primary inputs included a consistency index (K), flow behaviour (n), and yield stress (τ_y) as presented in eq.4. The interaction between these three rheology parameters with field data (velocity described as slurry flow speed (m/s), and pipe diameter and length) resulted in the energy pumping estimation for transporting the mine tailings as shown in eq.3. The linear energy estimation trend is compared with the energy pumping requirement resulted from HSM as shown in section 5.3.

The estimation of the linear pumping energy requirement is calculated based on the pressure loss (Pa) and the slurry flow (m^3/s) in eq.3.

$$E = \Delta P \, . \, Q \qquad \text{eq.3}$$

where: E = energy (watt/m) and Q = flow (m^3/s)

The calculation of pressure loss involves the rheology test results together with other parameters including velocity, pipe diameter, and pipe length. The resulting equation for the pressure loss is presented in eq.4 (Chilton and Stainsby, 1998):

$$\frac{\Delta P}{L} = \frac{4K}{D} \left(\frac{8V}{D}\right)^n \left(\frac{3n+1}{4n}\right)^n \left(\frac{1}{1-X}\right) \left(\frac{1}{1-aX-bX^2-cX^3}\right)^n \qquad \text{eq. 4a}$$

$$X = \frac{4L\tau_y}{D\Delta P} \qquad \text{eq. 4b}$$

$$a = \frac{1}{(2n+1)} \; ; b = \frac{2n}{(n+1)(2n+1)} \; ; c = \frac{2n^2}{(n+1)(2n+1)} \qquad \text{eq. 4c}$$

where: ΔP = pressure loss (Pa); K = Herschel-Bulkley consistency index ($Pa.s^n$) generated from the rheology test; n = Herschel-Bulkley flow behaviour index generated from the rheology test; V = velocity (m/s) was calculated as a function of the flow rate and pipe diameter; D = pipe diameter (m); L = pipe length (m), and τ_y = yield stress (Pa) generated from the rheology test.

4.2.3 Using HSM in water and energy nexus analysis

The experimental and analytical results were incorporated into a computer-based model called Hierarchical System Model (HSM) for synthesis and final analysis. The HSM is graphical, user-friendly software that allows users to build models of mine site water, energy, and emissions networks at arbitrary levels of detail. The typical application of HSM is for developing simplified systems-level models of mine site water and energy networks, in which the complex topology can be simplified to a level that is more easily comprehensible for management purposes, but still retains essential behaviours (Woodley and Keir, 2014, Woodley et al., 2014).

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. The relationships between these components within a coal mine context are shown in Fig.4.

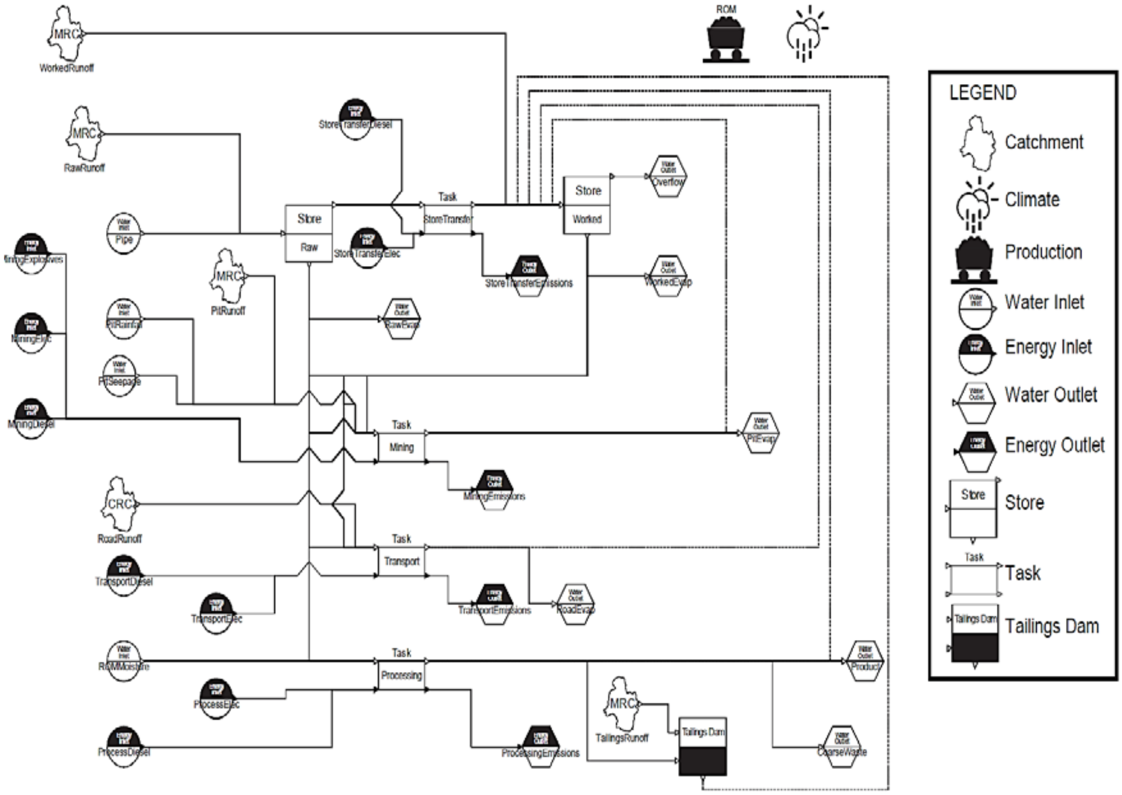

Fig.4. Schematic of mining operations in HSM

The HSM was developed by using a Modelica Integrated Development Environment (IDE) which is an equation based modelling language that has the ability to model complex and interconnected systems (Woodley and Keir, 2014). This modelling language was supported by data taken from field mine sites, and current literature as presented in Woodley and Keir (2014). The generated outputs of water and energy use highlighted the nexus between the two resources. The results of this model have been further validated by comparing them with other modelling outputs (Woodley et al., 2014). In this study, rheology data was fed into the HSM as an additional data input. The other data inputs into the HSM include:

- Parameters of the site water system such as volume, catchment areas, and surface areas of water storage;
- Geographical coordinates of site infrastructure related to the site water system;

- Climate data in the form of daily rainfall and pan evaporation time series;
- Estimates of the demands of water and energy from various components of the mine site operations; and
- Estimates of the make-up of energy sources required to meet the energy demands of the various operations on site.

In general, most of these data are not measured, and are estimated based on the experience of mine site staff. As it stands, there is no explicit consideration of input data uncertainty (and how this propagates through to model results) at this stage. Certainly this can be realised through uncertainty analysis of the model by a Monte Carlo simulation approach and various deleterious inputs. The author view, however, is that this provides little value for such an analysis as presented here.

In terms of the conversion of input data to output, the HSM uses a simple water and energy balance model to estimate the water pumping energy requirements between objects in the model; it assumes each water stream that connect objects within the model can be represented as a single virtual pipe of a prescribed diameter and hydraulic roughness (when in reality, there may be multiple connections). It is further assumed that for each inlet and outlet on a task object there is a single virtual pump of prescribed efficiency which may represent an array of physical pumps.

The HSM can be used to explore the relationship between water and energy either at the site or regional level, however, for this study, the authors focus only on the tailing management system. There were two main tasks considered in this study: processing tasks/activities and the tailings dam. As presented in Table 9, there are four water flows taken from HSM analysis: 1) store worked water to process; 2) store raw water to process; 3) excess water to store worked water; and 4) tailings transport to TSF.

5. Results and Discussion

The results are now discussed in three sections: rheology, pumping energy estimation, and the water and energy nexus. The analyses are focused on the processing task where the tailings are generated and transported to the TSF.

5.1 Rheological characteristic analysis

Different concentrations of coal tailings have been tested to determine the rheological characteristics for each concentration. Typical rheological properties of coal tailings are shown in Figs.6-7. The nature of the flow curves indicates that the viscosity has an initial plateau at low shear stresses (termed the zero-shear viscosity,η_0), followed by a highly shear thinning regime above a critical stress that is considered here to be an apparent yield stress. The figure includes fits of the yielding regime to the Herschel-Bulkley model in eq.1. However, the research did not determine a big difference in the viscosity values of each point in the 65% and 70% mass solids as an indication of the yield stress value.

The shear data in Fig. 5a-c and Fig.6, was obtained with the vane-shear rheometer and demonstrated that concentrated coal mine tailings are non-Newtonian fluids with yield pseudoplastic behaviour. This behaviour is shown the yield stress value being greater than zero ($\tau_0 > 0$) and the Herschel-Bulkley flow behaviour index being less than one ($n < 1$) (Sun et al., 2013, Rao, 2014) as shown in Table 7. In addition, the increasing slurry mass solids concentration was also accompanied by an increasing shear stress. For example, the shear stress value of the tailings slurries at 60% mass solids is higher than for that of 50% mass solids. The increasing shear stress has a close correlation with the increasing shear rate as well as increasing yield stress.

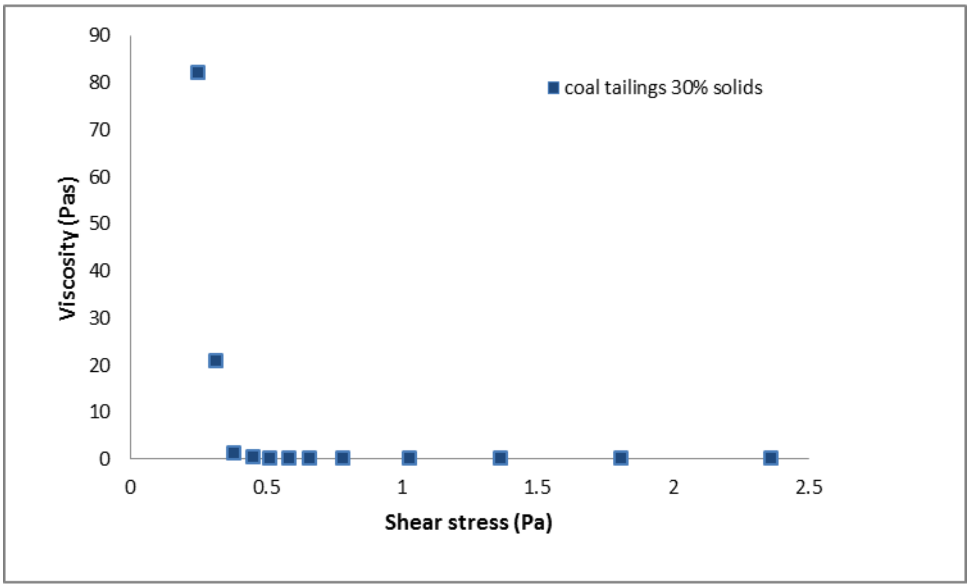

Fig.5a. Viscosity as a function of 30%-mass solids and shear stress

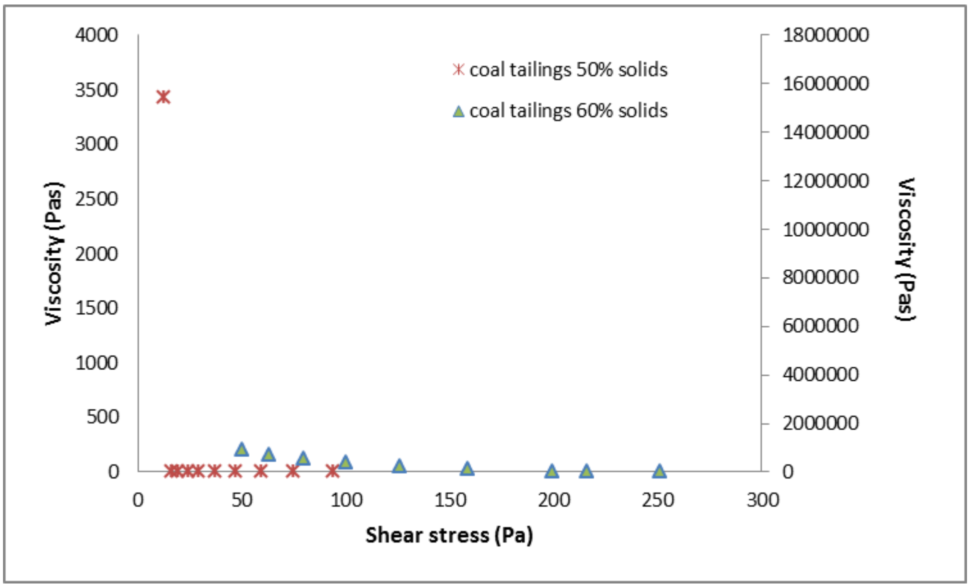

Fig.5b. Viscosity as a function of 50% and 60%-mass solids and shear stress

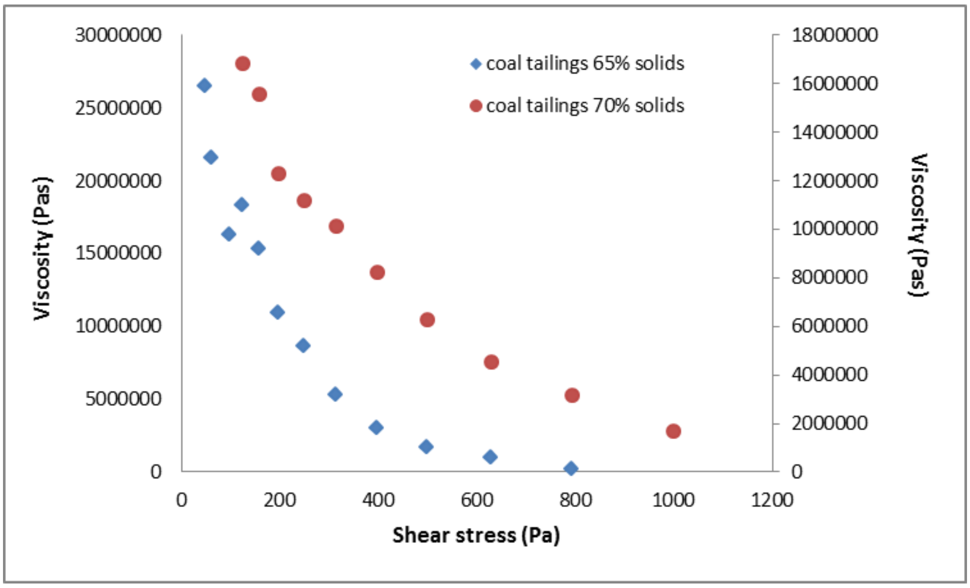

Fig.5c. Viscosity as a function of 65% and 70%-mass solids and shear stress

The rheology analysis also shows that only three options for tailings slurry can be transported by pipe (pumpable): 30%, 50%, and 60% mass solids. The others two options (65% and 70% mass solids) have very high yield stress as seen in Table 6 which means both are difficult to pump. Higher mass solids options which are not pumpable need to be managed with other disposal strategies such as a filter press but these have not been considered in this study.

The yield stress increases exponentially with the solids mass concentration as shown in Fig.7. The yield stress also increased significantly when the solids mass concentration was between 50 and 60%. The detailed rheological characteristics of coal tailings are presented in Table 6. These results demonstrate that the coal tailings yield stress is an important parameter associated with the transport and disposal of tailings. Increasing the value of yield stress generates a higher volume of tailings transported to the TSF and a lower tailings footprint. The yield stress also contributes to the pipeline operations where the high yield stress value reduces the problem associated with pipeline operations as the tailings can be pumped in laminar flow (Nguyen and Boger, 1998). The laminar flow creates less solids deposition problems during transporting. However, high yield stress value is automatically triggered for increasing pumping energy (see sections 5.2 and 5.3) as well as capital and operating costs.

5.2 Estimation of linear pumping energy

The energy estimation which includes pressure drop and pumping power consumption can be calculated from the basic flow property data such as those found in Fig.5-7 and Table 6. The results for the pumping energy estimation are presented in Table 7 and Fig.8 by using the rheological characteristics data and equations as shown in section 4.2.3.

The three tailings slurry options presented in Table 7 show that the highest energy requirement occurred when the tailings mass solids changed from 30% to 50% as seen in Fig 8. Increasing the mass solids from 50% to 60% led to an increase in energy used by 35 watts (14% higher). An increase in the amount of energy used is closely correlated with a dramatic increase in yield stress value (see Table 6) for all three mass solids slurry concentrations.

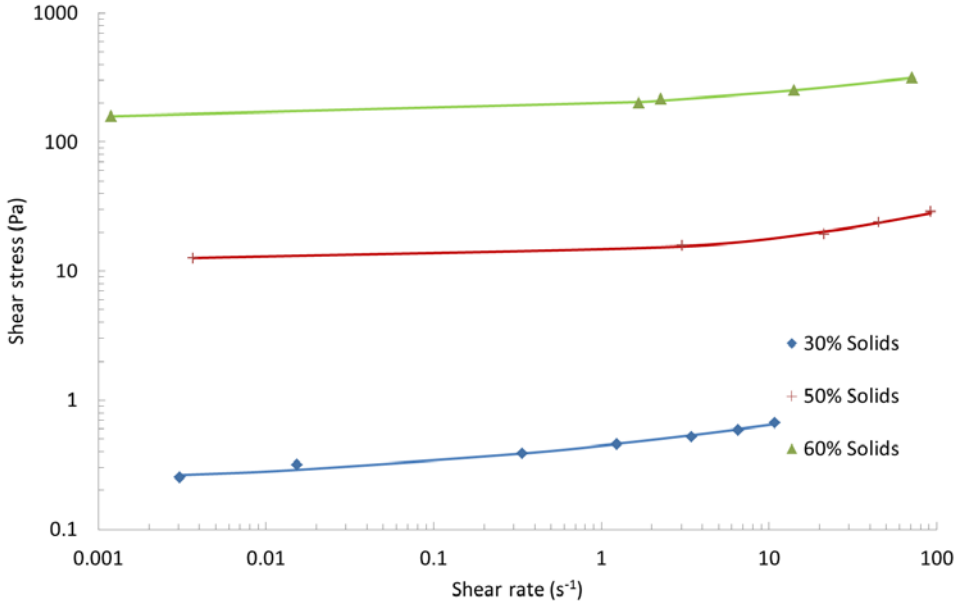

Fig.6. Shear stress as a function of mass solids and shear rate

Table 6

Rheological characteristics of the tailings

Mass solids (%)	Rheological equation	R^2	Yield stress (τ_o)	Flow behaviour indexes (n)
30	$\tau = 0.21 + 0.233 \text{ x } (\dot{\gamma})^{0.266}$	0.99	0.21	0.266
50	$\tau = 12.46 + 1.826 \text{ x } (\dot{\gamma})^{0.476}$	0.99	12.46	0.476
60	$\tau = 152.69 + 44.338 \text{ x } (\dot{\gamma})^{0.302}$	0.99	152.69	0.302
65	-	-	> 1,178[2]	-
70	-	-	> 2,700[2]	-

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[2] The yield stress (Pa) is too large – not pumpable.

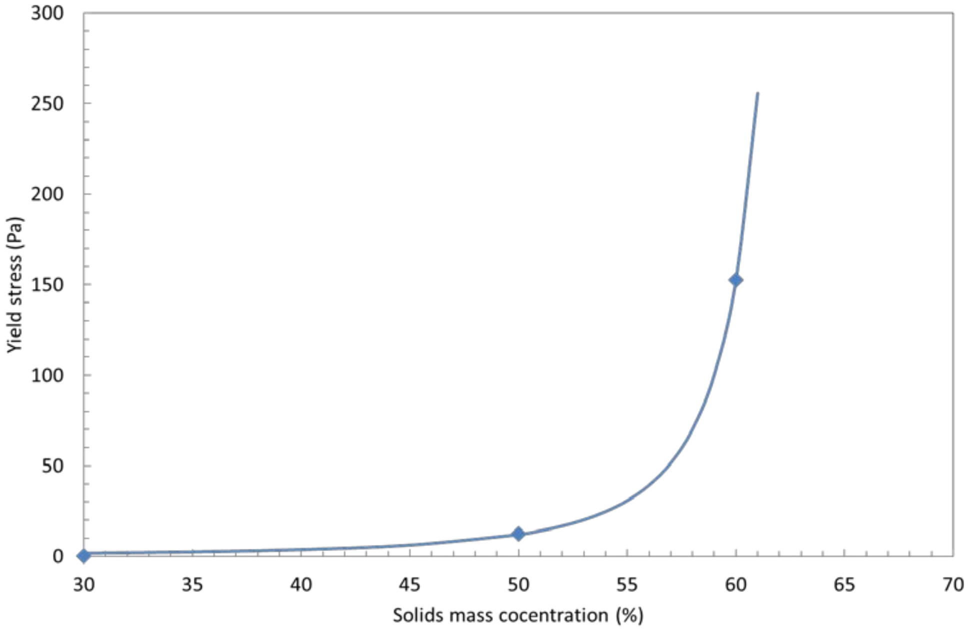

Fig.7. Yield stress versus solids mass concentration (w/w)

Table 7

Linear pumping energy - estimation

Mass solids (%)	Flow (m^3/s)	coefficients			ΔP (Pa)	Energy (watt/m)
		a	b	c		
30	0.009	0.653	0.235	0.073	4.129	0.039
50	0.016	0.512	0.330	0.157	151.633	2.370
60	0.019	0.623	0.289	0.087	1,996.401	37.445

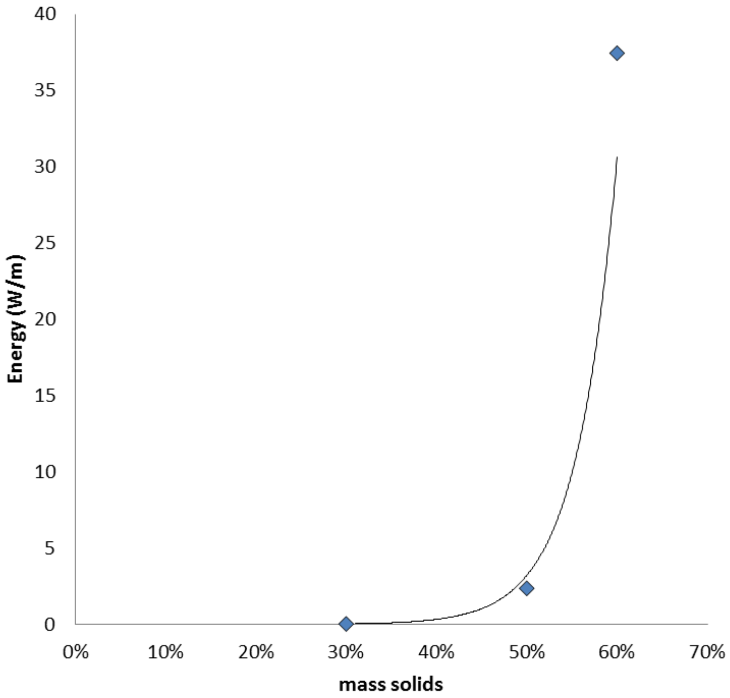

Fig.8. Linear energy pumping estimation of coal tailings

5.3 Discussion on the water and energy nexus in coal tailings management

Water and energy are two key inputs in mining operations. The increasing demand for water and energy use has a direct impact on mining companies' sustainability performance and production costs. Therefore, it is important to consider the correlation between these two major inputs during process planning, particularly regarding mine tailings management given its high demand for both inputs.

As described in section 4.2.3, the HSM can be used as a tool to identify the relationship between water and energy use. The procedure for calculating water distribution energy requirements is as follows: (i) the length of each 'pipe' is calculated using the geographic coordinates associated with each object which is then multiplied by a tortuosity coefficient, representing the bends, curves etc. within each pipe; (ii) the difference in elevation between the beginning and end of each pipe is calculated; (iii) the head loss (energy loss due to friction) in each pipe is calculated using the current flow rate and the hydraulic roughness of the pipe; and (iv) the energy requirement for each virtual pump is then calculated based on the current flow rate, the virtual pump efficiency, and the differential head (the sum of the elevation difference and the head loss within the pipe) between the beginning and end of each pipe. A detailed analysis on how the HSM works including formula, and concept can be found in Woodley et al. (2014).

The rheology results were used as one of the main inputs to the HSM in generating the water and energy correlation as presented in Table 8-9 and Fig.9-10. In Fig.4, a schematic diagram shows mining operations where water used in the processing task has three sources: the excess water from raw material moisture content, worked water storage, and raw water storage. More than 70% of processing plant (CHPP) water consumption is supplied from the worked water store as shown in Table 8. The worked water store receives the water from a runoff inlet, the raw water store, excess water, and the tailings decant water as described in Fig.4.

As presented in Table 8, the lowest total water volume consumed by CHPP is for tailings management Option 1 (tailings slurry) with 69,428 ML water/year and the total volume difference with Option 2 and 3 is approximately 11,513 ML/year (16%) and 15,268 ML/year (22%) respectively. In addition, the volume of excess water pumped to worked water storage increases by more than 50% in Option 2 (50% mass solids) and Option 3 (60% mass solids).

Table 8

Processing water balance (ML/y)

Processing Task/ % solids		INLET				OUTLET				
		ROM	Worked water store	Raw water store	Total	Excess water	Product	Coarse water	Tailings water	Total
Opt-1	30%	8,882	51,654	8,892	69,428	38,933	11,547	296	18,652	69,482
Opt-2	50%	10,355	62,472	8,114	80,941	51,602	13,461	345	15,532	80,941
Opt-3	60%	10,835	65,610	8,250	84,696	57,247	14,086	361	13,002	84,696

As expected, the consumption of water needed for transporting tailings to the TSF decreased with increased tailings mass solids. As seen in Fig.9, around 18,652 ML water/year is required for transporting tailings with 30% mass solids (Option 1) and the water demand declines around 30% when using Option 3 at 60% mass solids.

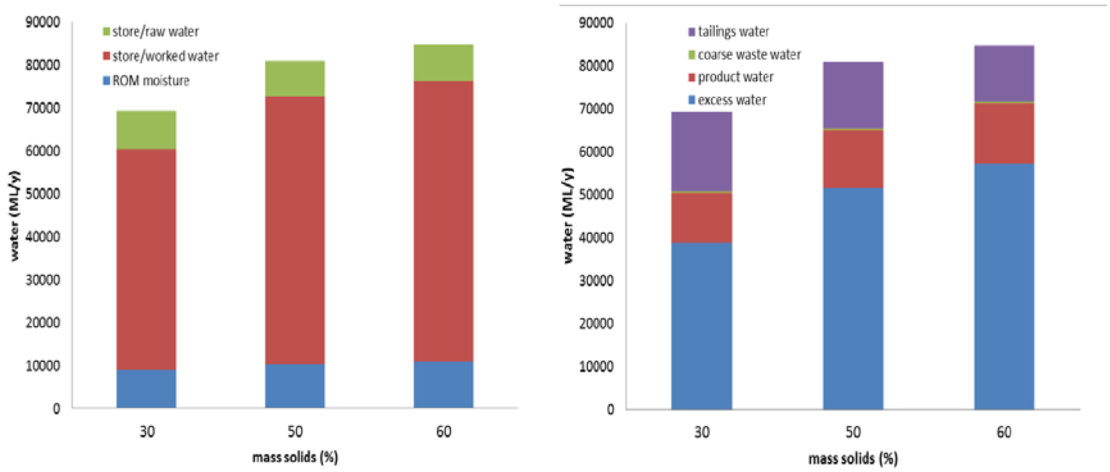

Fig.9. Water inlet and outlet in processing task

Overall, the decrease in water used in transferring tailings to the TSF lowers the volume of decanting water generated from the TSF as presented in Fig.10. Tailings disposal Option 3 generates decant water 33% lower than slurry tailings disposal option. This means that tailings water transporting to the TSF can be reduced by around 30% with the application of Option 3. Decreasing the water load to the TSF should also increase the capacity and extend the lifespan of the facility.

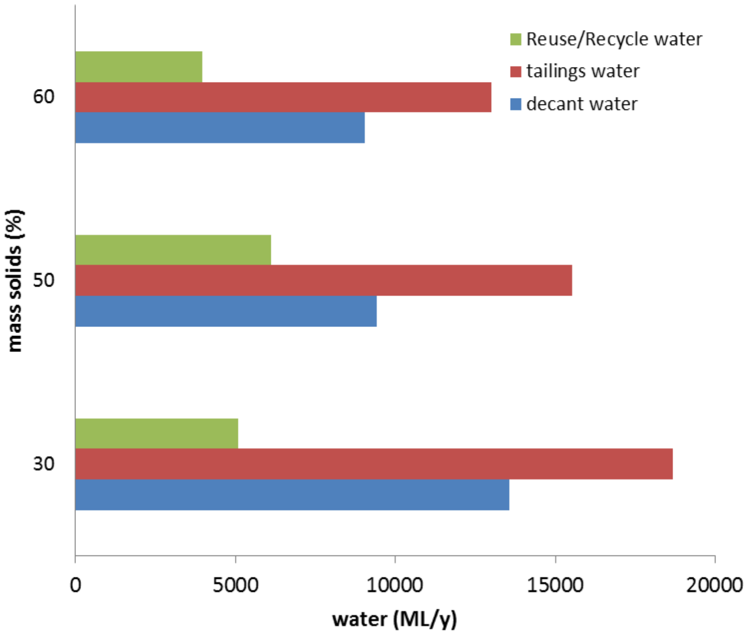

Fig.10. Water balance in TSF

The water distribution to and from the processing task in the case study used two methods: a gravity fed and pumping system. The pumping system is used to transport store worked water (SWW) to the CHPP, store raw water (SRW) to the CHPP, excess water to the SWW, and tailings from the CHPP to the TSF. The total energy required to transport water and tailings is presented in Table 9.

The energy required in pumping water from the store worked water to the CHPP is in the range of 40 to 51 TJ/year with the average difference in energy usage of each option being approximately 17%. The highest difference in energy usage occurs when coal tailings are pumped to the TSF as shown in Table 9. The energy pumping used in Option 2 to transport tailings into the

TSF is 53 times higher than Option 1 and 881 times higher if tailings disposal Option 3 is selected.

Table 9

Energy required for processing task (TJ/y)

Flow	Energy (TJ/y)		
	Opt-1 (30% solids)	Opt-2 (50% solids)	Opt-3 (60% solids)
Store worked water to Process	40.303	48.745	51.194
Store raw water to Process	4.610	4.207	4.277
Excess water to store worked water	12.459	16.514	18.320
Tailings transport to TSF	0.639	34.759	563.749

Therefore, the energy consumption for tailings transport from the CHPP to the TSF is strongly dependent on the mass percent solids as shown in Fig.11. The energy usage increases dramatically when the mass percent solids change from 50% to 60%. This result also corresponds well with the theoretical estimation from a rheology perspective (see section 5.2).

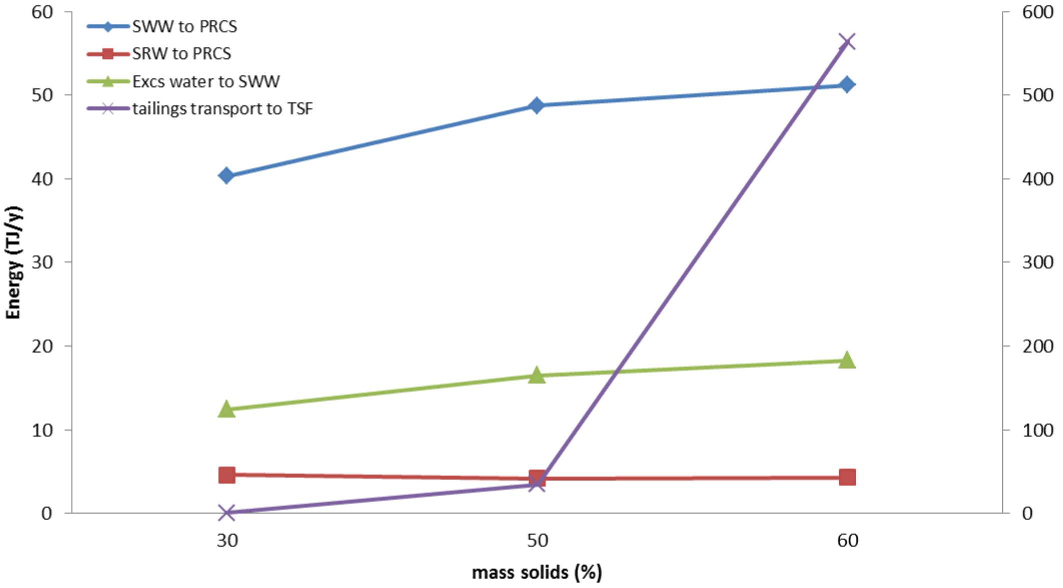

Fig.11. Energy consumption for processing task

Table 10

Tailings transportation option summary

Options	Water	Decant water	Energy	Water/Energy Ratio	Reuse Water Ratio
	(ML/y)	(ML/y)	(TJ/y)	(ML/TJ)	(%)
Tailings disposal-Option 1 (30% solids)	18,652	13,552	0.639	29,189	38
Tailings disposal-Option 2 (50% solids)	15,532	9,409	34.759	447	65
Tailings disposal-Option 3 (60% solids)	13,002	9,040	563.749	23	44

The results from all three tailings disposal options are summarized in Table 10. The base case option (tailings slurry) transports water from the CHPP to the TSF at approximately 18,652 ML/y with 0.6 TJ energy use per year. Option 1 also generated a ratio between water consumption for tailings distribution and the volume of decant water at 38%. Increasing mass solids to 50% in Option 2 resulted in the lowering of water use to 15,532 ML/y whilst consuming 34.7 TJ/y of energy. In addition, Option 2 also reduces the water that is managed in the TSF by 30% and this can be seen from the high water reuse ratio. The reuse water ratio resulting from choosing Option 2 is 65% and the highest ratio compared with other options. Option 3 with 60% mass solids achieved a water savings of 3,119 ML/y compared to the base case option with approximately 563 TJ/y energy required which is the highest of all three tailings management options examined.

6. Conclusions

This paper discusses the synergy and trade-offs between water and energy use in coal mine tailings management. Three of five mass percent solids options, which are pumpable tailings, were analysed further by using HSM to determine the optimum method for transporting tailings to the TSF. The results of this analysis highlight the importance of tailings disposal strategies in mine water management and the significance of the correlation between water and energy use. From the results presented, it can be concluded, firstly, the optimum option in terms of water and energy conservation, and water management is Option 2 for the tailings with 50% mass solids for this particular coal mine site. Secondly, coal mine tailings with a mass percent solid above 65% cannot be transported by pipeline. Thirdly, the water and energy nexus is not only associated with the pumping system but also with the technology used in processing. The outcome of this study is to provide guidelines for water and energy usage to assist in the decision making of tailings management strategies for coal mining. A good strategy is essential for improving sustainability performance of mine tailings disposal throughout the life of a mine.

Further study is required to assess the contribution of various other technologies in tailings management in terms of their energy and water consumption. Additional assessment of pumping and processing technology systems will provide a more complete estimation of energy and water usage in a particular tailings disposal strategy. Environmental and economic perspectives should also be considered in the assessment. These two considerations would complement this study to generate a more comprehensive framework for decision makers in choosing the appropriate tailings disposal strategies for a particular mine site. Examining the trade-off between water and energy use in tailings management is a good start in improving both the efficiency and sustainability performance of mine tailings management.

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Alternative tailings disposals: are they improving mine tailings management performance?

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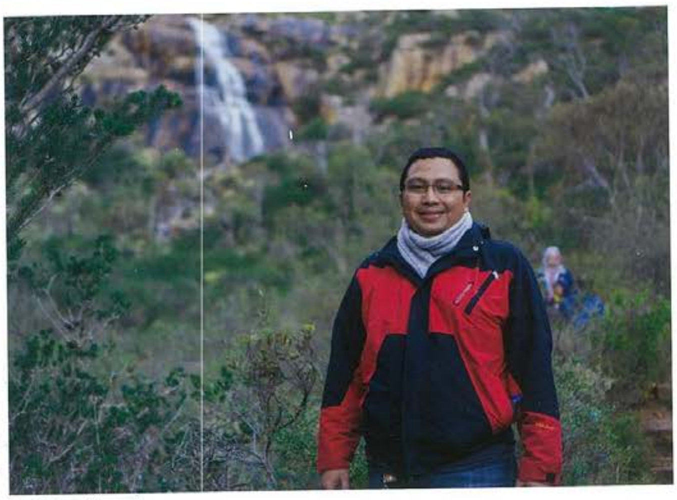
The mining industry has two sides to it: on one hand, it provides multiple benefits, but on the other, it also creates some problems. These two sides should be managed to improve mine sustainability. Besides the production and safety components, environmental performance is also an important factor in determining a mine's sustainability level. These factors could be an entry point to get the social licence to operate.

Waste, including tailings, is a key environmental issue that must be managed by mining companies. Tailings are a by-product of mineral processing, and are managed through either direct or indirect disposal methods. Globally, only 0.6 per cent of mines apply direct tailings disposal methods, including riverine tailings disposal and submarine tailings disposal, while the remainder apply indirect methods.

Mine tailings management

The global mining industry produced around 14 billion tonnes of tailings in 2010[1]. The different characteristics of tailings depend on the type of minerals mined; however, tailings commonly consist of heavy metals. When there is a large volume of tailings, this heavy metals content could cause irreversible environmental impacts. From 1917 to 2009, there were 237 environmental accident cases associated with tailings – 17 of these cases occurred in the 2000s. One important example was the failure of a gold mining tailings storage facility (TSF) in Baia Mare, Romania, in 2000. This accident resulted in the contamination of water supplies, affecting more than two million people. Poor tailings management – including poor water control, dam construction and high rain intensity – was the main trigger of such accidents.



Joni Safaat Adiansyah

Water plays a critical role in minimising tailings accidents, as it is one of the key parameters for tailings dam stability. In platinum and copper mines, approximately 186 cubic metres per hour (for platinum) and 4783 cubic metres per hour (for copper) of water is required to transport tailings with 50 per cent[2] and 30 per cent[3] mass solids respectively into the TSF. Therefore, the TSF is the largest water sink at most

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[1] Jones, H., Boger, D.V., 2012, *Sustainability and waste management in the resource industries*

[2] Moolman, P.L., Vietti, A., 2012, *Tailings disposal: an approach to optimize water and energy efficiency*

[3] Gunson, A.J., Klein, B., Veiga, M., Dunbar, S., 2012, *Reducing mine water requirement*

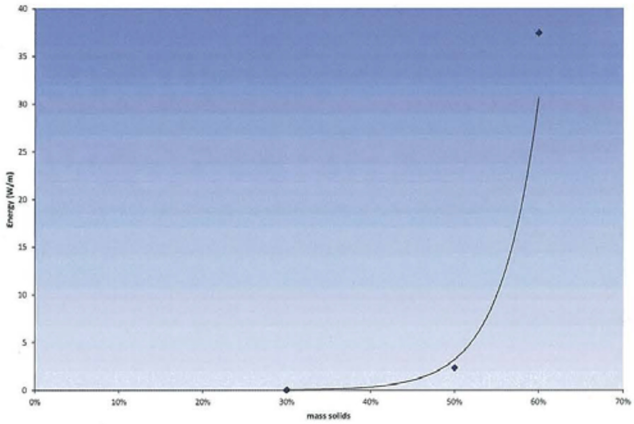

Figure 1. Linear energy pumping estimation of coal tailings[4]

mine sites. Reclaiming water from the TSF is a common strategy used at mine sites to reduce tailings dam risks, and this strategy also increases the water conservation during mine operations.

Water and energy nexus

Water and energy are the two main sustainability indicators associated with tailings management, and they are also considered key inputs in general mining operations. Water and energy, therefore, directly affect mine sustainability performance and production costs. Considering the correlation between these two inputs during the planning stage will increase the benefits for mining companies.

In terms of tailings management, water and energy use is greatly influenced by the mass per cent solids in tailings slurry. The mass per cent solids also contribute to the behaviour of tailings during the transportation process. This behaviour can be observed from a tailings rheology test. An example of water and energy consumption in coal tailings transport is presented in Figure 1, where three mass per cent solids scenarios were tested: 30 per cent, 50 per cent and 60 per cent. The energy requirement increases by 35 weight or measurement, or by a multiple of 15 when mass solids are increased from 50 per cent to 60 per cent. An increase in the amount of energy used is closely related to a dramatic increase in yield stress value, which is the minimum shear required for flow to occur.

This example demonstrates the importance of water and solids content, energy and yield stress during tailings distribution. Proper management of these components can reduce the problems during tailings flow from the processing plant to the disposal area.

Alternative tailings disposal as a solution

Currently, more than 80 per cent of mines worldwide apply a conventional tailings disposal method, where the tailings per cent solids range between 20 per cent and 30 per cent. Employing such conventional tailings requires the mine site to supply more water to the processing plant. This increases the water volume discharged to the TSF and leverages the risk of tailings dam accidents, such as water overtopping and dam failures. To combat this risk, strategies that increase the mass per cent solids in tailings slurry can be employed. These strategies include thickened tailings, tailings paste and filtered/dry stacking tailings (Table 1).

The use of these methods reduces water use in tailings slurries by up to 80 per cent, but the cost of energy consumption increases. Mine sites should consider both the cost and the environmental impacts prior to using an alternative tailings disposal (ATD) method as its primary tailings management method. For mines located in arid or semi-arid climates, the ATD could contribute to increasing the level of water conservation. The trade-off between the cost and benefit of applying these methods should be estimated up to the life of mine, and the results compared with conventional tailings methods.

In summary, determining an appropriate mine tailings disposal method requires mining companies to consider multiple factors, including water and energy consumption, operational and capital costs, production rate and tailings flow behaviour. If these factors are incorporated and considered appropriately, a mine site can identify tailings methods by which it can improve the sustainability of its operations.

Mine site	Location	Type of mine	Disposal strategy
Sunrise Dam: gold	Australia	Surface	Thickened
Kidd Creek: copper-zinc	Canada	Surface	Thickened
Alcoa World: alumina	Australia	Surface	Dry stacking
Esperanza: copper-gold	Chile	Surface	Thickened
Boliden Garpenberg: lead-zinc	Sweden	Underground	Paste backfill

Table 1. Some applications of alternative tailings disposal worldwide

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[4] Adiansyah, J.S., Rosano, M., Vink, S., Keir, G., Stokes, J.R., 2016, *Synergising water and energy requirements to improve sustainability performance in mine tailings management*

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Research article

Application of a life cycle assessment to compare environmental performance in coal mine tailings management

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ABSTRACT

This study compares coal mine tailings management strategies using life cycle assessment (LCA) and land-use area metrics methods. Hybrid methods (the Australian indicator set and the ReCiPe method) were used to assess the environmental impacts of tailings management strategies. Several strategies were considered: belt filter press (OPT 1), tailings paste (OPT 2), thickened tailings (OPT 3), and variations of OPT 1 using combinations of technology improvement and renewable energy sources (OPT 1A–D). Electrical energy was found to contribute more than 90% of the environmental impacts. The magnitude of land-use impacts associated with OPT 3 (thickened tailings) were 2.3 and 1.55 times higher than OPT 1 (tailings cake) and OPT 2 (tailings paste) respectively, while OPT 1B (tailings belt filter press with technology improvement and solar energy) and 1D (tailings belt press filter with technology improvement and wind energy) had the lowest ratio of environmental impact to land-use. Further analysis of an economic cost model and reuse opportunities is required to aid decision making on sustainable tailings management and industrial symbiosis.

1. Introduction

Coal is utilized in many countries worldwide as a fossil fuel. Globally, the utilization of coal is 3.4 and 3.8 times higher than use of oil and natural gas, respectively (Osborne and Gupta, 2013). In total, coal supplied 29% of the world's primary energy in 2013 (Thomas, 2013). As illustrated in Table 1, the significant contribution of coal is at least in part due to its widespread geological distribution and to the large reserves, estimated to be around 860 billion tonnes.

These numbers indicate that coal-based industries have an important contribution to make to a country's development, not only in developed but also in developing countries. In Australia, for example, more than 64% of electricity generated comes from coal, 21.3% from natural gas, 7.2% from hydropower, and 4.4% from windpower (World Nuclear Association, 2013). In another example, Indonesia, a developing country, aims to generate 35,000 MW of electricity over the next five years, with coal-fired power plants contributing 55% of the total power generated (Perusahaan Listrik Negara, 2015). The demand for coal, currently led by the BRIC (Brazil, Russia, India, and China) economies, is predicted by Osborne and Gupta (2013) predicted to increase more than 50% between 2013 and 2030. Coal processing is needed to produce saleable coal to meet market demand, as run-of-mine (ROM) contains both coal and gangue mineral impurities. These processes, which include comminution, classification, concentration, and dewatering, take place in a coal handling and preparation plant (CHPP). An inevitable outcome of this processing is the production of tailings.

Coal tailings, also referred to as fine coal rejects, are produced from fine coal processing. The classification of fine coal is based on particle size in the range 0.15 mm–1.0 mm. Fine coal processing represents about 10–20% of the CHPP feed (Honaker et al., 2013; Kumar et al., 2014). This fine coal processing generates around 30% reject material, consisting of both coarse rejects and fine rejects (tailings). This means that 0.6–1.2 million tonnes per annum (Mtpa) of tailings are generated by coal mine sites with 20 Mtpa of ROM. Failure to manage tailings effectively can increase mining operation cost and result in severe environmental damage and human health consequences (Adiansyah et al., 2015; Kossoff et al.,

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Application of a life cycle assessment to compare environmental performance in coal mine tailings management

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Abstract

This study compares coal mine tailings management strategies using life cycle assessment (LCA) and land-use area metrics methods. A hybrid method (the Australian indicator set and the ReCiPe method) were used in this study to assess the environmental impacts of tailings management strategies. Several strategies were considered: belt filter press (OPT 1), tailings paste (OPT 2), thickened tailings (OPT 3), and variations of OPT 1 using combinations of technology improvement and renewable energy sources (OPT 1A–D). Electrical energy was found to contribute more than 90% of the environmental impacts. The magnitude of land-use impacts associated with OPT 3 (thickened tailings) were 2.3 and 1.55 times higher than OPT 1 (tailings cake) and OPT 2 (tailings paste), while OPT 1B (tailings belt press with technology improvement and solar energy) and 1D (tailings belt press filter with technology improvement and wind energy) had the lowest ratio of environmental impact to land-use. Further analysis on economic cost model and reuse opportunities is also required to aid decision making on sustainable tailings management and industrial symbiosis.

Keywords: life cycle assessment; thickened tailings; tailings paste; belt filter press; environmental impacts; land use

1. Introduction

Coal is utilized in many countries worldwide as a fossil fuel. Globally, the utilization of coal is 3.4 and 3.8 times higher than use of oil and natural gas,

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respectively (Osborne and Gupta, 2013). In total, it supplied 29% of the world's primary energy in 2013 (Thomas, 2013). As illustrated in Table 1, the significant contribution of coal is, at least in part, due to its widespread geological distribution and to the large quantity of coal reserves worldwide. This is estimated to be around 860 billion tonnes.

Table 1

Distribution of proved coal reserves

Locations	Volume (billion tonnes)	Percentage (%)
Europe/Eurasia	304.4	35.4
Asia Pacific	264.9	30.8
North America	245.1	28.5
Middle East/Africa	32.7	3.8
South America	12.9	1.5

Source: BP Statistical Review of World Energy in Thomas (2013)

These numbers indicate that coal-based industries have an important contribution to make to a country's development, not only in developed but also in developing countries. In Australia, for example, more than 64% of electricity generated comes from coal, 21.3% from natural gas, 7.2% from hydropower, and 4.4% from windpower (World Nuclear Association, 2013). In another example, Indonesia, a developing country, aims to generate 35,000 MW of electricity over the next five years, with coal-fired power plants contributing 55% of the total power generated (Perusahaan Listrik Negara, 2015). The demand for coal, currently led by the BRIC (Brazil, Russia, India, and China) economies, is predicted by Osborne and Gupta (2013) predicted to increase more than 50% between 2013 and 2030. Coal processing is needed to produce saleable coal to meet market demand, as run-of-mine (ROM) contains both coal and gangue mineral impurities. These processes, which include comminution, classification, concentration, and dewatering, take place in a coal handling and preparation plant (CHPP). An inevitable outcome of this processing is the production of tailings.

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Although the application of LCA in mining is not as widespread as in some other fields (e.g. agriculture or food), some mining LCA studies can be found in the literature. The goals of these LCAs vary and include evaluating the environmental impact of two different alternative technologies for the disposal of mineral mine tailings (Fernandez-Iglesias et al., 2013), comparing the environmental impact of belt conveyors and off-higway trucks in surface mining (Erkayaoğlu and Demirel, 2016), identifying the environmental profile of gold production in terms of embodied energy and water, greenhouse gases, and solid waste (Norgate and Haque, 2012), reviewing the LCA methodology used in the mining industry (Awuah-Offei and Adekpedjou, 2010), underground mine development to the post-closure phase (Reid et al., 2009), and estimating land use equivalent factors in mining operations (Spitzley and Tolle, 2004). Results have been presented in the literature covering various minerals including bauxite (Bovea et al., 2007), copper (Memary et al., 2012), iron and ore (Ferreira and Leite, 2015; Haque and Norgate, 2015), nickel (Mistry et al., 2016), and coal (Burchart-Korol et al., 2016; Ditsele and Awuah-Offei, 2012). Recent literature, however, has not considered LCA and land-use impacts of different coal tailings management. This study attempts to fill this gap and discover the novelty of environmental and land-use impacts in coal mine tailings management.

The aim of this study is to compare the environmental performance/impact of different mine tailings management strategies, and to evaluate the magnitude impact of land-use change. To achieve these objectives, three mine tailings strategies and five improvement strategies were selected and applied at a coal mine site located in New South Wales (NSW) Australia. The potential impacts of each of these strategies were analysed using SimaPro with two impact methods: the Australian Indicator and ReCiPe (Simapro manual PRe Consultants, 2008). The analysis of land-use impact was based on the method developed by Spitzley and Tolle (2004) and Milà I Canals et al. (2007).

2. Methodology

2.1 Base case and scenario definition

The case selected is an open pit mine that is projected to extract about 20 million tonnes per annum (Mtpa) of ROM coal and operate for 20 years. Three scenarios were developed in order to compare the potential impacts of different tailings management strategies, as shown in Table 2. These scenarios seek to reduce the volume of water transported in tailings by increasing the percentage of solids. Scenario 3 is the base case scenario, with the highest percentage water content. The use of tailings paste was selected for Scenario 2, with the percentage solids increasing to 50% compared to Scenario 3. Scenario 1 involves tailings cake, with the lowest percentage water content. Scenario 1 was also subject to an additional technology improvement of the flotation system, as shown in Table 2. Two systems were replaced, namely the aeration and sparging technologies that could decrease energy consumption in a flotation tank, as noted in Kohmuench et al. (2010). Altered mechanical dewatering systems were applied to achieve the final water content prior to disposal. The four scenarios are described in section 2.3.1.

Table 2

Coal tailings management strategies for each scenario

Scenario	Segregation	Mechanical dewatering	Tailings transport
1. Tailings with 65% solids 1.A Tailings with 65% solids – flotation technology improvement	Flotation column cells with additional of frother and collector.	#1. Thickener with additional of anionic flocculant; #2. Belt press with additional anionic and cationic flocculants.	Transported by truck to the tailings disposal area.
2. Tailings with 50% solids	Flotation column cells with additional of frother and collector.	#1.Thickener with additional of anionic flocculant; #2. Paste thickener with an additional anionic flocculant.	Pumping to the tailings disposal area.
3. Tailings with 30% solids	Flotation column cells with additional frother and collector.	Thickener with additional of anionic flocculant.	Pumping to the tailings disposal area.

2.2 Goal and scope

The objectives of this study were to develop an inventory of different tailings management scenarios, to assess and compare the environmental impacts of each tailings management scenario, and to determine the associated land-use impacts. In addition, the most sustainable management option for fine coal tailings management was also to be determined. The functional unit (FU) is defined as 1 tonne of fine coal concentrate slurry generated by flotation cells.

2.3 Life cycle inventory (LCI)

A life cycle inventory (LCI) considers the input and output of a product throughout its life cycle (ISO 14044). In this study, the product was fine coal concentrate slurry from flotation cells which also generates tailings as a by-product. This section describes the system boundary and operation of each scenario, the data sources, and some of the main assumptions of this study.

2.3.1 System boundary and description

The LCA system boundary mainly consists of three stages: segregation of fine coal, mechanical dewatering, and tailings transportation. Fig.1 shows the life cycle stages, with each of the three scenarios consisting of several processes including segregation of coal from its impurities, chemical mixing, water and tailings pumping, and electricity usage.

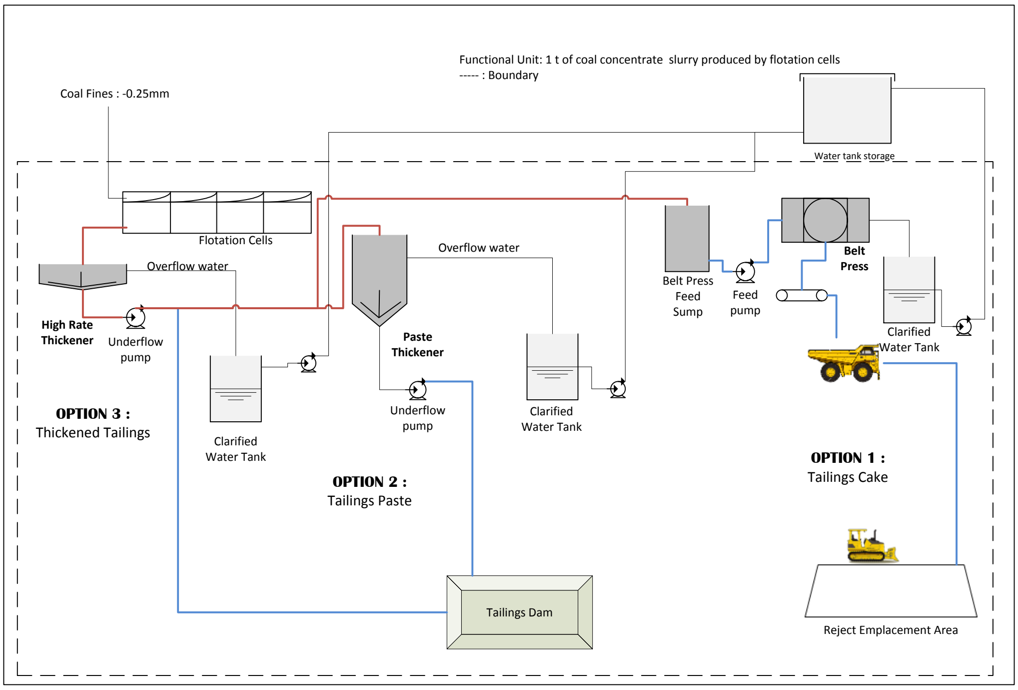

Fig.1. Flow diagram of coal mine tailings strategies

Flotation cells are fed with raw coal slurry originating from the de-sliming process in the CHPP, where raw coal particles smaller than 0.1 mm are separated. Two types of chemicals are utilized to separate coal from its impurities: methyl isobutyl carbinol (MIBC) as a frother and diesel oil as a collector. The segregation process generates two products, namely coal concentrate slurry and tailings slurry. This study is focused on comparison of three options for management of the tailings slurry generated by flotation cells. The different handling methods of coal tailings are applied when flotation cells generate tailings with 20% solids or more.

Option one: tailings cake using belt press filters

The first two steps of this option (i.e. flotation and thickening) are also used in options two and three. The thickener underflow 30% solids are pumped into a belt press feed sump and distributed to the belt press filter machine as shown in Fig.2.

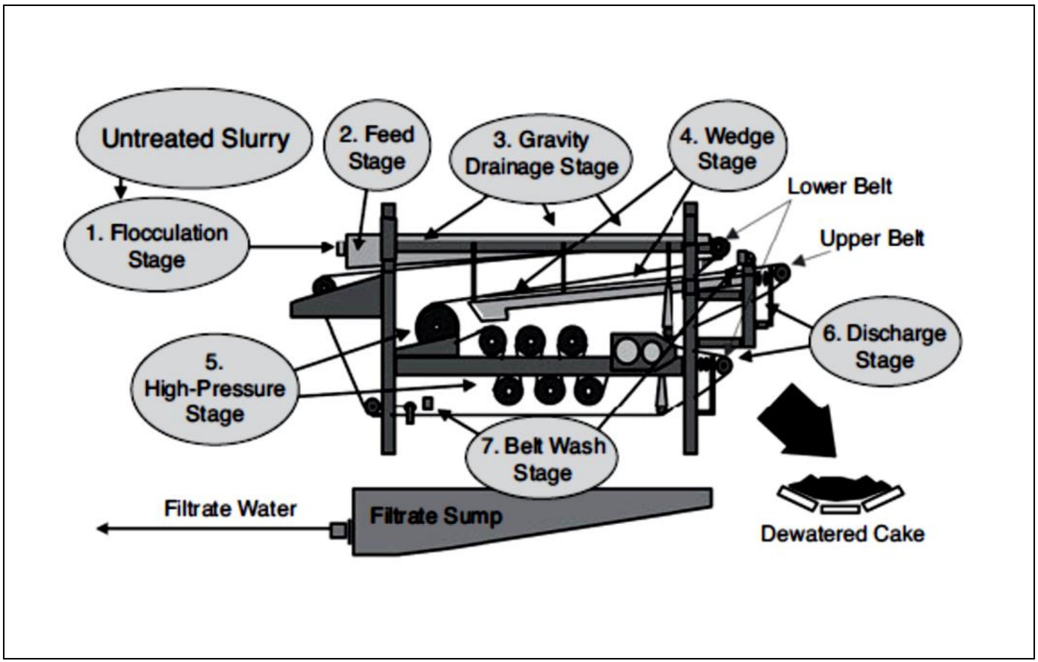

Fig.2. Belt press filter operations (Fenzel, 2012)

During the flocculation stage, the fine coal tailings must be flocculated using two types of polymer: an anionic flocculant and a cationic coagulant. The free water in the flocculated slurry is drained by gravity through the drainage (lower) belt, leaving a mat of solids. Pressure is first applied in the wedge stage, squeezing the remaining water out of the tailings. Further dewatering occurs during the high-pressure stage when the tailings solids are compressed and sheared between belts and rollers. Tailings with 65% solids are discharged from the belt press filter and are transferred by conveyor to a transfer point, from where trucks transport the tailings cake to a disposal area (reject emplacement).

Option two: tailings paste using paste thickener

The tailings from flotation cells flow by gravity to a tailings thickener and anionic flocculant is added to the tailings thickener to assist in the settling and aggregation of tailings. Underflow tailings from the thickener with 30% solids are pumped into a paste thickener, as an extension of the normal thickening process. An anionic flocculant is added to the paste thickener to bind the fine particles together. Flocculated particles with 50% solids settled at the bottom of the paste thickener are then pumped and transported by pipeline into the tailings disposal area. The overflow water from the thickener and paste thickener flows to a clarified water tank by gravity.

Option three: thickened tailings using thickeners

The tailings from flotation cells flow by gravity to a tailings thickener and anionic flocculant is added to the tailings thickener to assist in settling and aggregation. Underflow tailings with 30% solids from the thickener are pumped and transported by pipeline into the tailings dam. The overflow water from the thickener flows to the clarified water tank by gravity.

2.3.2 Data collection and main assumptions

LCI modelling was performed using Simapro 8.0 software. Necessary materials, energy, chemicals, and equipment were identified for each of the three tailings management options. Site-specific data were obtained from a publicly available consultant report (QCC Resources Pty Ltd: 'dewatering option report'). To complete the LCI, laboratory results and information from the literature were used as supporting data. Assumptions made during the inventory analysis elaboration stage are as follows:

- The water used in the three options are from a close-cycle water system, with the reclaimed water generated from each tailings management process returned to the plant and reused.
- There are two types of disposal areas used for final tailings disposal: a tailings dam for tailings with 30% and 50% solids, and reject emplacement area for tailings with 65% solids.
- The energy consumption for underflow pumping was obtained from rheology laboratory results generated in previous research by Adiansyah et al. (2016).

- Other data related to equipment maintenance, labour, revegetation, and tailings disposal site monitoring and inspections were excluded from the study due to lack of data availability.

2.4 Life cycle impact assessment (LCIA)

As shown in Fig.3, life cycle impact assessment (LCIA) is the third stage of LCA, after the goal and scope definition, and life cycle inventory (LCI) development. At this stage, potential impacts are assessed based on defined impact categories (goal and scope definition) and the environmental flows identified (inventory analysis).

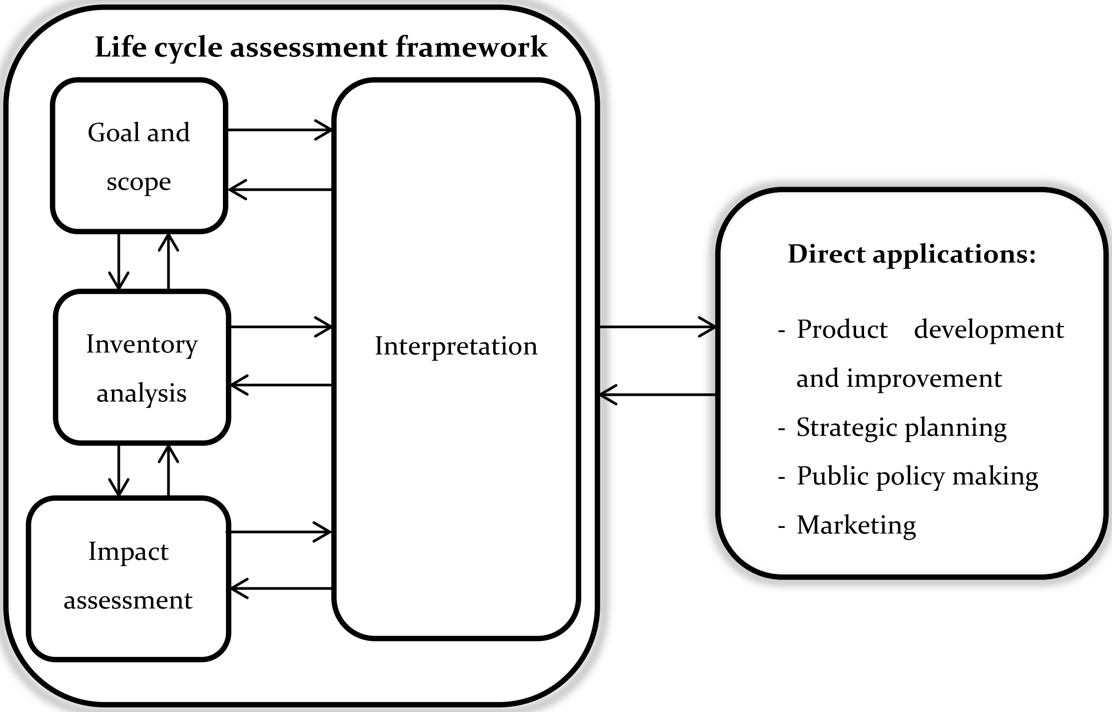

Fig.3. Life cycle assessment framework (International Organization for Standardisation, 2006)

2.4.1 Potential environmental impacts

The method employed to analyse the potential environmental impacts of each scenario was the Australian indicator set methods version 2.01. This method is composed of 12 impact categories (midpoint): global warming (GW), eutrophication (EU), land-use (LU), water use (WU), solid waste (SW), fossil fuels (FF), minerals (MN), human toxicity (HT_C and $_{NC}$) (carcinogenetic and non-carcinogenetic), aquatic ecotoxicity (AE_{FW} and $_{MA}$) (freshwater and marine aquatic). However, only seven impact categories are typically considered to be associated with mining activities: global warming (GW), human toxicity, freshwater aquatic ecotoxicity, eutrophication, land use, water use, and energy use (Awuah-Offei and Adekpedjou, 2010; Mistry et al., 2016; Santero and Hendry, 2016). In addition, this method only considers one factor (global warming) in its weighting calculation and the single score generated from this method refers to the number (tonnes) of carbon dioxide equivalent ($tCO_{2\text{-eq}}$) released. As one of the steps required in LCIA, the weighting factor has an important role as a variable to integrate various environmental impacts and to contribute in environmental impact interpretation (Itsubo et al., 2015). This is an obvious limitation of the Australian indicator set methods.

In order to address this limitation, the authors opted to use the ReCiPe method as well to calculate the environmental endpoints. This method was developed by a number of institutions including RIVM and Radbound University, Institute of Environmental Sciences (CML) at Leiden University, and PRe Consultants. Three types of endpoint categories are included, as shown in Table 3: damage to human health (HH), damage to ecosystem diversity (ED), and damage to resource availability (RA).

Table 3

Endpoint categories of ReCipe Method

Impact category name	abbr.	Indicator name	Unit
damage to human health	HH	disability-adjusted life years	DALY
damage to ecosystem diversity	ED	loss of species during a year	species.yr
damage to resources availability	RA	increased cost	$

Adapted from (Goedkoop et al., 2013)

2.4.2 Land-use impacts

Two land-use elementary flows are land occupation and land transformation, with the differences between the two associated with the land occupation type and period (Koellner et al., 2013; Milà I Canals et al., 2007). Koellner et al. (2013) defined the terms as follows: land transformation aims to modify the current land use to align with an intended use, such as mine revegetation to help establish grazing areas, whilst land occupation is utilized for production purposes and requires ongoing maintenance such as land use during mining operations.

Currently, there are challenges related to land use modelling using biodiversity indicators. Souza et al. (2015) noted several limitations including the absence of functional and population effects and the oversimplification of the real dynamics and complexity of species interactions. On this basis, the authors decided to use the surface area occupation method to evaluate land-use impacts. Here, land occupation impact (LOI) is the function of three variables: Area (A), Time (t), and Quality (Q) (Lindeijer, 2000) as presented in Equation (1).

$$\text{LOI} = \text{Area } (A) \text{ x Time } (t) \text{ x Quality } (Q) \tag{1}$$

The use of land to support mining operations results in a number of environmental impacts. These impacts are mainly caused by functional changes in the land prior to and during mine operations. Mining companies are required to revegetate, in order to restore the land function to its original condition. In this study, the authors assumed that the pre-mining and post-mining land quality would be similar (Q=1). However, this assumption does not apply when permanent degradation has occurred.

3. Results and discussion

3.1 Inventory analysis

Four mine tailings disposal scenarios were assessed in terms of material and energy inputs as shown in Table 4. The paste tailings strategy generated the highest energy consumption, mainly from two sources: column flotation contributed 85% and the paste thickener contributed 12.9% of total energy use. The energy consumed by the paste thickener to produce 50% mass solids was 4.1 KWh/t, while use of the belt-press to increase the solids content in tailings to 65% required around 1.9 KWh/t (QCC, 2013).

Table 4

Material input for different tailings management options

Material	Unit	Dewatering options			
		Tailings cake (belt press)	Tailings cake (belt press with upgrade technology)	Paste tailings (paste thickener)	Thickened tailings (thickener)
Total Energy	kWh	918.3	509	1,016.6	887.2
Column flotation		864.5	455.3	864.5	864.5
Thickener		20.75	20.75	20.75	20.75
Underflow pump		0.2	0.2	0.2	1.9
Belt press		32.9	32.9	-	-

Paste thickener		-	-	131.2	-
Chemical	kg	16.1	16.1	8.3	5.8
Machine: Truck and Dozer	lt	49.3	49.3	-	-
Land use	ha.m	0.00155	0.00155	0.00249	0.00352

The different levels of energy consumption associated with each scenario were mainly due to the differences in energy use by the installed dewatering technology. For example, the belt press used to produce tailings with higher mass percent solids than the paste thickener required 9.7% less energy and generated 18.7% fewer tailings by weight. This means that using the belt press provided two advantages (lower energy use and higher tailings solids production) over use of the paste thickener. In addition, producing higher tailings solids also means less land required for tailings disposal, as shown in Table 4.

The introduction of new technology into the base case scenario could reduce energy use. Technological improvement during aeration and sparging in option 1A (belt press with upgraded technology) resulted in a decrease in energy consumption by more than 45% of the total energy usage. As a result, option 1A had the lowest energy use compared to other scenarios. However, this scenario then had the highest level of chemical input including MIBC, anionic and cationic flocculant used in the flotation and belt press system.

The combinations of these data were assessed by life cycle impact assessment to estimate their contribution to environmental impacts, as presented in Section 3.2 and 3.3. Detailed inventory data (input materials, energy and machines) for all scenarios are presented in the supplementary information.

3.2 Impact evaluation analysis

Data presented in Section 3.1 shows that energy has been identified as one of the main contributors to the environmental impacts associated with tailings management. The energy source plays an important role in determining the magnitude of the environmental impact. In this case study, a coal-fired power plant was the main energy source used by the mine site. As clearly shown in Table 5, the environmental impact hotspots indicate that the electricity generated by the coal-fired power plant contributed more than 90% of the total environmental impact.

Table 5

Environmental impact hotspots

Environmental Impact	Hotspots		
	OPT1: Belt Press	OPT2: Paste Thickener	OPT3: Thickener
Global Warming (GW)	Electricity, black coal, 96.4%	Electricity, black coal, 98.4%	Electricity, black coal, 98.6%
Eutrophication (EUT)	Electricity, black coal, 92.5%	Electricity, black coal, 96.6%	Electricity, black coal, 97%
Land use (LU)	Electricity, 98%	Electricity, 99.5%	Electricity, 99.8%
Solid waste (SW)	Electricity, black coal, generate fly ash, 1.10 m^3	Electricity, black coal, generate fly ash, 1.45 m^3	Electricity, black coal, generate fly ash, 1.14 m^3
Cumulative Energy Demand (CED)	Black coal mine operations, 91.1%	Black coal mine operations, 94.2%	Black coal mine operations, 94%
Human toxicity- non cariogenic (HT)	Electricity, black coal, 97.5%	Electricity, black coal, 99.2%	Electricity, black coal, 99.4%
Human toxicity- cariogenic (HT)	Electricity, black coal, 96.3%	Electricity, black coal, 98.9%	Electricity, black coal, 99.3%
Freshwater aquatic-ecotoxicity (FWAE)	Electricity, black coal, 66.5%	Electricity, black coal, 89.4%	Electricity, black coal, 93.8%

Improvement strategies were introduced to reduce the environmental impact (hotspots percentage), as follows: 1) Technology improvement in column flotation by replacing the aeration supply system and sparging method. The aeration supply uses a blower instead of a compressor, and the agitator method is used to replace the recycle pump system; 2) Introducing renewable energy to change the current mine site energy mix. Two types of renewable energy (solar and wind) were considered in this study, with these being the two main sources of renewable electricity generation in New South Wales (NSW) after snowy hydropower (Haylen, 2014; NSW Government, 2015; The Climate Institute, 2011). The use of renewable energy creates variations in tailings management options, as shown in Table 6. The authors focused only on improvement strategies (i.e. Options 1, 1A, 1B, 1C, 1D, and 1E) because these scenarios generate more tailings solids and require less land compared to other options.

Table 6

Scenario improvement options

Tailings management	Types
Option 1	Tailings cake with belt press
Option 1A	Tailings cake belt press with technology improvement
Option 1B	Tailings cake belt press with technology improvement and 100% Solar RE
Option 1C	Tailings cake belt press with technology improvement and 10% Solar RE
Option 1D	Tailings cake belt press with technology improvement and 100% Wind RE
Option 1E	Tailings cake belt press with technology improvement and 10% Wind RE

3.2.1 Comparison of midpoint categories

A total of eight mine tailings management scenarios were assessed during the impact evaluation stage, as shown in Fig.4. For ease of presentation, each scenario was normalized by dividing with the scenario that generates the highest impact in each category. However, this does not mean that the impacts from different categories can be compared against one another because they are not expressed using the same units.

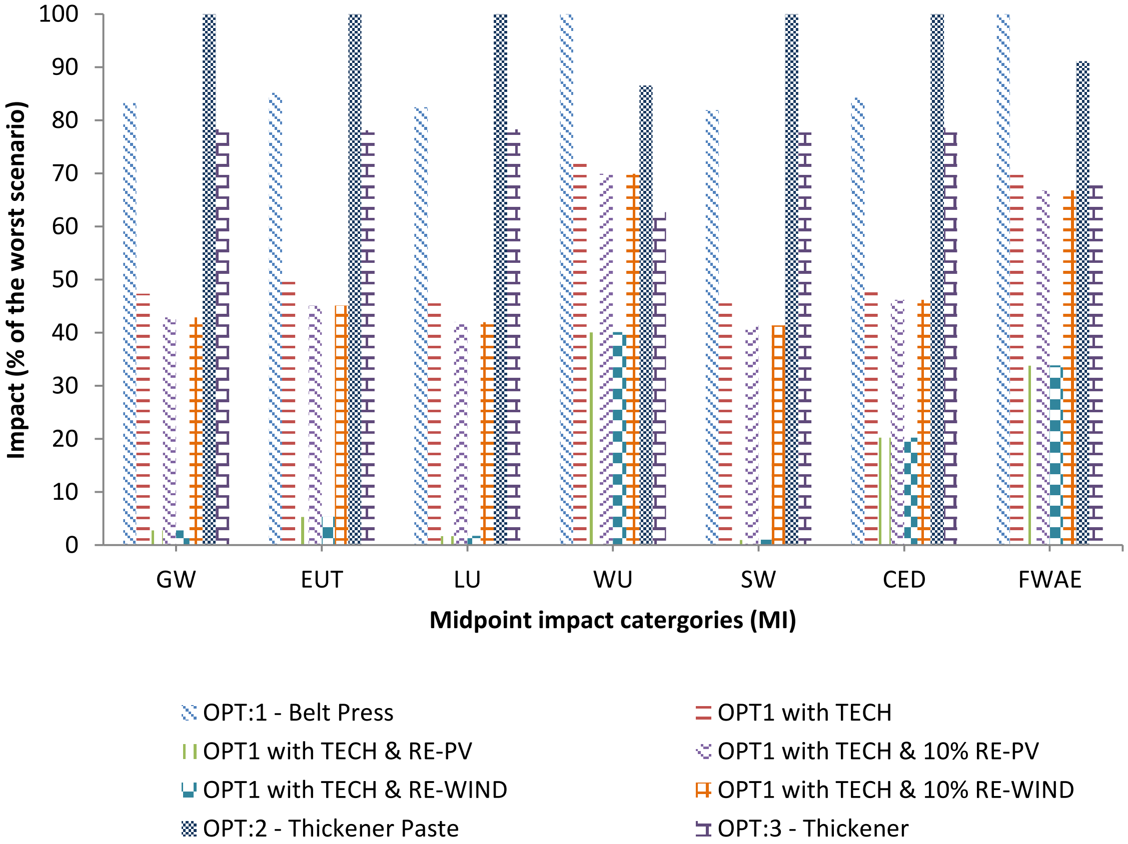

Fig.4. Environmental impacts – midpoint result

The mine tailings management option that generated the highest environmental impact in most of the impact categories was Option 2 – thickener paste. All categories (GW, EUT, LU, SW, CED, and HT) were largely dominated by the operation of the flotation tank and paste thickener which consumed a large amount of energy. The highest water use was Option 1 which required 2.8 m^3 water per tonne solids (QCC, 2013) for belt press operations. The higher water usage of this option resulted in higher results for two impact categories (WU and FWAE) compared to other options. Different conditions were also applied for Option 1 with technology improvement and renewable energy installation. The introduction of technology and renewable energy contributed to reducing the impacts of WU and FWAE because less water was used to generate energy. It was estimated that energy consumption declined by approximately 45% compared to Option 1 (OPT 1) and 43% compared to Option 3 (OPT 3).

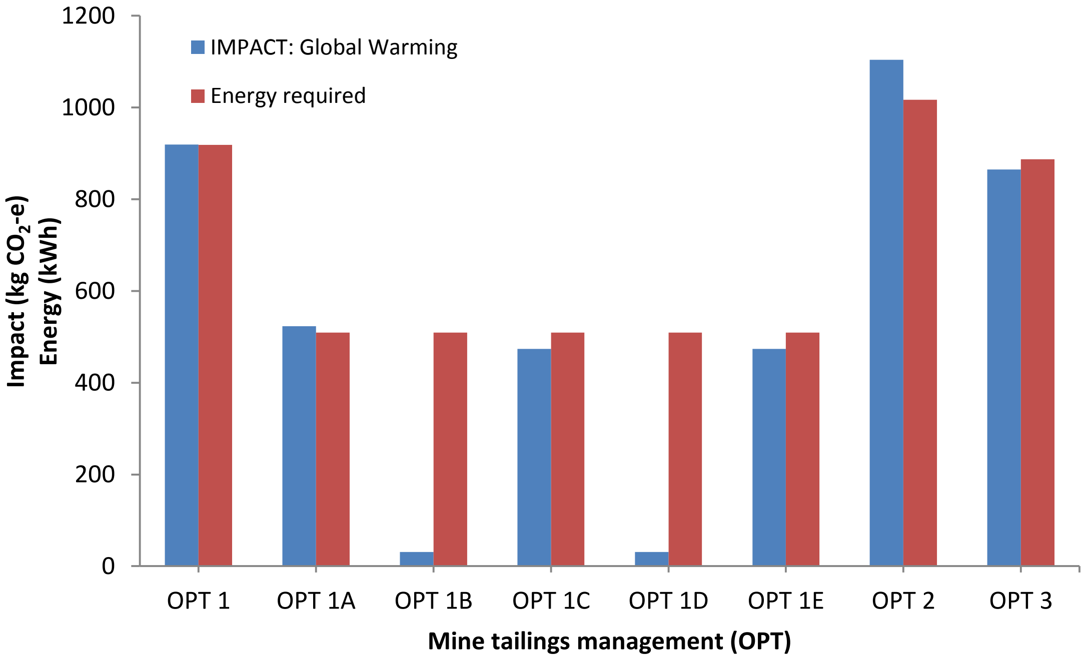

Fig.5. Global warming impact for each option

The authors provide an example of the comparison between energy use and global warming impact to give an overview of the impact of technology and renewable energy for each option as shown in Fig.5. Six Option 1 scenarios (OPT: 1, 1A, 1B, 1C, 1D, and 1E) were examined with results showing that technology improvement contributed 43% GW reduction; this impact reduction increased by up to 97% when technology improvement and renewable energy were combined.

3.3 Lifecycle damage categories

Fig.6 provides a global overview of impacts associated with Human Health (HH), Ecosystem Diversity (ED), and Resources Availability (RA) for each option.

As mentioned in the ReCiPe methodology (Goedkoop et al., 2013), environmental issues were addressed via three damage scores (known as endpoints): 1) HH, covering climate change, ozone depletion, toxicity, and human health associated with PM_{10} and ozone; 2) ED, covering climate change, acidification, toxicity, and land-use; 3. RA, covering mineral resource depletion, and fossil fuel depletion.

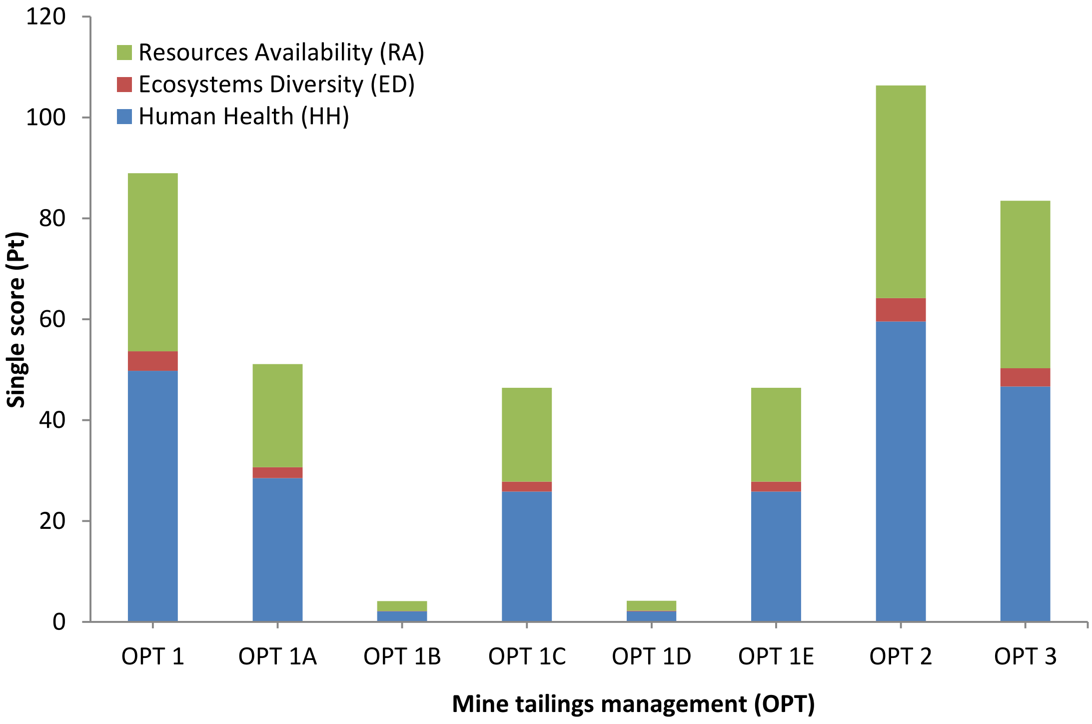

Fig.6. Endpoint impact (Single score) for each option

Option 1 shows a higher score compared with option 3 for all damage categories. This impact score reduces significantly when technology and renewable energy (Option 1B and 1D) are introduced as shown in Fig.6. Option 1B generates the lowest impact score (4.2), especially compared to Option 2 (106.4), which had the highest impact score in all damage categories.

3.4 Land use

Land use change associated with mining operations can lead to substantial impacts including wildlife habitat loss, contamination of water and land, chemical contamination of surface and ground water, and lowering of the water table (Milà I Canals et al., 2007; Miranda et al., 2003). Mining operators prepare a mine plan document, addressing management of land change to avoid or prevent these substantial impacts throughout the life of mine. Two classifications of land are generally used: disturbed land and non-disturbed land. Disturbed land is allocated to mine operation activities and companies have an obligation to rehabilitate these areas.

3.4.1 Land use impact evaluation

As noted above, the case study open pit coal mine is located in New South Wales (NSW) Australia with production rate up to 20 Mtpa. ROM coal is cleaned to produce coal with an ash content of around 24%. ROM extracted from the open pit is processed in the CHPP to produce 70% coal (product) and 30% waste coal (rejects). Coal rejects consist of 25% fine reject/tailings and 75% coarse rejects. The total tailings generated range from 0.1 Mt dry/yr in the early exploitation stage to 9.6 Mt dry/yr from the fifth year until the end of mine life. Tailings are disposed of at a Tailings Storage Facility (TSF). Three disposal options were assessed in this study, as shown in Table 7, to estimate the land use equivalent factor for each tailings management option.

Table 7

Land use equivalent factor

Mine tailings dewatering method	Total years of deferred land use (yr)	Cumulative land disturbed (ha)	Cumulative tailings production (t)	Equivalent factor (ha-yr/t)
OPT 1: Belt press (tailings cake)	22			
Year 5		67.0	25,230,952.6	0.000019
Year 10		188.8	38,816,850.2	0.000022
Year 15		310.5	38,816,850.2	0.000022
Year 20		432.3	38,816,850.2	0.000022
OPT 2: Paste thickener (tailings paste)	23			
Year 5		107.8	31,044,337.4	0.000028
Year 10		303.7	47,760,519.1	0.000033
Year 15		499.7	47,760,519.1	0.000033
Year 20		695.6	47,760,519.1	0.000033
OPT 2: Thickener (thickened tailings)	25			
Year 5		152.3	38,802,546.2	0.000043
Year 10		429.1	59,696,224.9	0.000051
Year 15		706.0	59,696,224.9	0.000051
Year 20		982.8	59,696,224.9	0.000051

Pre-mining land use is mostly classified as class IV to VI (grazing land). The mine rehabilitation strategy indicates that post-mining land use will be dominated (more than 50%) by woodland use normally associated with rural land capacity class IV to VI (GSS Environmental, 2012). The total disturbed land varies, depending on the strategy used for tailings management. Option 1 results in the lowest land area affected (432.3 ha), generating 26.3-t tailings per 50.9-t coal slurry processed in a flotation tank. Implementation of Options 2 and 3 increased the area of land disturbed for tailings disposal to 61% and 41%, respectively. Based on the total average amount of tailings production of 35 Mt over the mine life, this equal to 0.000021 ha-yr/t of tailings. Results indicate that the land-use magnitude impacts of using Option 3 as a tailings management strategy are 2.3 and 1.6 times higher than when using Option 1 and Option 2.

3.4.2 Land use and energy requirements

The estimation of land-use presented in Section 3.4.1 shows that Option 1 uses less land compared with the other two options (Option 2 and Option 3). On the other hand, the energy consumption of Option 1 is higher than of Option 3, as discussed in Section 3.1. This contributes directly to the magnitude of the environmental impacts generated.

Introducing renewable energy in Option 1B-1E reduces the magnitude of their environmental impacts. However, this strategy also increases the area of land required for renewable energy production. Table 8 compares the land occupied by various types of energy generation technologies.

Table 8

Land occupied for electricity generation

Technology	Land use (m^2/GWh)
Coal	3,642
Solar Thermal	3,561
Photo Voltaic (PV)	3,237
Wind	1,335

Source: Australian Wind Energy Association (2016)

Based on the area (m^2) of land required to generate 1 GWh of energy presented in Table 8, the authors estimate that the greatest additional land (6.5 ha) that would need to be occupied by renewable energy would be required for Option 1B, as shown in Table 9. The land requirement increases gradually, depending on the mining production rate, and peaking initially during the fifth year of mining operations.

Table 9

Additional land required for renewable energy

Options		Land required (ha)			
		Year 1	Year 2	Year 3-4	Year 5-20
OPT 1B	100% Solar-PV	0.32	3.24	5.50	6.47
OPT 1C	10% Solar-PV	0.03	0.32	0.55	0.65
OPT 1D	100% Wind	0.13	1.34	2.27	2.70
OPT 1E	10% Wind	0.01	0.13	0.23	0.27

The choice of renewable energy technology significantly affects the land requirement. The land required for wind energy sources to generate 100% and 10% of 20 GWh energy is 2.7 ha and 0.27 ha respectively. Wind energy sources required 59% less land compared to a solar-PV energy source.

3.5 Scenario comparison

Mine tailings management options provide a wide range of opportunities for mining companies to determine the best tailings disposal option based on their mining characteristics. For this case study, eight scenarios were developed and are shown in Table 10. The introduction of technology and renewable energy sources significantly reduced the environmental impact points (ENV). The average percentage reductions of the environmental impact points in Option 1, 2, and 3 were 66%, 71%, and 64%, respectively. However, the land requirement for these Options increased. The average percentage increase in land-use due to inclusion of renewable energy facilities was 6%.

Tabel 10

Ratio between environmental impact and land use

Options	Total Environmental Impact (ENV)	Land use (LND)			Ratio (ENV/LND)
		Land use for tailings disposal	Additional land for RE	Total land use	
	(Pt)	(ha)	(ha)	(ha)	(%)
OPT 1	88.9	432.3	-	432.3	20.6
OPT 1A	51.1	432.3	-	432.3	11.8
OPT 1B-Solar (100%)	4.1	432.3	6.47	438.8	0.93
OPT 1C-Solar (10%)	46.4	432.3	0.65	432.9	10.7
OPT 1D-Wind (100%)	4.2	432.3	2.70	435.0	0.97
OPT 1E-Wind (10%)	46.4	432.3	0.27	432.6	10.7
OPT 2	106.4	695.6	-	695.6	15.3
OPT 3	83.5	982.8	-	982.8	8.5

The advantages of technology improvement and renewable energy utilization are also demonstrated by the percentage ratio of environmental impact to land-use as presented in Table 10. The implementation of these two strategies contributes to a change in the Option 1A-1E average ratio which is 1.5%-13% lower compared to other options.

3.6 Limitations of the study

The application of ReCiPe, a European method, to calculate endpoint environmental impact in an Australian mining context has some limitations. Nevertheless, this approach was assumed to be the best available at the time, as the Australian method has even more limitations. For example in the Australian endpoint method, some of the impact categories including eutrophication, and land-use were not operational with regional normalization and weighting factors. In addition, this method only sets the greenhouse impact category as a single score. As a result, the authors opted to use ReCiPe (worldwide) for the endpoint method because it integrates normalization and weighting factors into all impact categories. However, the limitations of this approach nevertheless need to be borne in mind, as there are significant differences between Australia and European environmental impact contexts.

Another challenge of this study related to data availability because these data are limited publicly. The data used were gathered from various sources including consultant reports, books, and research papers. In some cases, reasonable assumptions were also made where applicable. This might create a problem with the accuracy of results generated. For instance, the authors did not consider the quality of coal mined during the operation period. The volume of coal produced depends on the quality of the coal mined. For example, higher impurities in coal lower the amount of coal (product) generated and this may also increase water and energy consumption during processing.

Finally, it should be noted that this study is specific to an open pit coal mine in NSW, Australia. Application of the method to another mine could lead to different results because of the specific characteristics of each mine. The same applies to the fact that the electricity grid mix in NSW has a very high percentage of fossil fuel energy (black coal) which might substantially increase impacts related to electricity production.

4. Conclusions

Coal mine tailings can be transported in various forms including wet or dry. Wet methods usually involve use of a pipeline to transport tailings from CHPP to TSF. Dry methods, including belt press methods, seek to reduce the water content in tailings slurry to form tailings cake. Tailings cake generated by the belt press method is then disposed of. Some coal mine sites implement a co-tailings disposal method, in which the tailings cake is disposed of together with coarse coal. Alternative disposal methods provide an opportunity for mine sites to select a method that is suited to their site characteristics. Environmental impacts and land-use variables can be used as parameters to determine the feasibility of different tailings disposal methods that increasing the sustainability performance of mining waste management.

The results of this study indicated that thickened tailings (Option 3) generated the lowest environmental impact compared to the belt press (Option 1) and paste thickener (Option 2) methods. However, in terms of land-use, Option 3 occupied the highest land, close to 1,000 ha. This highest land-use makes this option as an unattractive proposition compared to the other two options (Option 1 and Option 2). Two strategies (technology improvement and renewable energy sources) were introduced into the belt press option that required the least area of land. These measures can significantly reduce the overall environmental impact. The two lowest ratios of environmental impacts to land-use were generated by Option 1B (0.93 %) and Option 1D (0.97 %). Option 1D requires less land (1.0%) than does Option 1B.

This study also indicates the importance of considering the environmental impact and land use aspects of coal mine sites prior to selecting a tailings disposal method. Further analysis of economic aspects and reuse opportunities is also required for comprehensive discussion of sustainable tailings management and industrial symbiosis.

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"Comparing The Carbon Footprint Of Two Different Technologies In Mine Tailings Management: A Life Cycle Assessment Perspective"

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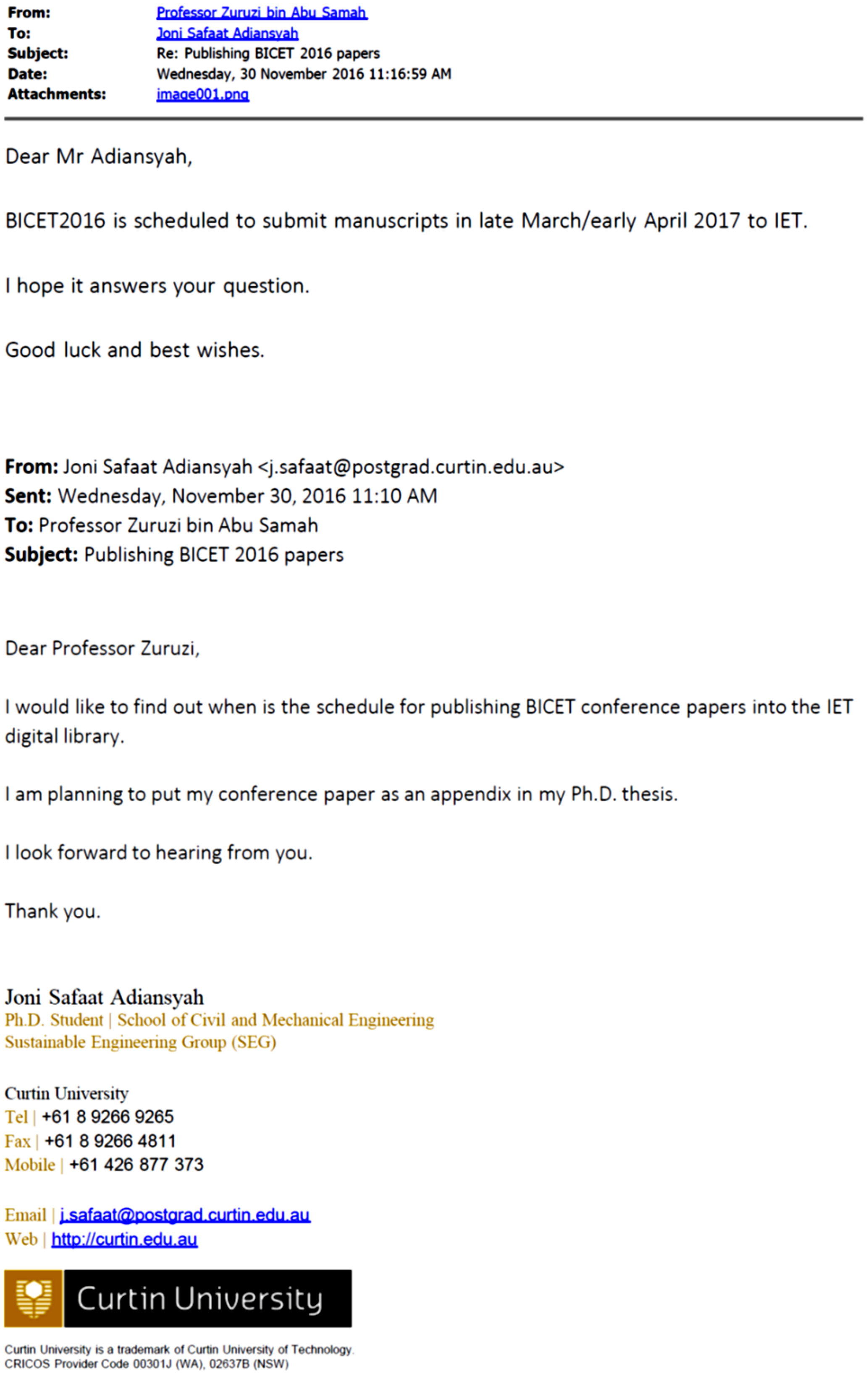

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Comparing the carbon footprint of two different technologies in mine tailings management: a life cycle assessment perspective

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Keywords: carbon footprint, mine tailings management, life cycle assessment, tailings paste, thickened tailings

Abstract

This paper compares coal mine tailings management using life cycle assessment (LCA). The Australian indicator set method (SimaPro) was used to assess the carbon footprint of two technologies used in mine tailings management. These technologies were paste thickener (OPT 1) and thickened tailings (OPT 2). The extended strategies for OPT 1 were also proposed by improving flotation technology and introducing renewable energy sources (OPT 1A-G). These strategies changed fine coal segregation technology from column flotation to stack cell (OPT 1A) and substituted fossil fuels to renewable energy with various reduction percentage of 10%, 30%, 50% (OPT 1B-G). The results of the analyses show that OPT 1 generated the highest carbon footprint compared to base case scenario (OPT 2). Replacing column flotation with stack cell contributed to the reduction of carbon footprint by 18%. The renewable energy (the wind and solar) utilisation of 10%, 30%, and 50% affected vary on the carbon footprint reduction from 24% to 44%.

1. Introduction

Mining processing plants produce two types of materials which have economic value and non-economic value. The by-product, known as tailings, consists of small quantities of minerals or metals, chemicals, organics, and process water [1; 2]. Jones and Boger [3] revealed that mining industry generated around 14 billion tonnes of tailings during 2010. The large volume of tailings can create a massive environmental footprint and the severe environmental impacts. There were 237 environmental pollution cases worldwide associated with tailings since 1917 to 2009 [4]. A proper tailings management is required to minimise the mine tailings impacts.

Coal mining generates tailings from fine coal recovery process. Fine coal commonly has particle size ranges between -1.0 mm and -0.5 mm, and represents 10-20% of the total Coal Handling Processing Plant (CHPP) feed [5; 6]. The fine coal recovery can increase the saleable coal produced by mine site. In another hand, this processing generates tailings, increases energy consumption, and requires more land for disposal area. Therefore, the proper selection for mine tailings management strategy is required to reduce the environmental impacts and increase benefits value.

2. Methodology

The life cycle assessment (LCA) is used to analyse the carbon footprint generated by two mine tailings management strategies. Based on [7] that LCA is defined as a technique to assess the environmental aspects and potential environmental impacts of product, process, or service throughout their cycle process i.e. cradle-to-grave. LCA can also assist stakeholders in identifying opportunities to improve the environmental performance, selecting the relevant environmental performance indicators, and promoting environmental awareness of a company [7]. There are four interrelated steps in LCA method as follows:

- Determining the goal and scope of project;
- Compiling an inventory of relevant material inputs and environmental releases;
- Evaluating the potential environmental impacts associated with identified inputs and releases;
- Interpreting the environmental impact results.

The hypothetical situation in a coal mine was selected to describe the carbon footprint generated by mine tailings management. The case selected is an open pit mine that projected to extract 20 million tonnes per annum (Mtpa) of Run-of-mine (ROM) and operates for 20 years. Two technologies applied were Deep cone thickener, and high rate thickener. These technologies increase the tailings mass percent solids up to 50% (tailings paste), and 30% (thickened tailings). The coal-fired power plant supplies the mine site electricity demand.

There were two main scenarios of mine tailings management with seven variations assessed (Table 1). These scenarios were tailings paste (OPT 1) and thickened tailings (OPT2). Some variations of OPT 1 were developed by introduction two components: stack cell flotation and renewable energy. Detailed scenario variations were as follows:

- Scenario 1A (OPT 1A): using stack cell flotation in segregation stage;
- Scenario 1B (OPT 1B): using stack cell in segregation stage and introducing 10% of solar energy (PV);

- Scenario 1C (OPT 1C): using stack cell in segregation stage and substituting 30% of fossil fuel with solar energy (PV);
- Scenario 1D (OPT 1D): using stack cell for segregating fine coal and tailings, and utilizing 50% of solar energy (PV);
- Scenarios 1E-G (OPT 1E-G) have the similar specifications as OPT 1B-D, but the type of renewables installed was wind power.

Table 1 Mine tailings management scenario

Components	Scenario								
	1	1A	1B	1C	1D	1E	1F	1G	2
Column flotation	√	-	-	-	-	-	-	-	√
Stack cell flotation	-	√	√	√	√	√	√	√	-
Deep cone	√	√	√	√	√	√	√	√	
Thickener	-	-	-	-	-	-	-	-	√
Renewable Energy	-	-	√	√	√	√	√	√	-

3. Results and discussion

The goal of this study is to determine the management option for fine coal tailings management. The Functional Unit is defined as 1 ton of fine coal concentrate slurry generated by flotation cells. Flotation tank had 40% recovery and required 50.855 ton of fine coal slurry to produce one ton coal concentrate slurry.

3.1 Inventory analysis

The material and energy inputs are presented in Table 2. Paste tailings scenario generated the highest electricity consumption contributed by column flotation (85%) and paste thickener (12.9%). The introduction of new technology (stack cell flotation) into OPT 1 can reduce almost 50% of total energy usage. This technology has different aeration and sparging system compared to column flotation that consumes more energy as presented in [8]. As a result, scenarios 1A-G had the lowest energy use compared to other scenarios.

Table 2 Materials inventory

Material	Unit	Scenarios		
		Paste tailings (#1)	Paste tailings with stack cell flotation (#1A-G)	Thickened tailings (#2)
Total Electricity	kWh	1,016.6	597.45	887.2
Flotation		864.5	455.3	864.5
Thickener		20.75	20.75	20.75
Underflow pump		0.2	0.2	1.9
Deep cone thickener (Paste)		131.2	131.2	-
Chemical	kg	8.3	8.3	5.8

Sources: Kohmuench *et al.* [8]; Adiansyah *et al.* [9]; Kohmuench *et al.* [10]; QCC [11]; Sanders [12]

The combinations of these data (Table 2) were assessed in life impact assessment (LIA) stage to estimate their contribution to carbon emissions as presented in Figure 2.

3.2 Impact assessment

Energy has been identified as the main contributor to the carbon footprint associated with tailings management. In paste tailings scenario (with technology improvement), for example, the coal-fired power plant as the main energy source contributed to more than 90% of total global warming impact (see Figure 1).

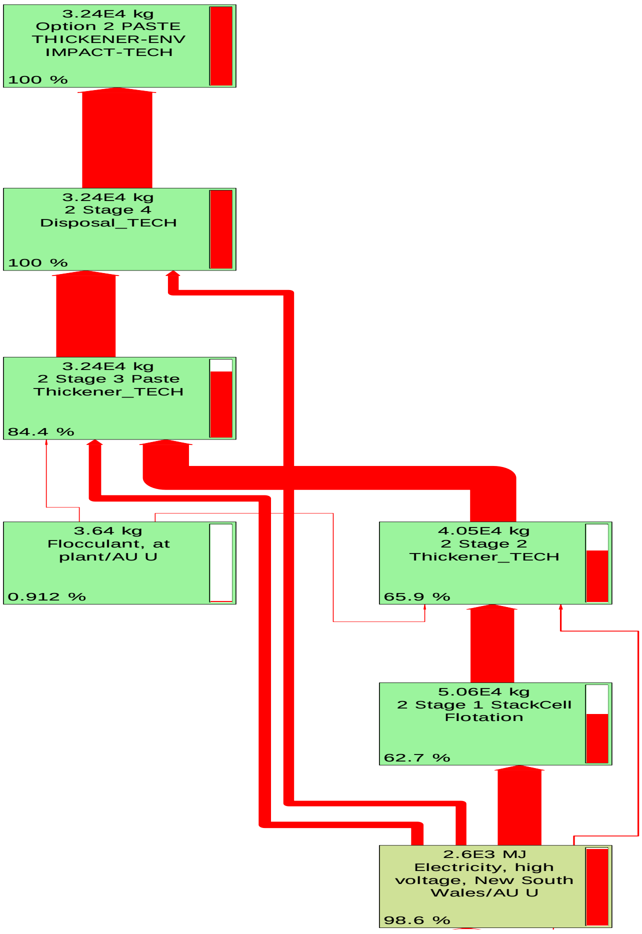

Figure 1 Environmental impact hotspots

There are two strategies adopted to reduce the global warming impact as follows:

1. Using stack cell flotation which uses the blower for aeration supply and agitator method.
2. Substituting fossil fuel energy source with the wind and solar power sources where these two renewable energies have a high intensity at the mine site area.

3.2.1 Comparison of carbon footprint

A total of nine mine tailings management scenarios were assessed during the impact assessment stage as shown in Figure 2. The scenario that produced the highest carbon footprint was OPT 1 which used paste technology and 100%

fossil fuel energy. OPT 1 generated 28% higher carbon footprint compared to base scenario (OPT 2).

Replacing column flotation with stack cell flotation (OPT 1A) resulted in decreased carbon footprint of 18% compared to OPT 2. The combination of technology improvement and substituting fossil fuel energy with renewable energy affected the number of carbon dioxide equivalent (CO_2-e) emitted. As seen in Figure 2 that this strategy was able to reduce the carbon footprint by 24%, 33%, and 43% for OPT 1B, 1C, and 1D respectively. The results also indicated that increasing of 20% renewable energy utilisation (from OPT 1B to OPT 1C) generated 150% CO_2-e reduction.

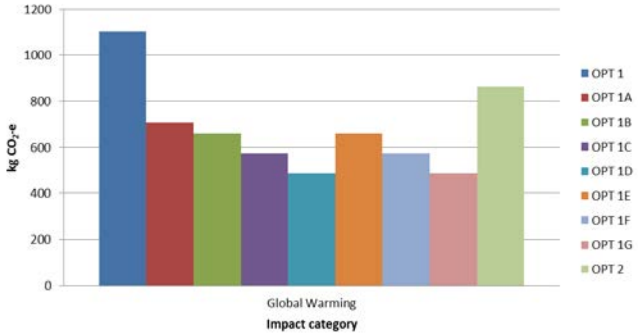

Figure 2 Carbon footprint

The analysis produced the similar results for other scenarios (OPT 1E-G). Different type of renewable energy used did not provide significant differences in the results.

4. Conclusion

There are various strategies in coal mine tailings management including tailings paste, and thickened tailings. Selection of technology used in tailings disposal method affects the amount of energy consumption. This correlate also with the carbon footprint generated.

This paper indicated that tailings paste strategy combined with technology improvement, and renewable energy provided low carbon footprint compared to the base scenario (thickened tailings). Another advantage of using this strategy is a higher land-use reduction for tailings disposal area due to the less water content in transported tailings. Further analysis of land-use and economic aspects is essential for improving the sustainability performance of mine tailings management.

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Research paper

Life cycle cost estimation and environmental valuation of coal mine tailings management

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ABSTRACT

Sustainable mining management is increasingly seen as an important issue in achieving a social license to operate for mining companies. This study describes the life cycle cost (LCC) analysis and environmental valuation for several coal mine tailings management scenarios. The economic feasibility of six different options was assessed using the Net Present Value (NPV) and Benefit-Cost Analysis (BCA) methods. These options were belt press (OPT 1), tailings paste (OPT 2), thickened tailings (OPT 3), and OPT 1 with technology improvement and renewable energy sources (OPT 1A-C). The results revealed that OPT 1A (belt press technology with stack cell flotation) was the first preference in terms of LCC while OPT 1C (belt press technology with stack cell flotation and 10% wind energy) generated the highest benefits value (BCA) compared to the other options. The LCC and BCA components and the volume of GHG emissions were used to determine the best option. Normalization of these three elements resulted in the selection of Option 1C as being the most cost-effective option.

1. Introduction

Environmental management is a crucial tool for any activity that generates adverse impacts and mining is one such activity. Mining operations pose potential hazards to human health and the environment during exploration, production, and closure stages (Adiansyah, Haque, Rosano, & Biswas, 2017). These impacts, presented in Table 1, should be avoided/minimized and managed to prevent environmental disasters. Developing hazard management strategies is also necessary in order to obtain a social license to operate mines.

The first step of managing environmental impacts is to prepare a comprehensive environmental management plan. This document mainly describes potential environmental impacts and risks, environmental monitoring, measurement activities, control strategies, and environmental audits (Commonwealth of Australia, 2014). The tools that are usually employed to study the environmental impacts of different systems include life cycle assessment, life cycle costing, net present value, and benefit-cost analysis (Ahlroth, Nilsson, Finnveden, Hjelm, & Hochschorner, 2011; Erkayaoğlu & Demirel, 2016; McLellan, Corder, Giurco, & Green, 2009). These tools can be used to determine the feasibility of the environmental management strategies for mining operations.

Tailings, categorized as mine waste, are among the materials that might contribute to environmental contamination, as presented in Table 1. In coal mining, tailings are generated from fine coal, which represents about 10–20% of the Coal Handling and Preparation Plant (CHPP) feed (Honaker, Kohmuench, & Luttrell, 2013; Kumar, Bhattacharya, Mandre, & Venugopal, 2014). There are two main arguments for considering coal mine tailings to be a critical issue in waste management. First, global coal reserves are estimated to be 860 billion tonnes (Thomas, 2013). Second, coal is listed as the second-largest energy source in the world (Energy Information Administration, 2016; Perusahaan Listrik Negara, 2015; World Nuclear Association, 2013). The International Energy Outlook 2016 report published by the U.S. Energy Information Administration predicts an increase in coal consumption between 2012 and 2040 at an average rate of 0.6% per annum (Fig. 1) (Energy Information Administration, 2016). This means that the global consumption of coal could increase from 153 quadrillion Btu in 2012 to 180 quadrillion Btu by 2040, which would cause a

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Life cycle cost estimation and environmental valuation of coal mine tailings management

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Abstract

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Keywords: tailings disposal, economic assessment, environmental valuation, net present value, benefit-cost analysis

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1. Introduction[2]

1.1 Background

Environmental management is a crucial tool for any activity that generates any adverse impacts and mining is one such activity. Mining operations pose potential hazards to human health and the environment during exploration, production, and closure stages. These impacts presented in Table 1 should be avoided/minimized and managed to prevent environmental disasters. Developing hazard management strategies is also necessary to obtain a social license to operate the mines.

The first step of managing the environmental impacts is to prepare a comprehensive environmental management plan. This document mainly describes potential environmental impacts and risks, environmental monitoring and measurement activities, control strategies, and environmental audits (Commonwealth Of Australia, 2014). The tools that are usually employed to study the environmental impacts of different systems include life cycle assessment, life cycle costing, net present value, and benefit-cost analysis (Ahlroth et al., 2011; Erkayaoğlu and Demirel, 2016; McLellan et al., 2009). These tools can be used to determine the feasibility of the environmental management strategies for mining operations.

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[2] LCC : Life Cycle Costing

BCA : Benefit Cost Analysis

CHPP : Coal Handling and Preparation Plant

BTM : Benefit Transfer Method

Table 1

Potential environmental impacts in a mining cycle

Stage	Activities	Potential Environmental Impact
Exploration	Drilling or trenching, land clearing, camp and road development	- Sediment runoff and increased Total Suspended Solid (TSS) - Spills of fuels and other contaminants - Disturbance to wildlife
Construction	Infrastructure and facilities development such as power lines, roads, tailing storage facility, water treatment plant, processing plant, and camp	- Habitat fragmentation - Contamination of water, and land - Declining species populations - Increasing Particulate Matter (PM) into the air - Altered patterns of drainage and runoff
Operation/Production	Blasting, excavation, ore/waste transporting, milling/grinding ore, and tailing deposition/transport	- Habitat fragmentation - Chemical contamination of surface and ground water - Declining species populations - Toxicity impacts to organisms - Decreased water tables - Increased erosion and siltation - Mine acid drainage pollution - Tailing slurry overflow (affected to terrestrial ecosystem) - Increased greenhouse gas emissions related to energy consumption
Mine closure	Revegetation, re-contouring of stockpiles/pits and	- Persistent contaminants in surface and ground

	monitoring seepage	waters - Expensive, long-term water treatment - Persistent toxicity to organisms - Loss of original vegetation/ biodiversity - Permanent topography changes

Source: Adiansyah et al. (2015), Bell et al. (2001), Bian et al. (2009), Franks et al. (2010), Kossoff et al. (2014), Miranda et al. (2003), Zhengfu et al., (2010).

Tailings, categorized as mine waste, are among the materials that might contribute to environmental contamination, as presented in Table 1. In coal mining, tailings are generated from fine coal, which represents about 10-20% of the Coal Handling and Preparation Plant (CHPP) feed (Honaker et al., 2013; Kumar et al., 2014). There are two main arguments for considering the coal mine tailings as a critical issue in waste management. First, the global coal reserves are estimated to be 860 billion tonnes (Thomas, 2013). Second, coal listed as the second-largest energy source in the world (Energy Information Administration, 2016; Perusahaan Listrik Negara, 2015; World Nuclear Association, 2013). The International Energy Outlook 2016 report published by the U.S. Energy Information Administration predicts an increase in coal consumption between 2012 and 2040 at an average rate of 0.6% per annum (Fig.1) (Energy Information Administration, 2016). This means that the global consumption of coal could increase from 153 quadrillion Btu in 2012 to 180 quadrillion Btu by 2040, which would cause a corresponding increase in the volume of tailings.

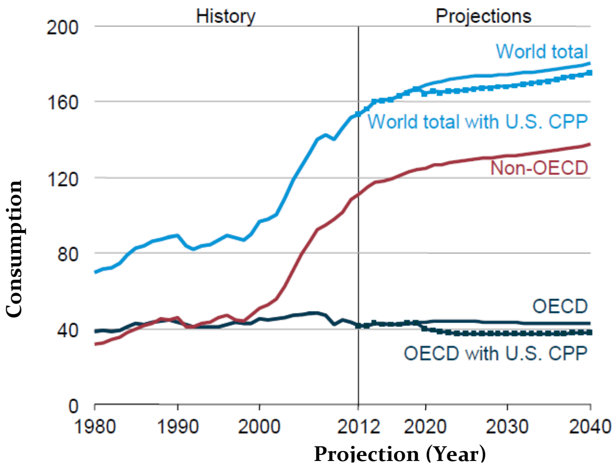

Fig.1 World coal consumption in quadrillions Btu (Energy Information Administration, 2016)

Mining projects currently apply various types of tailings disposal strategies, including conventional tailings disposal, thickened tailings, and tailings paste (Adiansyah et al., 2015). The two most important sustainability indicators (water and energy) used for selecting the best tailings disposal method are discussed by Adiansyah et al. (2016). This study assesses the links between these indicators to determine the optimum scenario associated with water and energy consumption. The implementation of sustainability criteria in all mining activities is also endorsed by the International Council of Mining and Metals (ICMM) when the organization was established in 2001. A sustainable tailings framework was introduced by Adiansyah et al. (2015) and consists of eight steps including analyzing the water-energy nexus, environmental assessment, and economic analysis. These steps enable mining companies to determine the most effective and efficient strategy for their tailings disposal.

1.2 Objectives

This paper aims to estimate the financial value of six different tailings disposal methods in coal mining. A comparison of cost analysis is presented to determine the most preferable option in terms of cost, benefit, and environmental impact. The estimation is based on two economic perspectives: life cycle costing and environmental valuation (Australian Government, 2014;

Finnveden and Moberg, 2005; Harrison, 2010; Höjer et al., 2008). These two perspectives assess the cost of coal tailings disposal at different time scales. Life cycle costing represents the life cycle flow and depends on the functional unit as determined in the life cycle assessment while environmental valuation generates the cost and benefit of each disposal method during the lifetime of the mine.

To achieve the above objectives and to assess the material input and output during fine coal processing, a life cycle flow chart was created as shown in Fig.2. A desk study was also conducted to determine the economic value of materials involved in the processing flow. Section 2 provides a review of the previous studies on life cycle costing and environmental valuation of mining operations. Section 3 presents the methodologies used in the data analysis including data sensitivity based on three different discount rates. Sections 4 and 5 discuss the results of the net present value and benefit-cost analyses for each tailings management option.

1.3 Limitations of the study

One of the biggest challenges facing the research in the mining field is the limited publicly available data due to disclosure policies (Haque and Norgate, 2015). Because of the lack of available information, assumptions are made for some parameters including the percent recovery from flotation tanks, rehabilitation period for each scenario, and maintenance costs.

Another constraint relates to the requirement of significant resources, i.e. time and money, when conducting environmental valuation studies (Damigos, 2006). Researchers in this field use methodologies which involve a substantial number of respondents. Such methods include the Contingent Valuation Method (CVM), Travel Cost Method (TCM), and Hedonic Pricing Method (HPM). For example, Burton et al. (2012) used the choice modeling method in their study that required 252 respondents to assess the environmental valuation of a bauxite mine site in Western Australia. Studies with such a large number of interviewees require sufficient time, and human and financial resources. To cope with the limited resources, some studies suggested using the Benefit Transfer Method (BTM), which has two types of approaches: value transfer and function transfer (Damigos, 2006; Mazzotta et al., 2015). The BTM is allowed to transfer available information (value) from studies completed in another location or context. This study uses the BTM combined with market-price based approach.

This study focuses on three environmental issues: water use, land use, and greenhouse gas (GHG) emissions. The volume of the tailings produced and the run-of-mine (ROM) data are two primary parameters for estimating the level of water conservation. Estimating the total land area required for disposing the tailings depends on these two parameters as well as the tailings density. Three different tailings densities used in this study were from two coal mines in Australia (GHD, 2013; New Hope Group, 2014). A life cycle assessment was conducted using SimaPro software to estimate the GHG emissions.

2. Discussion of the studies on life cycle costing and environmental valuation in mining

Mining development requires a large investment for capital expenditures and operating costs. For example, a copper mine in Indonesia that produces around 240 million attributable pounds of copper annually has an initial investment of approximately US $1.8 billion (Newmont, 2016; Newmont Nusa Tenggara, 2016). Other examples include the Barruecopardo project in Spain with a total capital cost of €70 million, the Hemerdon project in the United Kingdom with a total operating cost of €12.48 per ton ore, and the Pilbara Iron Ore project in Western Australia with direct mine capital cost of AUS $726 million (Gordon, 2014; Sánchez et al., 2015). Therefore, cost becomes one of the critical factors to determine the feasibility of mining development projects.

Mining companies commonly conduct financial analysis at the beginning of a project i.e. at the planning stage. Life cycle costing (LCC) and environmental valuation are two commonly used tools to assess various options necessary for mining operations including mine tailings disposal, processing technology, and power generation. These options assist the decision makers to select the most appropriate strategy for the exploration, production, and post-mining stages.

LCC and environmental assessment have not been studied as commonly in the mining industry as in other fields, such as building and forestry. Epstein et al. (2011) discussed the LCC of coal mining in the Appalachia region of the United States. The life cycle considered in that study was extraction, transport, processing, and combustion. The cost analysis called the "externalities cost" was based on a waste stream that created multiple impacts to human health and the environment. The authors proposed a number of recommendations including reducing the number of coal-fired power plants, promoting clean smart grids, and ending the mountaintop removal method (MTR). The environmental and economic performance of an enhanced landfill mining (ELFM) in Belgium was assessed by Danthurebandara et al. (2015) in their paper. The paper used integrated evaluation tools, LCA and LCC, and identified three factors that influenced the economic feasibility of EFLM: technology, regulations, and markets.

In the area of environmental valuation, there are some studies available in the Environmental Valuation Reference Inventory (EVRI) database. The authors of this paper found 24 out of more than 2,000 studies by conducting a search in EVRI using "mining" as a keyword. Two of those studies were conducted in Australia: Colliery-New South Wales and Jarrah Forest-Western Australia. The value of environmental and social impacts was the focus of an underground coal mining project assessment in Colliery, New South Wales (Economics, 2008). That study used willingness to pay (WTA) as a research method and the results are presented in Table 2. The Western Australia study considered bauxite mines and used choice modeling as a survey method to estimate the non-market environmental value of the rehabilitation of their mines (Burton et al., 2012). A total of 252 respondents completed the questionnaire and the results show that the in-situ rehabilitation was the most preferred option. Detailed monetary values of the options are presented in Table 2.

Table 2

Environmental value of two mine sites

Asset/endpoint	Financial value	Unit	Method
Stream protected from adverse affects of the mine	\$4.78 - \$5.13	kilometer	Willingness to pay
Additional job from mining	\$4.17 - \$4.91	year	Willingness to pay
Protect an additional upland swamp	\$0.43 - \$0.45	hectare	Willingness to pay
Protect an additional aboriginal site from adverse affects	\$0.37 - \$0.44	hectare	Willingness to pay
1% decrease in plant richness	\$2.41 million	percent	Willingness to accept
No habitat re-creation	\$77.39 million	habitat site	Willingness to accept
Decreasing population of the red-tailed black cockatoo	\$7.49 million	population	Willingness to accept
Decreasing population of the Chuditch	\$8.69 million	population	Willingness to accept

Source: Burton et al. (2012), Economics (2008)

Past studies have not assessed the mine tailings management strategies. This study attempts to fill the gaps in estimating the life cycle costing and environmental values of different coal mine tailings disposal methods.

3. Material and methods

Section 3.1 describes the process flow for each tailings management option. Table 3 outlines the six different scenarios considered in coal tailings management.

Table 3

Scenario for tailings management options

Tailings management	Characteristics
Option 1	Tailings cake with belt press
Option 1A	Tailings cake belt press with technology improvement
Option 1B	Tailings cake belt press with technology improvement and 10% Solar RE
Option 1C	Tailings cake belt press with technology improvement and 10% Wind RE
Option 2	Tailings paste with paste thickener
Option 3	Thickened tailings with thickener

Technology improvement and substituting 10% of the fossil fuel energy with renewable energy are two strategies introduced for Options 1A, 1B, and 1C. Section 3.2 describes the methodologies used in this study: LCC and environmental valuation.

3.1 Case study

The case selected is an open pit coal mine located in New South Wales, Australia. The mine is projected to extract around 20 million tonnes per annum (Mtpa) of the run-of-mine (ROM) coal. Three primary dewatering technologies were assessed: belt press, deep cone thickener (paste), and thickener. These technologies increase the percent solids in tailings and reduce the volume of water transported to the tailings disposal facility (Adiansyah et al., 2016).

The process flow of fine coal rejects is organized as illustrated in Fig.2, where four processes are involved: material input, processing, products, and final values. The four products generated during the process are saleable coal, tailings, water and land conservation, and GHG reduction.

Option 1. Dewatering the tailings via belt press technology

This option requires electricity, water, and chemicals to process the fine raw coal. Overflow from the flotation tank generates saleable coal in slurry form. The underflow slurry, categorized as tailings, requires further treatment in the thickener to increase its percent solids. This process in the thickener creates two material outputs: recycled water and tailings. The recycled water is pumped into water storage tanks, and underflow tailings are fed into the belt press to achieve its final percent solids portion of 65%. This stage produces additional recycled water for belt wash purposes while the tailings with 65% solids are transported to the co-disposal area (coarse rejects and tailings). Chemicals also play a significant role in the segregation and dewatering process. These chemicals have three functions as collectors, frothers, and flocculants. In this case study, a coal-fired power plant supplied 100% of the energy required. The authors also introduced technology improvements in Option 1A by replacing the type of flotation technology and incorporating 10% renewable energy (solar and wind power) for Options 1B and 1C as described in Table 3.

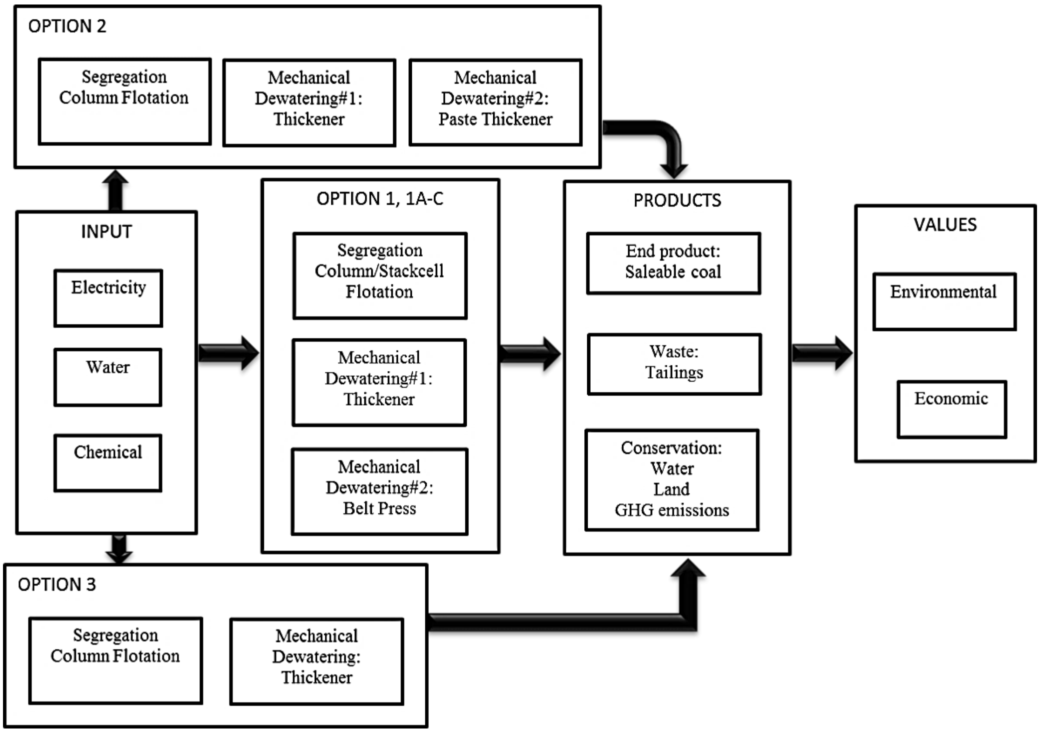

Fig.2 Process flow for each tailings management option

Option 2. Dewatering the tailings via the paste thickener technology

The primary inputs required for Option 2 are similar to Option 1; the difference lies in the total amount of these materials used. The fine raw coal segregated in the flotation tank into two products: saleable coal as flotation overflow and underflow tailings. The tailings thickener receives the underflow tailings from the flotation tank and increases the percent solids of tailings by adding Sodium Acrylate ($C_3H_3NaO_2$). This acts as an anionic flocculant to the tailings slurry and the process reclaims water, which is then distributed to the water storage tank. In order to attain a final percent solids level of 50%, a flocculant is added to the tailings in the paste thickener tank. Reclaimed water is generated by this process and pumped into the water storage tank. In this option, 100% of electricity is supplied from the coal-fired power plant.

Option 3. Dewatering tailings via thickener technology

This option creates tailings with 30% solids and transports these tailings by a pipeline to the disposal area (tailings dam). The first two processes in Option 3 (segregation and thickened tailings) are similar with the other two options. These processes generate recycled water pumped to the water storage tank. There is no renewable energy introduced in this option.

3.2 Economic assessment and environmental valuation

The authors consider economic and environmental perspectives when assessing the feasibility of each option. Both perspectives are based on the capital cost, operational cost, and benefits value. This enables the study results to provide a sufficient financial description and overview to determine the most viable option for the coal tailings disposal management.

3.2.1 Life cycle costing (LCC) method

LCC is an environmental system tool used to determine the most cost-effective alternative among different available scenarios/products from the life cycle perspective (AS/NZS, 2014; Finnveden and Moberg, 2005; Höjer et al., 2008). This tool is valuable when making a decision across various fields including disposal option technologies, comparison of alternative product strategies, and long-term financial planning (Standard, 2016). There are some important economic indicators associated with LCC: net present value (NPV), internal rate of return (IRR), and discounted rate (DR) (Brealey et al., 2012; Harrison, 2010).

To perform an LCC analysis for the options described in Section 3.1, the authors used a theoretical case study of a coal mine with a maximum production rate of 20 Mt per annum and a lifetime of 20 years. The functional unit had 1 tonne of fine coal concentrate slurry generated by flotation cells. The recovery percentage from flotation was assumed to be around 40%.

Capital cost and operational cost data were collected through literature review and a desk study as presented in Table 4. Procurements and facility developments such as the thickener, the paste thickener, and belt press filters are considered capital expenses. Daily expenses such as chemical and electricity costs are listed as operational expenses. The authors found that maintenance costs varied for each mine site and ranged between 0.2% and 1.45% of total capital costs. Therefore, this analysis used the median value of 0.83% of total capital costs when estimating the maintenance cost.

Table 4
Input values used in the cash flow model

Description	Value	Unit	Source	Normalization value (2016)
Capital Cost (CC)				
Thickener	2,000,000	$	(Bickert, 2004)	2,683,168
Paste thickener	700,000	$	(Bickert, 2004)	939,109
Belt press filter	350,000	$	(Bickert, 2004)	469,554
Column flotation	1,965,000	$	(Kohmuench et al., 2012)	1,561,218
Stackcell flotation	1,965,000	$	(Kohmuench et al., 2012)	1,561,218
Tailings dam	19,808,075	$	(QCC, 2013)	20,745,849
Co-disposal	2,518,519	$	(Bickert, 2004)	3,378,805
Solar PV	2,505,000	$/MW	(Jacobson et al., 2013)	2,623,594
Wind power	3,500,000	$/MW	(Windustry, 2012)	2,081,623
Operational Cost (OC)				
Chemical	4.5	$/kg	(QCC, 2013)	4.7
Electricity	51.6	$/MW	(Australian Energy Market Operator, 2016)	51.6
Reject conveying and trucking	1.5	$/ton	(QCC, 2013)	1.6
Co-disposal	0.3	$/ton	(Bickert, 2004)	0.4
Maintenance	0.83	% of CC	(Moolman and Vietti, 2012; QCC, 2013; Wang et al., 2007)	0.83

The value in Table 4 was normalized by using an average annual inflation rate to eliminate the value variation associated with the use of multiple sources of data. All the value have been converted into Year 2016 (Reserve Bank of Australia, 2016a).

A central feature of LCC is the application of the net present value (NPV). The steps to measure NPV as described in Callan and Thomas (2013) are as follows:

1. Calculate the future value (FV) of the costs by dividing the current value (CV) with the inflation rate (r) for the appropriate time period (t) as shown in Equation (1).

$$FV = \frac{CV}{(1+r)^t} \tag{1}$$

2. Select the appropriate discounted rate (DR).
3. Discount the FV for each time period (t) as shown in Equation (2).

$$PV = \frac{FV}{(1+DR)^t} \tag{2}$$

4. Sum the discounted value over all t periods to find the present value (PV) of costs.
5. Monetize NPV in real dollars by adding capital cost (CC) to total PV as shown in Equation (3).

$$NPV = CC + \sum_{t=0}^{t=n} PV \tag{3}$$

The authors used NPV to compare each option for the disposal of coal mine tailings, and subsequently to determine the most cost-effective strategy for the mine site.

3.2.2 Environmental valuation method

3.2.2.1 Valuation

A mining project evaluation is not only based on its financial profitability but also its sustainable development performance. According to Eggert (2001), sustainability is maintaining the level of environmental (e.g. water quality, air quality), economic (e.g. community income), and social parameters at their current standards. All stages of a mining project contribute to these three parameters, and so their contribution should be estimated or valued. Environmental benefit valuation utilized in this study has increasingly been considered an important tool in decision-making in the last decade (Damigos, 2006; Marre et al., 2016).

Use value and non-use value are two types of values that are commonly used in valuation methods. Use values consist of direct use (actual resources utilization, i.e. commercial purpose or recreation); indirect use (benefits gained from ecosystem functions, i.e. water and nutrient regulations); and option value (willingness to pay for future use of a resource as an insurance premium) (Damigos, 2006; Damigos et al., 2016; De Groot et al., 2002). Non-use values are associated with the non-physical consumption of goods or services. These include well-being, health, and comfortable feelings (Dlamini, 2012).

Generally, there are three categories of valuation techniques available (Damigos et al., 2016; De Groot et al., 2002) as follows:

(a) direct market valuation approaches such as market-price based and cost-based valuations, and production functions use data from the actual market;

(b) revealed preference approaches such as the Travel Cost Method (TCM) and the Hedonic Pricing Method (HPM) present an individual choice reflecting their behavior based on the market information;

(c) stated preference approaches such as the Contingent Valuation Method (CVM) and the Choice Modeling (CM) undertake a social survey to obtain individual preferences on the changes in environmental and social goods and services.

The goods or services are considered to determine the type of the evaluation method but most valuation studies require significant resources (time, labor, and money) to produce reliable estimates. These constraints on the valuation research can be overcome by using the Benefit Transfer (BT) method. BT is typically used to estimate the environmental benefits of a project based on the available information from previous studies and therefore it does not require as much time or money as the original valuation studies. The two main approaches in BT are value transfer and function transfer techniques (Damigos, 2006). The transfer occurs between the 'study site' (the original research site) and the 'policy site' (where the value is assigned). In this study, the market-price based approach and BT (value transfer) approach were used to estimate the value of the coal mine tailings management due to time and resource limitations. The values shown in Table 5 represent the base input data for the benefit-cost analysis (BCA) to compare each mine tailings option from an economic perspective.

Table 5

Direct use value

Description	Value	Unit	Sources	Normalization value (2016)
Operational Cost				
Chemical	4.5	$/kg	(QCC, 2013)	4.7
Electricity	51.6	$/MW	(Australian Energy Market Operator, 2016)	51.6
Reject conveying and trucking	1.5	$/ton	(QCC, 2013)	1.6
Co-disposal	0.3	$/ton	(Bickert, 2004)	0.4
Tailings dam	1.2	$/ton	(Bickert, 2004)	1.6
Reclamation cost:				

- Tailings dam	100,000	\$/ha	(Fenzel, 2012)	104,081
- Co-disposal	50,000	\$/ha	(Fenzel, 2012)	52,041
Reclamation bond	1,038	\$/ha	(Qugley, 2016)	1,038
Benefit Value				
Market:				
Saleable coal	88.35	\$/ton	(Index, 2016)	88.35
Water conservation	2,000	\$/ML	(Gillespie, 2012)	2,146
Land conservation	5,172.4	\$/Ha	(Gillespie, 2012)	5,550
Non-market:				
GHG reduction	10.8	\$/t CO_2-e	(World Bank and Ecofys, 2016)	10.8

The value in Table 5 was normalized by using an average annual inflation rate to eliminate the value variation associated with the use of multiple sources of data. All the value were converted into Year 2016 (Reserve Bank of Australia, 2016a).

3.2.2.2. Benefit-cost analysis (BCA)

BCA aims to improve decision making by providing cost and benefits information in present value dollar terms (Australian Government, 2016; Harrison, 2010). There are a number of advantages of BCA implementation including the assistance when identifying the cost-effective options, maximizing net benefits to the community, and providing quantitative and qualitative information for decision-makers (Australian Government, 2016).

The Australian Government (2016) introduced the following eights steps for preparing a full BCA:

(1) Specify the set of possible options.
(2) Calculate or measure the cost and benefits of the project i.e. capital cost, operational cost, and benefit value. This study uses BT and market-price based methods to value the benefits;
(3) Identify the impacts of each option.

(4) Predict the impact period. In this study the impact period was different for each mine tailings management option ranging between 22 and 25 years.

(5) Monetize (assign a dollar value) to the impacts. This study focuses on three environmental impacts: water conservation, land use, and GHG emissions as explained in Section 3.2.2.1.

(6) Calculate the present value by considering the discount rate of benefit and cost flows as shown in Equation (4).

$$NPV = \sum_{t=0}^{t=n} \frac{B_t - C_t}{(1 + DR)^t} \tag{4}$$

where B_t = the benefit at t period; C_t = the cost at t period; DR = the discount rate; t = the year.

If the (PVB-PVC) value for a particular option is greater than 0, the choice is considered feasible (Callan and Thomas, 2013).

(7) Conduct a sensitivity analysis to identify the effect of variable changes to overall cost and benefits of a project including discount rates and time horizons.

4. Results and discussion

4.1 Estimating life cycle costing

The estimated total quantity of materials required to generate 1 ton of fine-coal concentrate slurry is shown in Table 6. The largest electricity consuming option was OPT 2 which used the paste thickener technology, while the belt press technology of OPT 1 (OPT 1A-C) used higher amounts of chemicals compared to the other options.

Table 6

Amount of input into the process flow

Materials	Unit	Technology				Source
		Belt press (OPT 1)	Belt press (upgrade)[a]	Paste thickener (OPT 2)	Thickener (OPT 3)	
Total Energy:	kWh	918.3	509	1,016.6	887.2	(Adiansyah et al., 2016; Kohmuench et al., 2012; QCC, 2013)
Flotation		864.5	455.3	864.5	864.5	
Thickener		20.75	20.75	20.75	20.75	
Underflow pump thickener		0.2	0.2	0.2	1.9	
Belt press		32.9	32.9	-	-	
Paste thickener		-	-	131.2	-	
Chemical	kg	16.1	16.1	8.3	5.8	(Fawell et al., 2015; Owen, 1989; QCC, 2013)

[a]upgrade to stack cell flotation (OPT 1A-C)

The capital value (CV) of material inputs was calculated by multiplying the operating cost (OC) input (Table 4) with materials quantity (Table 6). Incorporating an inflation rate of 3% per year (Reserve Bank of Australia, 2016b) resulted in the total future values (FV) over the lifetime of the mine as shown in Table 7. Discounting the CV with a 7% discount rate (Australian Government, 2016, 2014) generated the highest present value (PV) for Option 2 followed by Option 3, Option 1B, Option 1C, Option 1, and Option 1A. There was a significant percent difference (226%) between the highest and the lowest values. The capital costs associated with the construction of the disposal area resulted in NPVs 10 times higher than the PVs as presented in Table 7.

Table 7

Net Present Value with 7% discount rate

Total Economic value ($)	Mine tailings management Option					
	OPT 1	OPT 1A	OPT 1B	OPT 1C	OPT 2	OPT 3
Future Value (FV)	1,066,474	1,066,137	1,066,827	1,066,676	3,518,714	3,590,956
Present Value (PV)	718,642	718,415	718,880	718,778	2,341,843	2,333,216
Net Present Value (NPV)	8,811,388	8,811,161	8,817,190	8,815,939	28,271,186	27,323,451
Preference	2	1	4	3	6	5

The three keys factors at this stage are the type of technology applied, market price, and consumption pattern. The combination of these factors can be observed in Option 2 with the highest NPV of $28,271,186 making it the least preferred option. The authors also calculated the NPV using the discount rates of 3% and 10% (Fig.3). Fig.3 shows that there is a consistency in the NPV analysis outputs despite the changes in the discount rate. Option 1A using the belt press technology with stack cell flotation and 10% renewable energy was found to be the most economically feasible option.

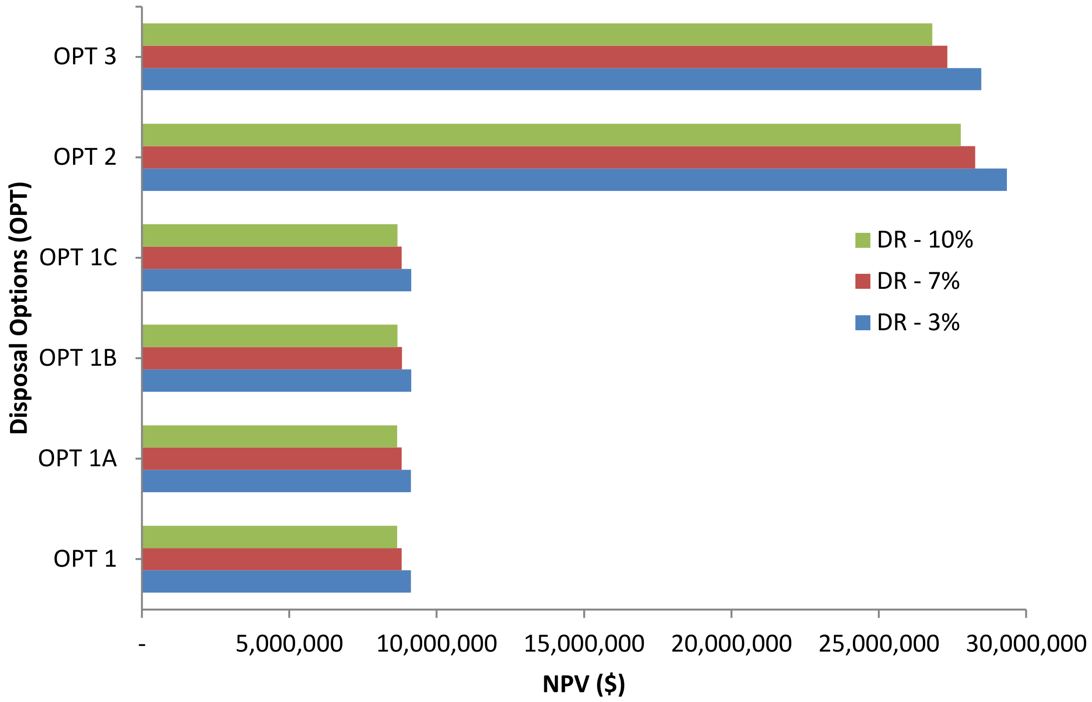

Fig.3 The influence of discount rate on NPV

Additionally, the NPVs of Option 1 and Option 1A-C differed only by 0.1%. This means that the ultimate decision to determine the optimal option will be influenced by other factors such as the benefits value (as discussed in Section 4.2).

4.2 Environmental valuation

This section compares the benefits of implementing different mine tailings management strategies. The authors focus on three environmental benefits: water conservation, land conservation, and GHG reduction. These environmental parameters are also mentioned by Adiansyah et al. (2016, 2015) as the main indicators of the sustainability of tailings management.

4.2.1 Water conservation

Water reclamation took place in all stages including the segregation process in flotation cells and the thickening process within the thickener tank. The initial raw fine coal slurry fed into the flotation cell consisted of 10% solids where the final mass percent of solids for Option 1, Option 2, and Option 3 was 65%, 50%, and 30%, respectively. Total water used and reclaimed is linearly correlated with the percentage of solids in tailings.

Option 1 using the belt press resulted in the highest water conservation. By taking a water tariff assumption of $2.97 per unit of water use (NSW Government, 2016), this option had a 220% and 476% cost-savings compared to Option 2 and Option 3, respectively (see supplementary data). Option 2, using the paste thickener, created 80% higher cost-savings compared to Option 3, which used the thickener method. All recycled water was fed into a closed-cycle system and was supplied back to the processing plant as processing water.

4.2.2 Land conservation

One of the critical components of tailings management is the land availability for the tailings disposal area. Total land use for each option during the lifetime of the mine has been discussed in Adiansyah et al. (2016), and Option 3 was found to require the highest disposal area. The authors in this study used Option 3 as a base case to compare the land conservation values with other options.

Calculated using the BT method, the land value was $5,550 per hectare (see Table 5). This value was multiplied by the total disposal area to produce the cost value for every hectare of land required during the tailings disposal process. As a reference scenario, the cost value of Option 3 was used as a deduction for the other values in all scenarios. Table 8 presents the results in which Option 1 and 1A generated the highest land conservation value of $3.1 million during the lifetime of mine.

Table 8

Total land conservation value

Tailings management	Total land value ($)	Additional information
OPT 1	3,055,393	column flotation
OPT 1A	3,055,393	stack cell flotation
OPT 1B	2,989,857	renewable energy
OPT 1C	3,028,323	renewable energy
OPT 2	1,594,172	column flotation
OPT 3	-	reference scenario

The introduction of 10% renewable energy in Option 1B and 1C increased the land use requirement for a renewable energy facility. On the other hand, the total land value of these options decreased by approximately 2% (Option 1B) and 1% (Option 1C) compared to Option 1.

4.2.3 GHG reduction

Electricity is the main contributor to each kilogram of carbon dioxide equivalent (CO_2-e) produced by the process flow. Consumption of electricity is strongly influenced by the type of technology used, for example stack cell flotation utilized less electricity compared to the column flotation. Table 9 presents the LCA results in which Option 1A-C generated less CO_2-e compared to the reference scenario (OPT 3). These scenarios generated 39.5%, 45.2%, and 45.2% less CO_2-e, respectively.

Table 9

Total GHG reduction value

Tailings management	Global warming[a] (kg CO_2-e)	Total GHG value ($)
OPT 1	920	-426
OPT 1A	523	2,646
OPT 1B	474	3,028
OPT 1C	474	3,028
OPT 2	1,104	-1,859
OPT 3	865	reference scenario

[a] life cycle assessment supplement data

The authors also used Option 3 as a reference scenario when calculating the value of carbon reduction. The calculation of the reduction value used a carbon market price of $10.8 per ton CO_2-e (World Bank and Ecofys, 2016). The results displayed in Table 9 indicate that Options 1A-C generated positive values, while Option 1 and 2 generated negative values. The negative values reflect the higher amount of carbon equivalent produced by those options as compared to the reference scenario. Options 1A-C contributed positive values in the range of $2,646 to $3,028 (referring to carbon market mechanism), and BCA discussed in Section 4.3 considers this value as a benefit.

4.3 Benefits cost analysis (BCA)

Tailings are a by-product of fine raw coal processing where the main product is saleable coal. These two products contribute to the financial flow of a mining company. Therefore, it is essential to identify the incremental costs and benefits for each option to determine the most cost-effective one.

This study focuses on four components considered to have a benefit value: (1) coal product generated from the fine raw coal processing, (2) water reclaimed from the segregation and dewatering process, (3) land conservation for the tailings disposal area, and (4) GHG reductions from renewable energy technology and application. These elements play a significant role in improving the sustainability level of the tailings management practices. The sum of these components represents the benefit value of each scenario and is used to determine the feasibility of each tailings disposal method. The benefits and costs of each option were evaluated based on a time horizon. The lifetime of a mining operation excluding the post-mine closure is estimated to be 20 years. One of the critical factors that determine the total time horizon of the tailings management is land rehabilitation. The average time required to reclaim the disposal area including the drying time and the reclamation process was two years for Option 1, three years for Option 2, and five years for Option 3 (EMGA Mitchell McLennan, 2012; Jones and Watkins, 2015).

The cost value of each option was calculated using the values from Tables 4 and 5 and shown in Table 10. Option 1C had the lowest total cost value compared to the other options. The deep cone thickener (paste) technology with the tailings dam method applied in Option 2 provided a total cost of 20% higher than that of Option 1C. This difference was mainly due to the low operational costs of the co-disposal operation (Table 5). The operational cost-saving by using Option 1C was $1.2 per ton compared to Option 2. Another option that used the thickener technology with tailings dam facility generated a total cost of 45% higher than Option 1C. This result is dominantly affected by the amount of solids in the tailings slurry where the solids content in Option 1C was 35% greater than Option 3.

In contrast to the total cost, the total net benefits presented in Table 10 showed that Option 1C produced the highest benefit ($996 million) compared to all other options. The three components contributing to these results were water conservation, land conservation, and GHG reductions as discussed in Section 4.2.

Table 10

Net Present Value (NPV) with 7% discount rate

Tailings management	Total cost ($)	Total benefits ($)	Total net benefits ($)	NPV ($)	Preference
OPT 1	371,328,738	995,812,427	624,483,690	307,376,828	4
OPT 1A	356,171,019	995,815,499	639,644,480	314,880,435	3
OPT 1B	354,291,359	995,750,345	641,458,986	315,775,687	2
OPT 1C	354,290,210	995,788,811	641,498,602	315,795,875	1
OPT 2	425,987,452	932,621,493	506,634,041	247,168,814	5
OPT 3	514,839,246	918,558,821	403,719,575	205,308,234	6

The total net benefits resulting from the quantification of costs and benefits during mine tailings operations were then discounted at a rate of 7% per year (Australian Government, 2016, 2014). This calculation presented in Equation (4) provided an NPV for each mine tailings management option. The highest NPV was for Option 1C, which uses the belt press technology with stack cell flotation instead of column flotation and 10% of fossil fuels substituted with wind energy.

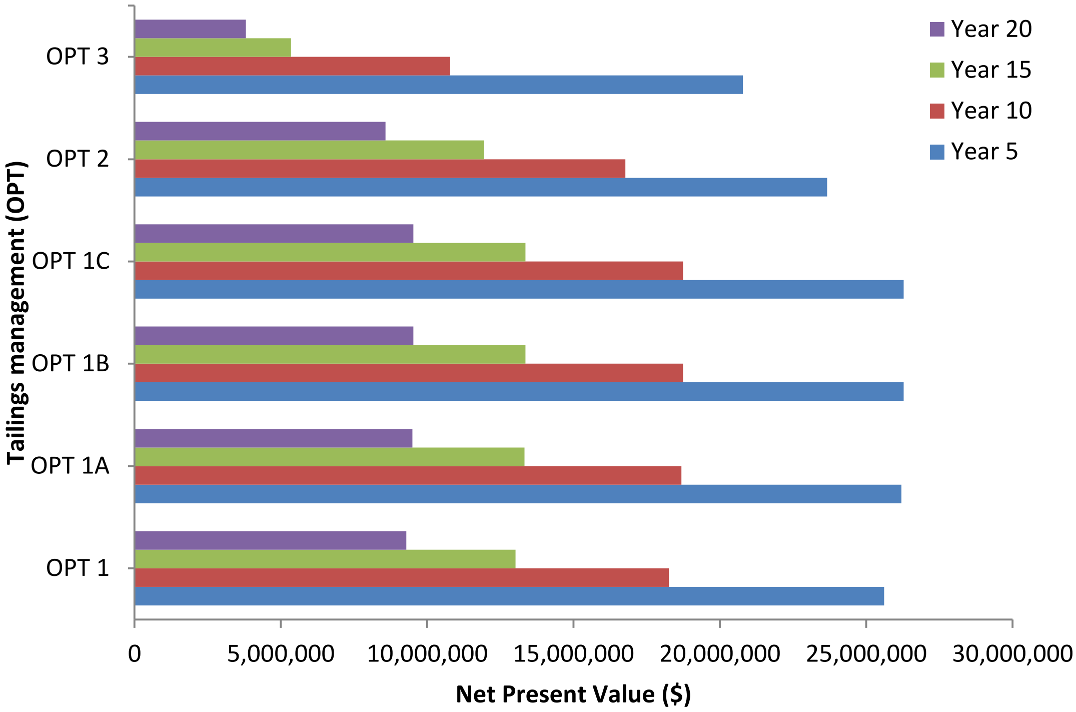

Fig.4 NPV of tailings management Option in different time horizon

The NPV results in every five years also showed that Option 1C was the most preferred scenario for this mine site (Fig.4). The average percent difference in the NPV for all options in Year 5, 10, 15, and 20 was 29%. It means that the discount rate of 7% contributed to the NPV reduction by more than a quarter of its original value in every five years. Table 10 and Fig.4 indicate that all options have higher Present Benefit Values (PBV) than the Present Cost Values (PCV). In other words, all options are considered feasible for application in this mining site (PBV-PCV > 0).

4.3.1 Sensitivity analysis

A sensitivity analysis is undertaken in a BCA to assess the data uncertainty that would affect the overall costs and benefits of the mine tailings scenario. In this study, the sensitivities to the lifespan and the discount rate were analyzed.

The discount rate in the BCA was analyzed by changing the rate from 7% to 3% and 10%. The NPV results for the three discount rates and four lifespans are shown in Fig.5. The results revealed that NPV increases as the discount rate decreases, as predicted. Changes in the discount rate contributed significantly to the total NPV, total operational cost, and total benefits value. A significant increase in NPV, by 47%, occurred when the discount rate was decreased from 7% to 3%. The increase in NPV was greater than 80% when the discount rate was reduced by 7% (from 10% to 3%).

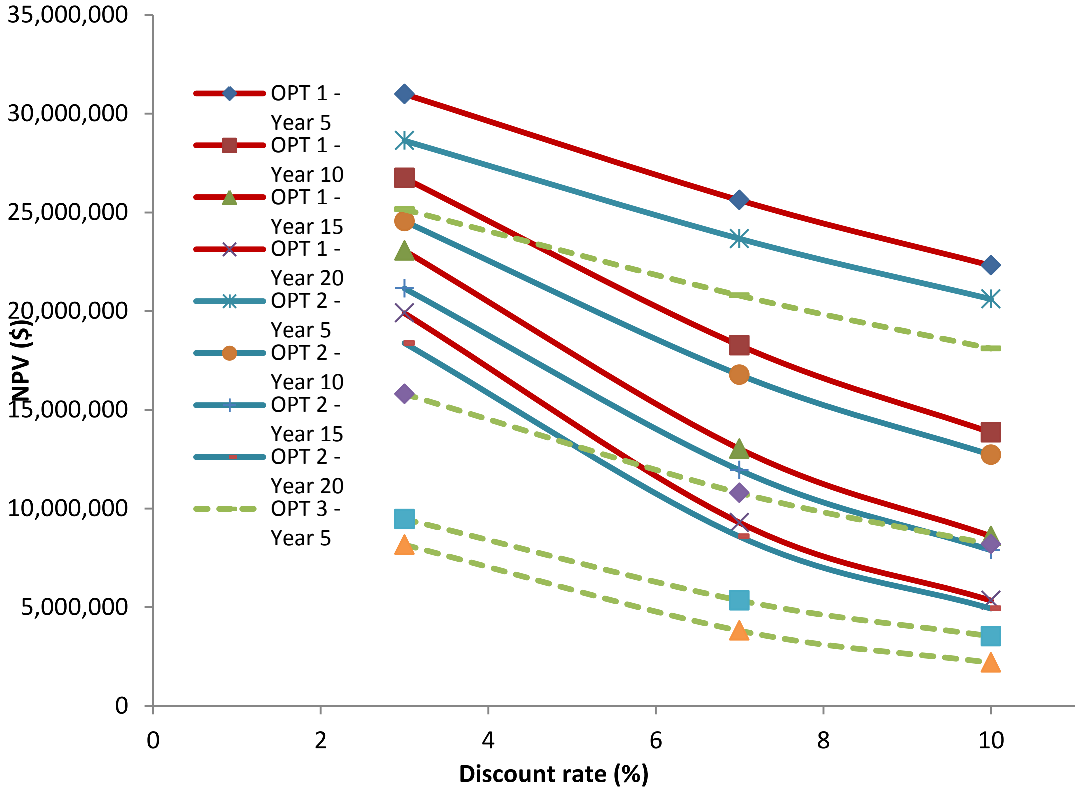

Fig.5 NPV with various discount rates

Overall, BCA was significantly affected by the changes in the discount rate, as the discount rate contributed to the future operational cost and benefits value. Therefore, BCA is considered to be sensitive to the discount rate and any differences in the rate should be considered when comparing the results with the other BCA studies.

4.4 Selection the optimum scenario

The most feasible scenario out of the six available options for tailings management was determined using a normalization approach where LCC, BCA, and GHG emissions were the main parameters. These parameters have different units (i.e. AU$, kilogram CO_2-e) and scales, therefore the value of these parameters was divided by their optimum values to provide the normalized results (Azapagic, 1999; Huppes and Ishikawa, 2005; Islam et al., 2014; Mangan and Oral, 2016). The results are presented in Fig.6 and the most feasible option was indicated as the one with the normalized value close to unity.

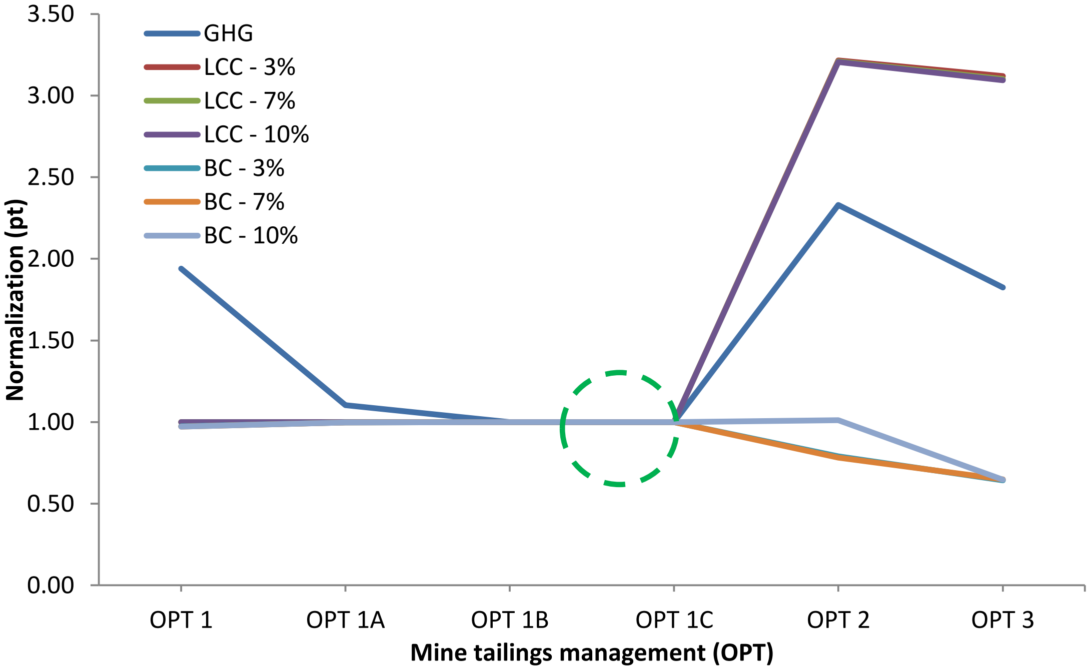

Fig.6 Normalized GHG, LCC, and BCA results

The best scenario (Option 1C) is the belt press operation with stack cell flotation and 10% fossil fuel substituted with wind power (detailed points as follows: GHG= 1, LCC 3%-10%≈ 1.001 and, BCA 3%-10%= 1). Option 1B and Option 1A also have values close to the most preferred scenario (Fig.6). Option 1B has similar characteristics to Option 1C except for the type of renewable energy introduced to the system: solar power (PV) versus wind power. The utilization of PV generates a land conservation value of 1.3% lower than the wind power. The third feasible option (Option 1A) is a scenario that uses the belt press as the main dewatering process to increase the mass percent of the solids in tailings up to 65% and that uses the stack cell flotation in the segregation process. In Option 1A, the electricity was supplied by a coal-fired power plant that amplified the GHG emissions to 10% higher than Option 1C. The utilization of fossil fuel energy as the electricity source decreases the LCC value by 0.1% and benefits value by 0.3% compared with the most feasible scenario (Option 1C).

5.1 Conclusions

This paper discusses the economic value of the coal mine tailings management activities. The economic value analysis is required to assist the stakeholders including mining companies and the government in determining the most feasible option from various available scenarios in terms of financial considerations and the environmental sustainability.

The study compares six options that use three different dewatering technologies: belt press, paste thickener, and tailings thickener. These technologies affect the water conservation volume, chemical use, and electricity consumption. Changes in the use of the raw fine coal segregation technology (column flotation to stack cell flotation) in Options 1A-C result in decreasing electricity consumption compared to other scenarios. The introduction of the renewable energy in Options 1B-C also increases the carbon reduction level in these two scenarios. In summary, Option 1C was found to be the most preferable scenario generating benefit values of 0.01% to 54% higher and LCC values of -0.1% to 221% lower compared to other scenarios.

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CENTRE FOR WATER IN THE MINERALS INDUSTRY

CWiMI Hierarchical Systems Model – User Guide

Ver 1.0

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14 February 2014

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AUSTRALIA

SMI CWiMI
Centre for Water in the Minerals Industry

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Table of Contents

1 Introduction

1.1 Introduction to the User's Guide

This document presents a user's guide to the Centre for Water in the Minerals Industry's (CWiMI's) Hierarchical System Model (HSM). This is intended to provide an easy to understand set of instructions for people wanting to execute and alter models using the HSM. For a more information about the HSM and its related themes please consult the Further Reading chapter or contact Dr. Alan Woodley (a.woodley@uq.edu.au) or Dr. Greg Keir (g.kier1@uq.edu.au).

1.2 Introduction of the HSM

The HSM allows mining companies to represent their water and energy interactions at the site and regional scale. The HSM can be used to explore these links and to identify areas of trade-offs and synergies. The HSM has been developed using the similar systems modelling approach to previous models developed by CWiMI, SiteMiser and WaterMiner (http://waterminer.smi.uq.edu.au) and the Mineral Council of Australia's Water Accounting Framework (http://www.wateraccounting.net.au) but extended to include energy/emissions and the ability to represent interactions on different scales. It is assumed that the reader of the report has a fundamental understanding of the components and methodology involved in the systems modelling approach, and how it has been applied in the HSM. For a thorough description of the HSM please refer to "Modelling the Water, Energy and Economic Nexus. ACARP Research Report C21033".

1.3 Introduction of Modelica

Modelica is a non-proprietary, object-oriented, equation based modelling language that can be used to model complex and interconnected systems. Both the Modelica language and the free Modelica Standard Library have been developed by the non-profit Modelica Association. Syntatically, Modelica resembles object-oriented programming languages, such as C++ or Java, but differs in two important respects: 1) it translates its models into objects which are executed by a simulation engine and 2) the primary content of models are equations, which represent equality rather than assignment. In Modelica, equations have no predefined causality and so the simulation engine needs to manipulate equations symbolically to determine their execution order and separate inputs and outputs. Further information on Modelica can be found at https://modelica.org/documents/.

1.4 Using the HSM with a Modelica Integrated Development Environment

We recommend that a Modelica Integrated Development Environment (IDE) is used in order to develop models with the HSM. An IDE provides a graphical user interface and a set of built in solvers and compilers making it an easy-to-use and efficient method for developing code.

The HSM has been built in Wolfram Alpha's SystemModeller (http://www.wolfram.com/system-modeler/) (specifically version 3.0) and this is the IDE that we recommend you use. A specific advantage of System Modeller is that the models can be integrated with Wolfram's other technologies such as Mathematica. SystemModeller is the IDE that will be used throughout this document and it is assumed that the reader of the document has access to it.

A list of other tools, including free tools, is available from the Modelica webpage (https://www.modelica.org/tools). Two commonly used free tools are OpenModelica (https://www.openmodelica.org/) and OneModelica (http://www.onewind.de/OneModelica.html).

2 HSM Basics

2.1 Loading the HSM

1. All of the components of the HSM are contained with a single Modelica mode file (hsm.mo). This file can be loaded either by double clicking on the file in explorer or by choosing **“File ->Open”** from the SystemModeller menu.

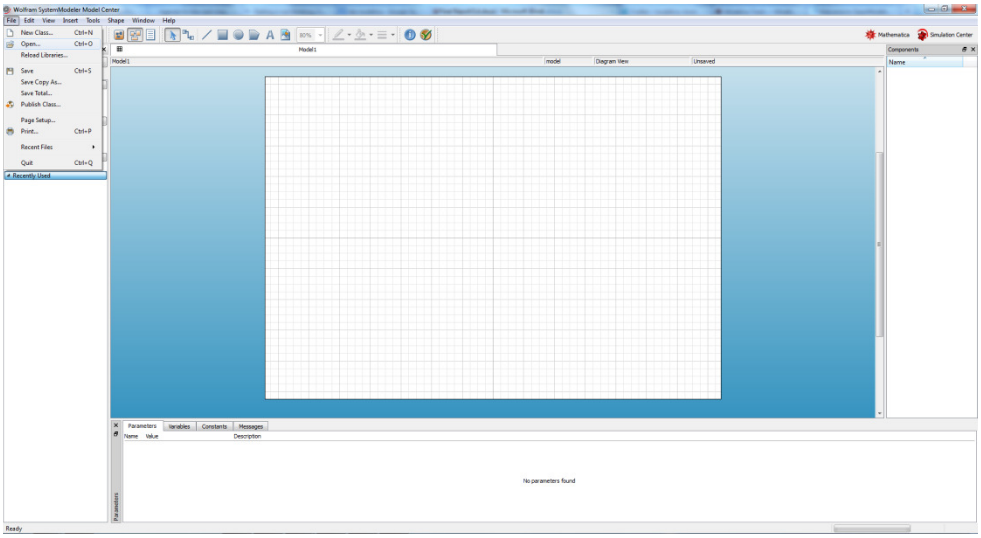
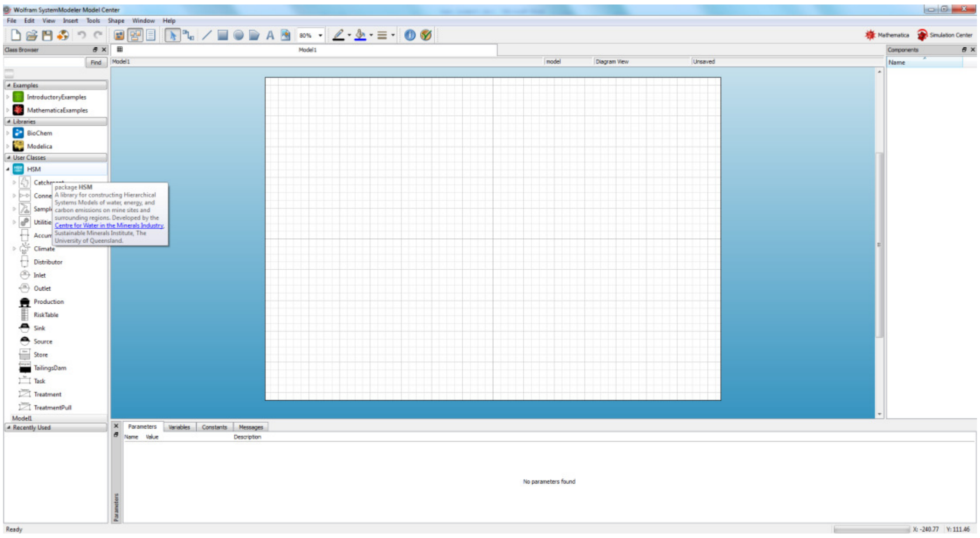


Figure 2-1 - Opening a file in SystemModeller

2. Once the HSM mode file has loaded, the user can click on its icon to reveal all of its components.

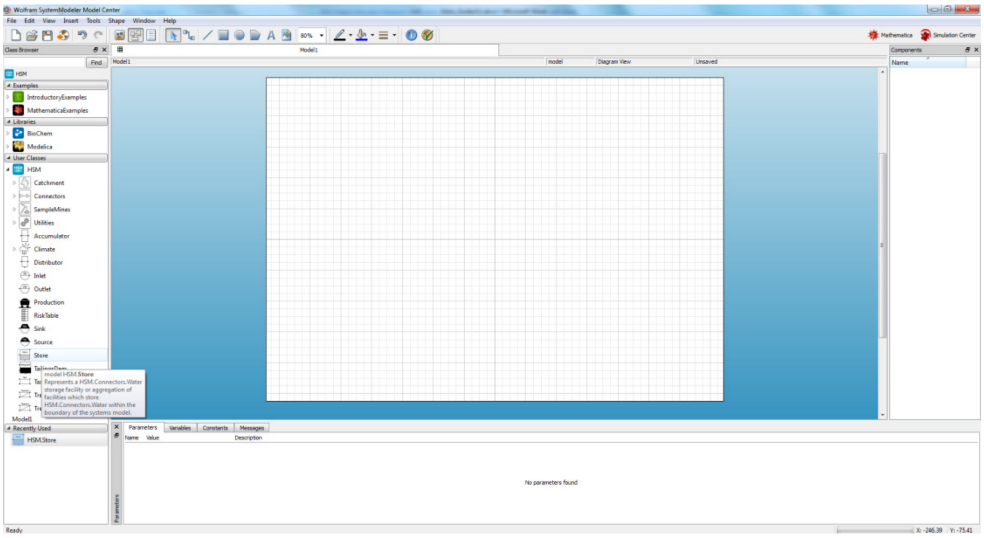


package HSM
A library for constructing Hierarchical Systems Models of water, energy, and carbon emissions on mine sites and surrounding regions. Developed by the Centre for Water in the Minerals Industry, Sustainable Minerals Institute, The University of Queensland.

Figure 2-2 – Listing the HSM components

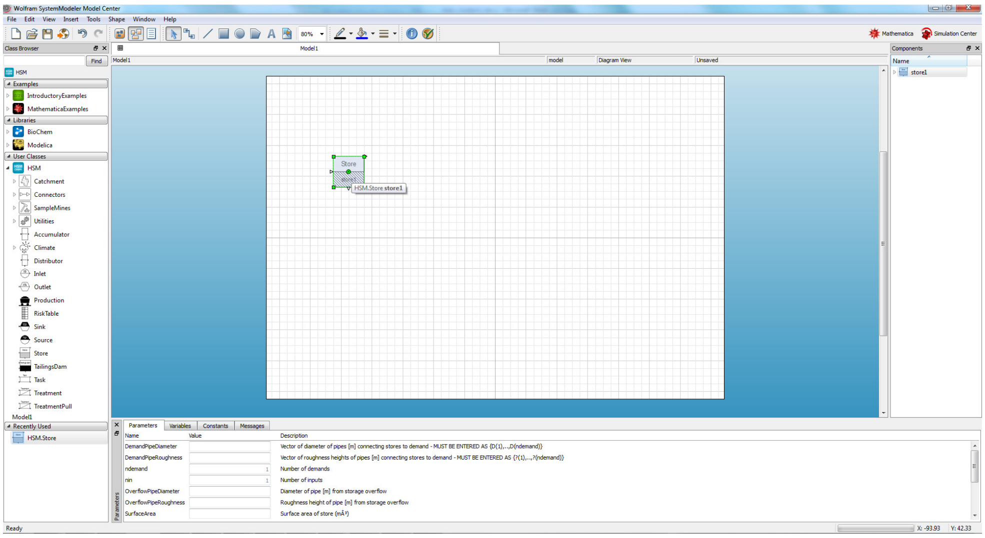
2.2 Adding Components

1. Individual components can be selected by dragging and dropping them on the gridded model area. Here, the user selects a Store component and drags it onto the grid.



model HSM.**Store**
Represents a HSM.Connectors.Water storage facility or aggregation of facilities which store HSM.Connectors.Water within the boundary of the systems model.

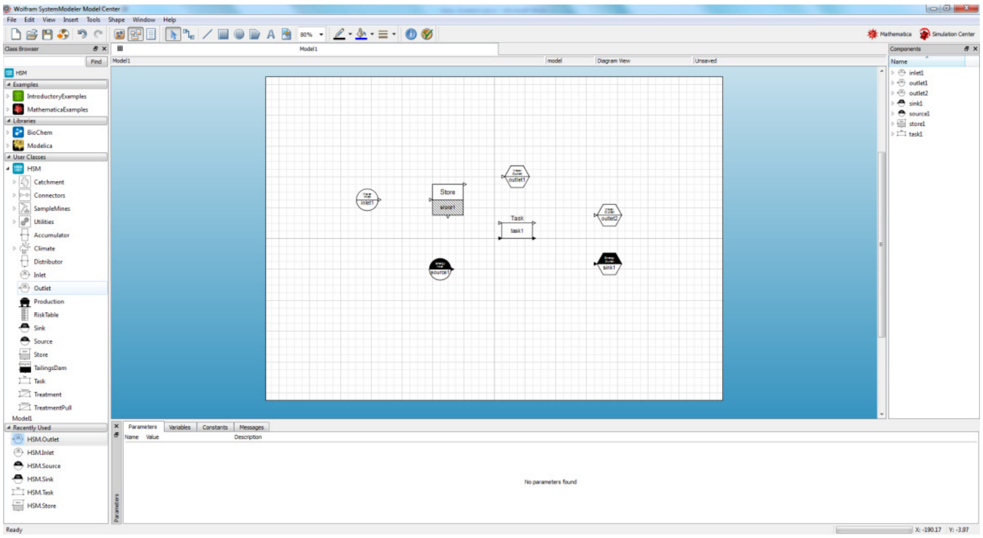
Figure 2-3 – Selecting a Store



Name	Value	Description
DemandPipeDiameter		Vector of diameter of pipes [m] connecting stores to demand - MUST BE ENTERED AS {D(1),..,D(ndemand)}
DemandPipeRoughness		Vector of roughness heights of pipes [m] connecting stores to demand - MUST BE ENTERED AS {?(1),..,?(ndemand)}
ndemand	1	Number of demands
nin	1	Number of inputs
OverflowPipeDiameter		Diameter of pipe [m] from storage overflow
OverflowPipeRoughness		Roughness height of pipe [m] from storage overflow
SurfaceArea		Surface area of store (mÂ³)

Figure 2-4 – Placing a Store on the grid

2. By selecting multiple components and dragging them onto the grid the foundation for a system is formed. Here a basic system is represented that contains: a Store, a Task, a Water Inlet, two Water Outlets, an Energy Inlet and an Energy Outlet.



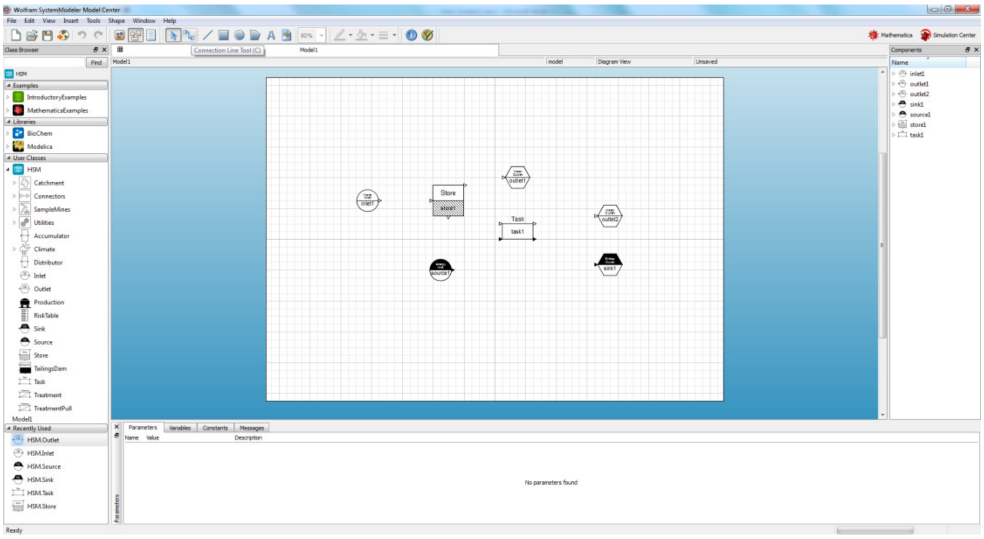
No parameters found

Figure 2-5 – A set of components

2.3 Connecting Components

1. Components can be connected together by a Connection Line. There are two types of Connections Lines: 1) a Water Connection Line that sends water between components and 2) an Energy Connection Line that send energy/emissions between components.

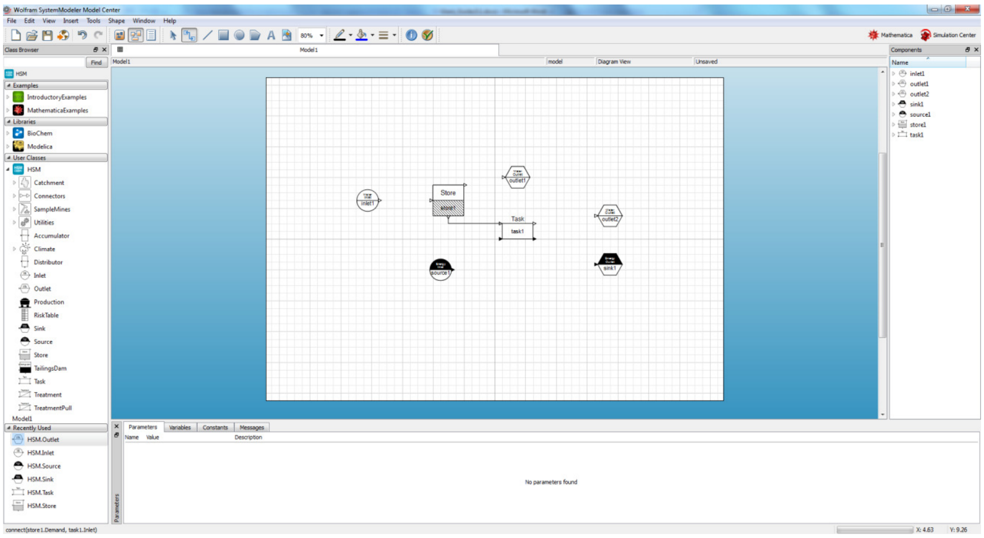
2. To select a Connection Lines, first click on the "**Connection Line Tool**" on the SystemModeller menu.



No parameters found

Figure 2-6 – Selecting a connection line

3. Next choose the source and destination component. Here a connection is made between the water out-connector of the Store and in-connector of Task.



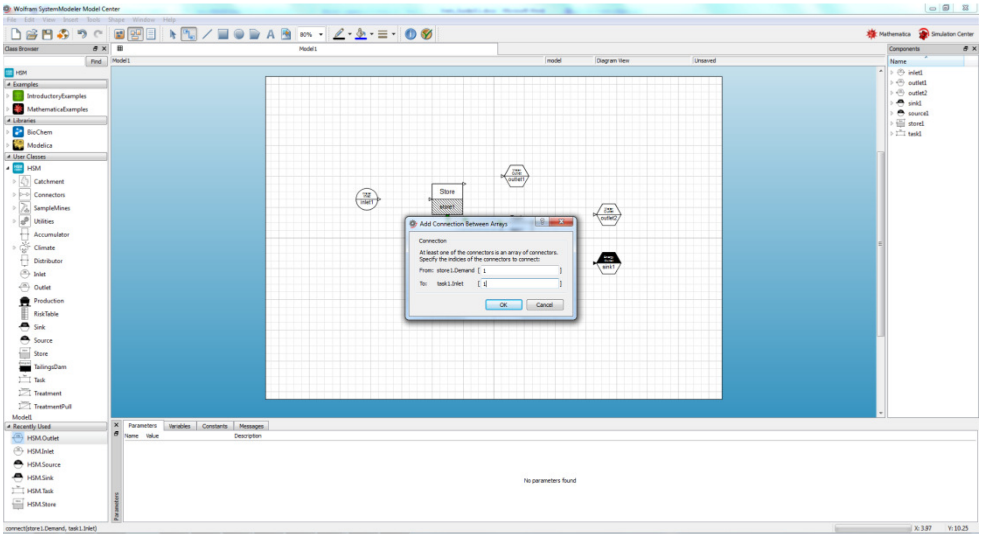
No parameters found

connect(store1.Demand, task1.Inlet)

Figure 2-7 – Selecting a connection line

Tip: When connecting together components, make sure to attach the appropriate Connection Line to the appropriate in-connector or out-connector (i.e. water in-connector/out-connector – white triangle, energy in-connector/out-connector – black triangle).

4. It is possible to connect more than one component to a single inlet/outlet. Here the Store's first outlet is connected to the Tasks first inlet.



Add Connection Between Arrays

Connection

At least one of the connectors is an array of connectors.
Specify the indicies of the connectors to connect:

From: store1.Demand [1]

To: task1.Inlet [1]

OK Cancel

No parameters found

connect(store1.Demand, task1.Inlet)

Figure 2-8 – Adding a connection line to the appropriate in and out connectors

5. By connecting together multiple components a system can be formed. This is explored in the next two chapters in terms of a Mine and a Region.

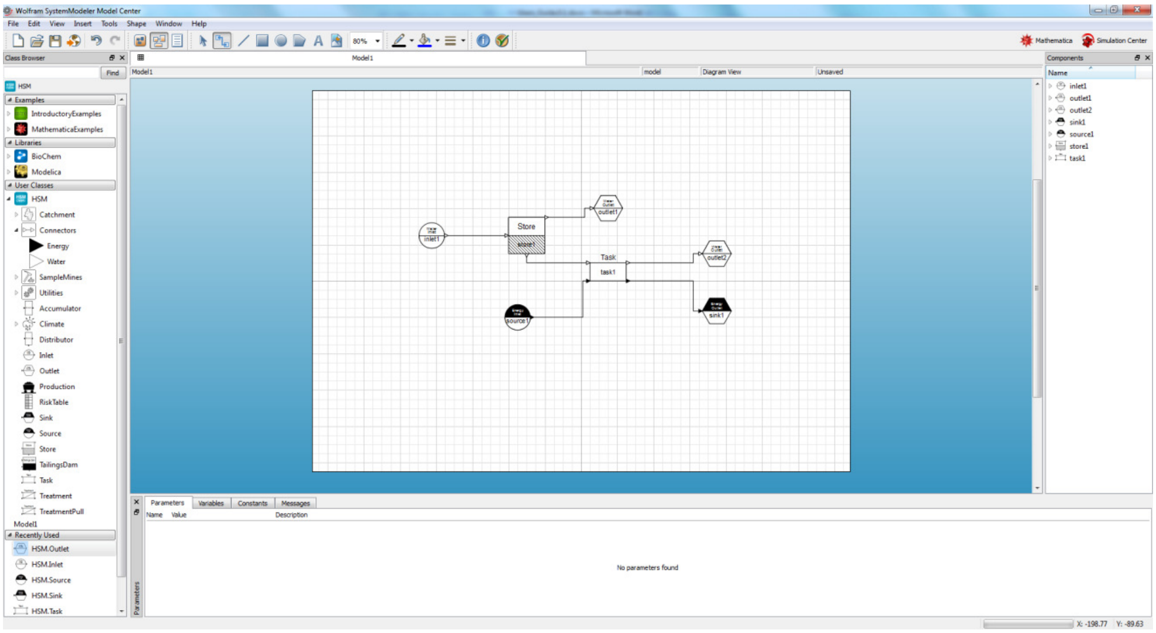


Figure 2-9 – A simple system of connected components

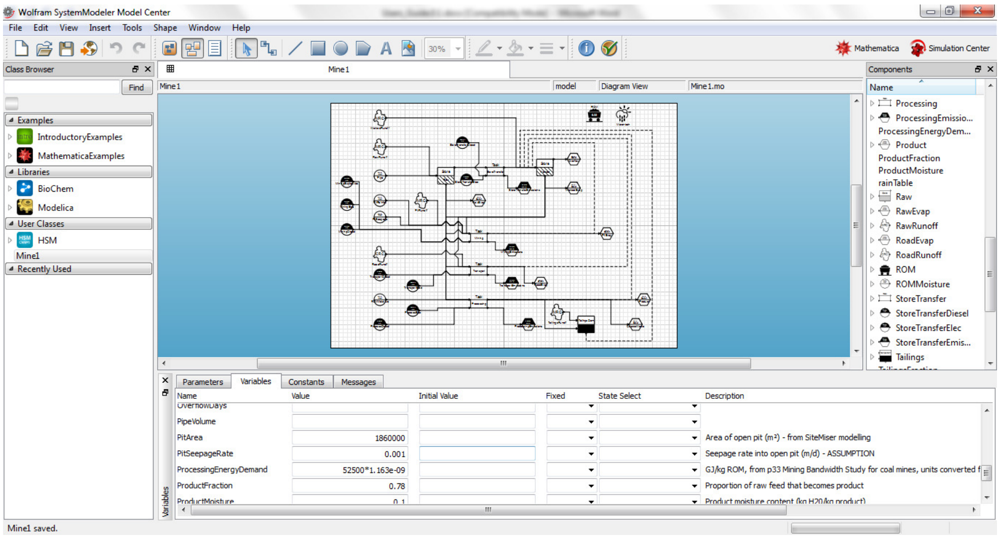
3 Modelling a Mine

3.1 Loading a Mine

1. Just like the HSM itself, Mines are usually stored as a single Modelica model file. Once again the file can be loaded either by double clicking on the file in explorer or by choosing **“File ->Open”** from the SystemModeller menu. Here, the user selects “Mine1.mo”, a case study used throughout the report for ACARP Project C21033.

3.2 Exploring the Mine

1. Once the Mine has been loaded its details can be explored by scrolling down through the information box in the bottom of the screen where the attributes of the Mine are listed (parameters, variables or constants). Here, a list of attributes is shown including the PitArea.

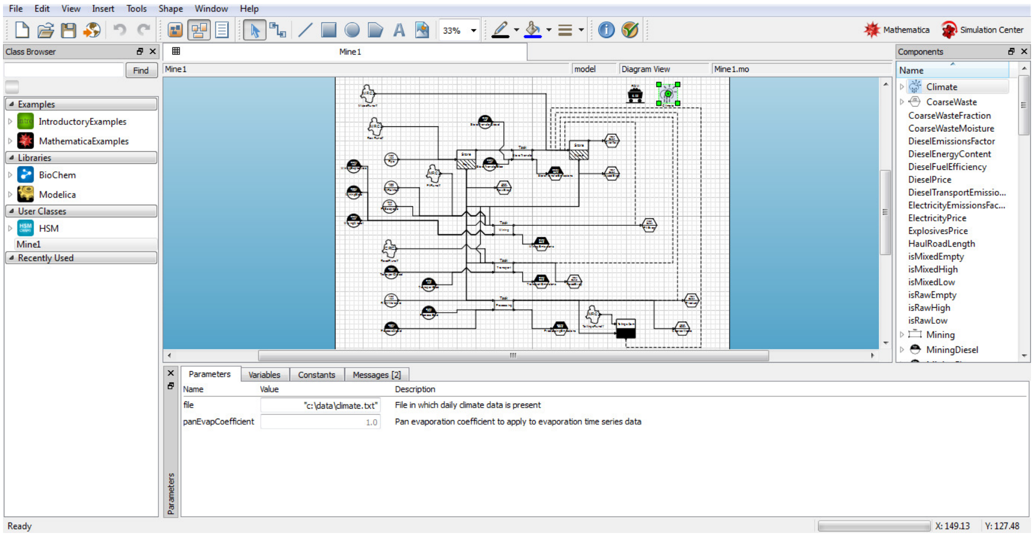


Name	Value	Initial Value	Fixed	State Select	Description
OverflowDays					
PipeVolume					
PitArea	1860000				Area of open pit (m²) - from SiteMiser modelling
PitSeepageRate	0.001				Seepage rate into open pit (m/d) - ASSUMPTION
ProcessingEnergyDemand	52500*1.163e-09				GJ/kg ROM, from p33 Mining Bandwidth Study for coal mines, units converted f
ProductFraction	0.78				Proportion of raw feed that becomes product
ProductMoisture	0.1				Product moisture content (kg H20/kg product)

Figure 3-1 – An example of a Mine showing its pit area

2. One attribute that needs to be set correctly is the climate variable. This is the text file in SILO DataDrill format (see http://www.longpaddock.qld.gov.au/silo/programmer_notes.html for details) that holds the rainfall and evaporation data. It is accessible by clicking on “Climate” in the grid. Here it is set to “*C:/data/climate.txt*” (including quotation marks).

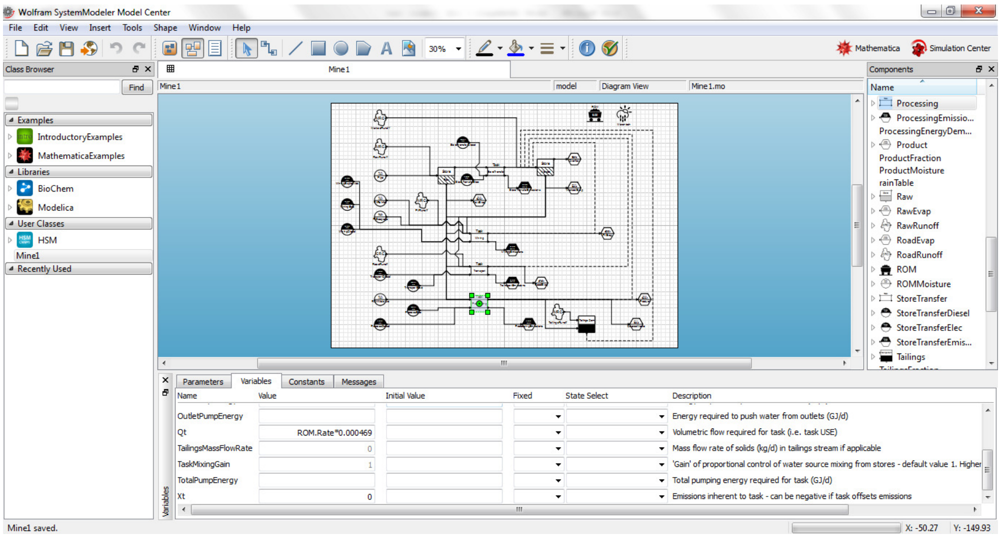
Tip: When specifying a data file it is best to specific its full name (for example: “C:/data/climate.txt” rather than its relative name (for example: “climate.txt”).



Name	Value	Description
file	"c:\data\climate.txt"	File in which daily climate data is present
panEvapCoefficient	1.0	Pan evaporation coefficient to apply to evaporation time series data

Figure 3-2 – The climate variable for the Mine

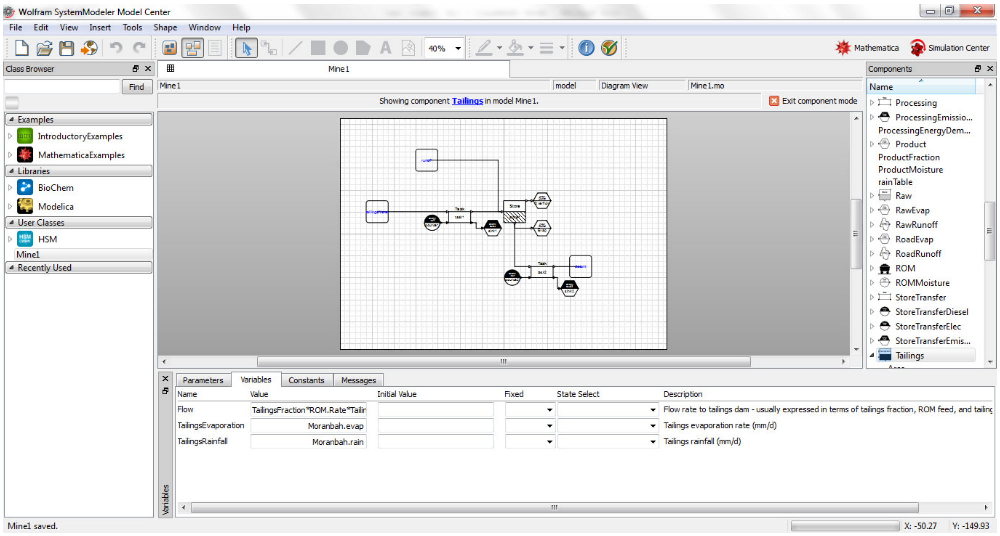
3. Individual components attributes can also be selected. First, by selecting a component by clicking on it within the model's grid, and then by exploring the information box as before. Here, it is shown that the daily water demand of the Processing Task is proportional to the rate of production.



Name	Value	Initial Value	Fixed	State Select	Description
OutletPumpEnergy					Energy required to push water from outlets (GJ/d)
Qt	ROM.Rate*0.000469				Volumetric flow required for task (i.e. task USE)
TailingsMassFlowRate	0				Mass flow rate of solids (kg/d) in tailings stream if applicable
TaskMixingGain	1				'Gain' of proportional control of water source mixing from stores - default value 1. Higher
TotalPumpEnergy					Total pumping energy required for task (GJ/d)
Xt	0				Emissions inherent to task - can be negative if task offsets emissions

Figure 3-3 –Water demand for the Processing task

4. Some components can contain sub components which can also be explored. Here, the user double clicks on the Tailings Dam component to reveal that it contains two Tasks (one to handle waste and the other to handle decant) and a Store. Clicking on the "**Exit Component Model**" button returns the user to the Mine.



Showing component **Tailings** in model Mine1.

Name	Value	Initial Value	Fixed	State Select	Description
Flow	TailingsFraction*ROM.Rate*Tailin				Flow rate to tailings dam - usually expressed in terms of tailings fraction, ROM feed, and tailing
TailingsEvaporation	Moranbah.evap				Tailings evaporation rate (mm/d)
TailingsRainfall	Moranbah.rain				Tailings rainfall (mm/d)

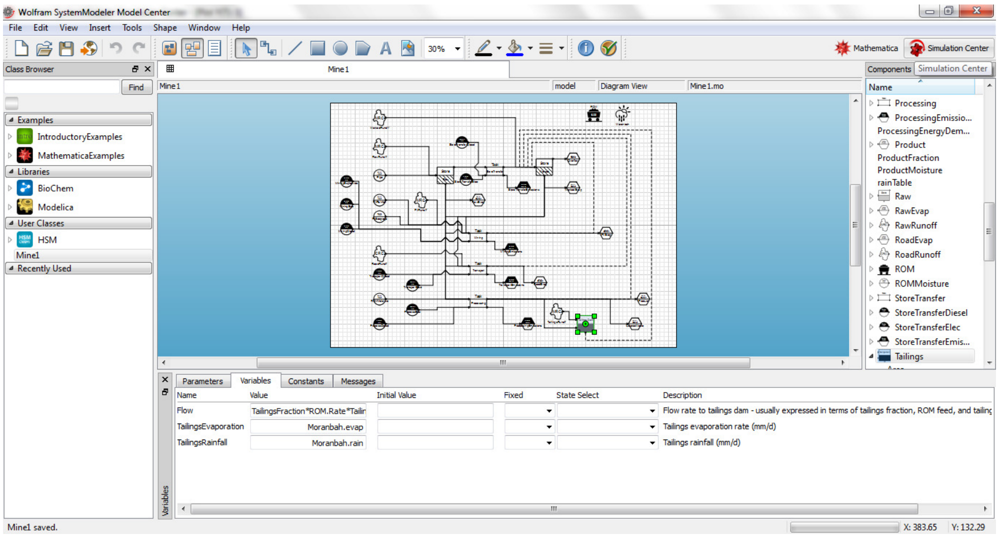
Mine1 saved.

Figure 3-4 –The Tailings Dam

Tip: Make sure to exit a subcomponent before you try to execute simulations (see next section), otherwise SystemModeller will try to execute just the subcomponent rather than the entire model.

3.3 Executing a Simulation

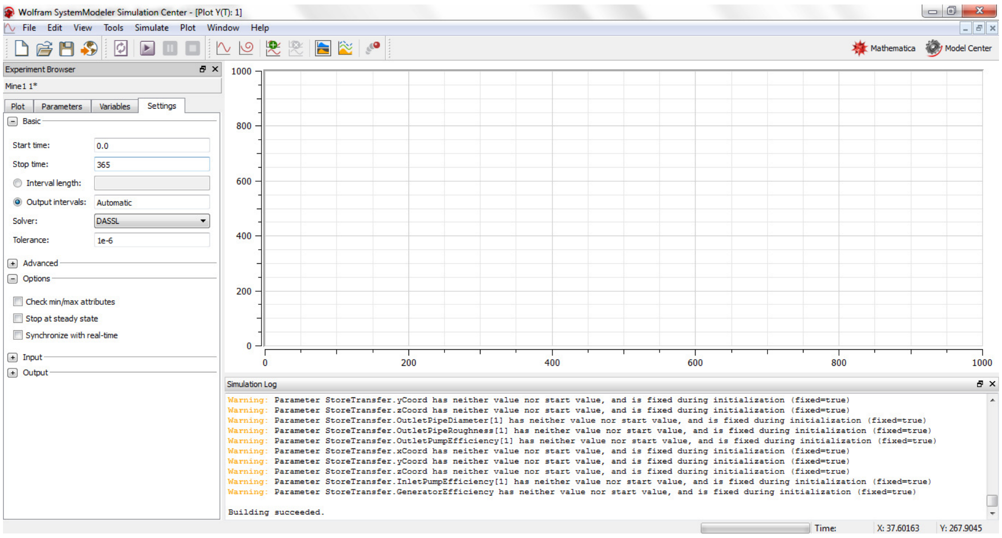
1. A simulation of the model can be executed by clicking on the “**Simulation Centre**” in the top right hand corner. This opens up the Simulation Centre programme and transforms the model into a format that be executed by the computer.



Name	Value	Initial Value	Fixed	State Select	Description
Flow	TailingsFraction*ROM.Rate*Tailin				Flow rate to tailings dam - usually expressed in terms of tailings fraction, ROM feed, and tailinc
TailingsEvaporation	Moranbah.evap				Tailings evaporation rate (mm/d)
TailingsRainfall	Moranbah.rain				Tailings rainfall (mm/d)

Figure 3-5 –Start Simulation Centre

2. Before performing a simulation the Start Time and End Time need to be specified, which in these cases specify the number of days that will be simulated. Here, the user specifies the Start Time as 0 and the End Time as 365, meaning that it will simulate a year’s worth of data.



Start time: 0.0
Stop time: 365
○ Interval length:
● Output intervals: Automatic
Solver: DASSL
Tolerance: 1e-6

☐ Check min/max attributes
☐ Stop at steady state
☐ Synchronize with real-time

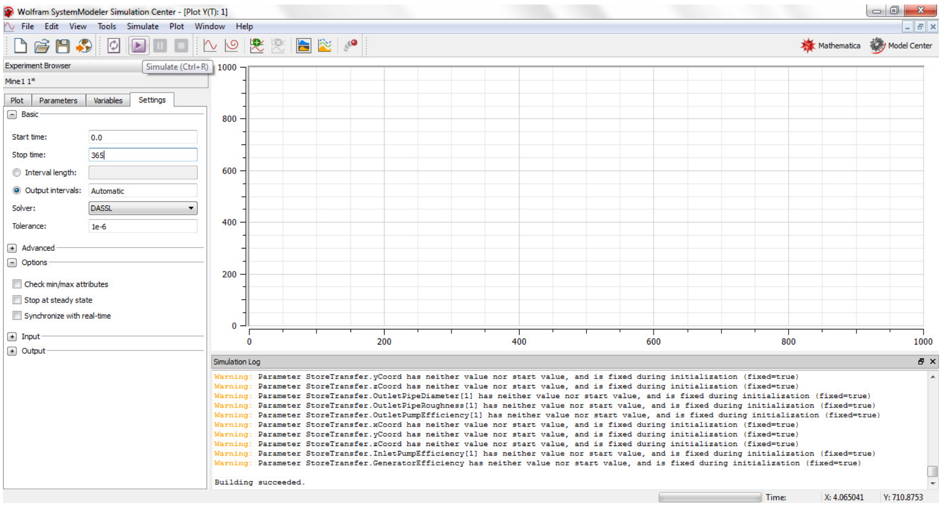
```
Warning: Parameter StoreTransfer.yCoord has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter StoreTransfer.zCoord has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter StoreTransfer.OutletPipeDiameter[1] has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter StoreTransfer.OutletPipeRoughness[1] has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter StoreTransfer.OutletPumpEfficiency[1] has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter StoreTransfer.xCoord has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter StoreTransfer.yCoord has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter StoreTransfer.zCoord has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter StoreTransfer.InletPumpEfficiency[1] has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter StoreTransfer.GeneratorEfficiency has neither value nor start value, and is fixed during initialization (fixed=true)

Building succeeded.
```

Figure 3-6 –Specifying start and end days

Tip: The time axis in SystemModeler displays seconds as the default time unit; however, the HSM is designed so that days are the basic time unit. While the default time axis label is ‘Time [s]’, the user should understand that the actual time scale in model output is in days.

3. To begin the simulation the user clicks on the “**Run Simulation**” link in the Simulation Centre Menu.



Start time: 0.0
Stop time: 365
○ Interval length:
● Output intervals: Automatic
Solver: DASSL
Tolerance: 1e-6

☐ Check min/max attributes
☐ Stop at steady state
☐ Synchronize with real-time

```
Warning: Parameter StoreTransfer.yCoord has neither value nor start value, and is fixed during initialization (fixed=true)
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Warning: Parameter StoreTransfer.GeneratorEfficiency has neither value nor start value, and is fixed during initialization (fixed=true)

Building succeeded.
```

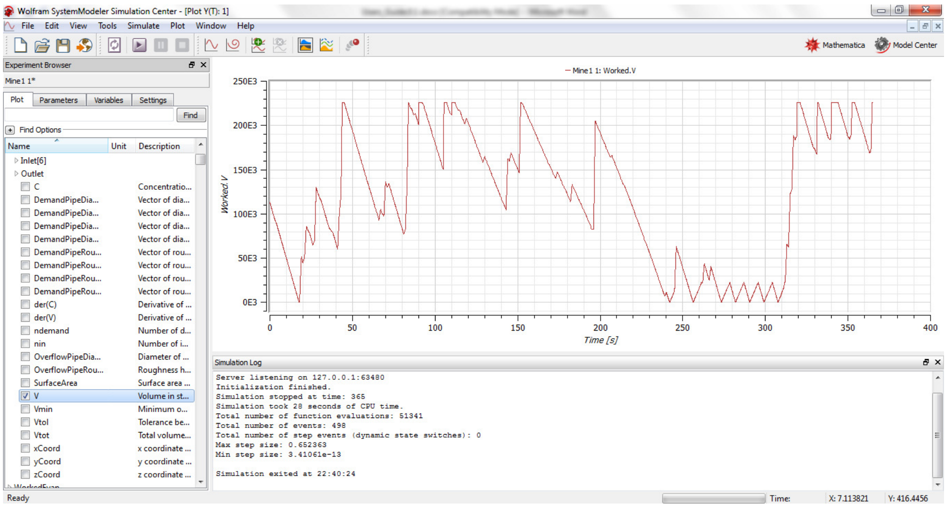
Time: X: 4.065041 Y: 710.8753

Figure 3-7 – Running a Simulation

3.4 Plotting Results

1. Once the simulation is complete, is results can be plotted. This is done by selecting the “**Plot**” tab in the “**Experiment Browser**” box on the left hand size and selecting which values to plot.

2. Here, the user wants to view the volume in the Mixed Store. First, the user clicks on “**Mixed**” to open up the Mixed Stores values, and then clicks the box next to the attribute “**V**” to plot its volume.



Name	Unit	Description
▷ Inlet[6]		
▷ Outlet		
☐ C		Concentratio...
☐ DemandPipeDia...		Vector of dia...
☐ DemandPipeDia...		Vector of dia...
☐ DemandPipeDia...		Vector of dia...
☐ DemandPipeDia...		Vector of dia...
☐ DemandPipeRou...		Vector of rou...
☐ DemandPipeRou...		Vector of rou...
☐ DemandPipeRou...		Vector of rou...
☐ DemandPipeRou...		Vector of rou...
☐ der(C)		Derivative of ...
☐ der(V)		Derivative of ...
☐ ndemand		Number of d...
☐ nin		Number of i...
☐ OverflowPipeDia...		Diameter of ...
☐ OverflowPipeRou...		Roughness h...
☐ SurfaceArea		Surface area ...
☑ V		Volume in st...
☐ Vmin		Minimum o...
☐ Vtol		Tolerance be...
☐ Vtot		Total volume...
☐ xCoord		x coordinate ...
☐ yCoord		y coordinate ...
☐ zCoord		z coordinate ...

```
Server listening on 127.0.0.1:63480
Initialization finished.
Simulation stopped at time: 365
Simulation took 28 seconds of CPU time.
Total number of function evaluations: 51341
Total number of events: 498
Total number of step events (dynamic state switches): 0
Max step size: 0.652363
Min step size: 3.41061e-13

Simulation exited at 22:40:24
```

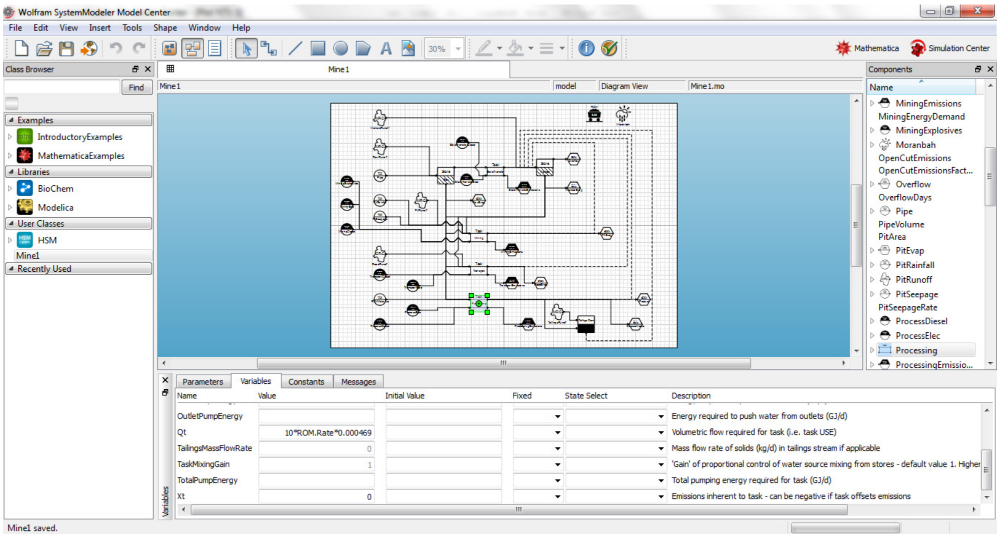
Time: X: 7.113821 Y: 416.4456

Figure 3-8 –Plotting the volume of the Mixed Store

3. After, plotting results the user can close the set of the results by clicking on the “x” in the “**Experiment Browser**” box.

3.5 Defining Behaviour

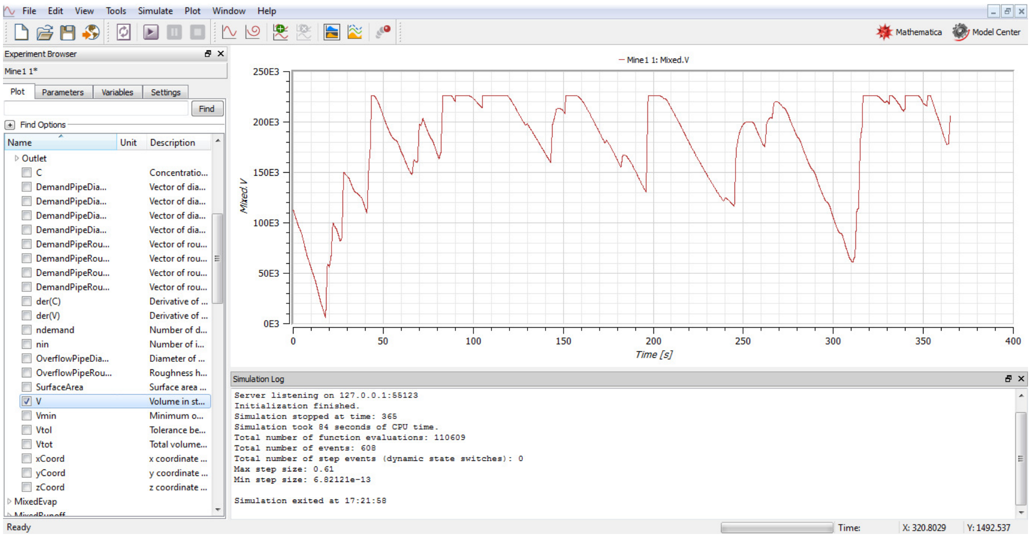
1. The behaviour of the system can be defined by changing the attribute of a component. This allows users to explore how the Mine acts under different configurations.
2. First, go back to System Modeller and click on the component to change. Here, the user clicks on the Processing Task.
3. Next, change one of the component's attributes (either parameter, variable or constant) by changing its value in the information box. Here, the users changes the water used in the processing plant by a factor of 10 by changing the Qt attribute of the Processing Task from "ROM.Rate*0.000469" to "10 * ROM.Rate*0.000469".



Name	Value	Initial Value	Fixed	State Select	Description
OutletPumpEnergy					Energy required to push water from outlets (GJ/d)
Qt	10*ROM.Rate*0.000469				Volumetric flow required for task (i.e. task USE)
TailingsMassFlowRate	0				Mass flow rate of solids (kg/d) in tailings stream if applicable
TaskMixingGain	1				'Gain' of proportional control of water source mixing from stores - default value 1. Higher
TotalPumpEnergy					Total pumping energy required for task (GJ/d)
Xt	0				Emissions inherent to task - can be negative if task offsets emissions

Figure 3-9 – Changing the value of the Processing demand

4. As before, the user can perform a simulation and plot the results. This will allow the user to observe how the increased Processing demand changes the volume in the Mixed Store, in this example particularly around day 240.



```
Server listening on 127.0.0.1:55123
Initialization finished.
Simulation stopped at time: 365
Simulation took 84 seconds of CPU time.
Total number of function evaluations: 110609
Total number of events: 608
Total number of step events (dynamic state switches): 0
Max step size: 0.61
Min step size: 6.82121e-13

Simulation exited at 17:21:58
```

Figure 3-10 – Impact of change to Processing Task's demand on Mixed Store's volume

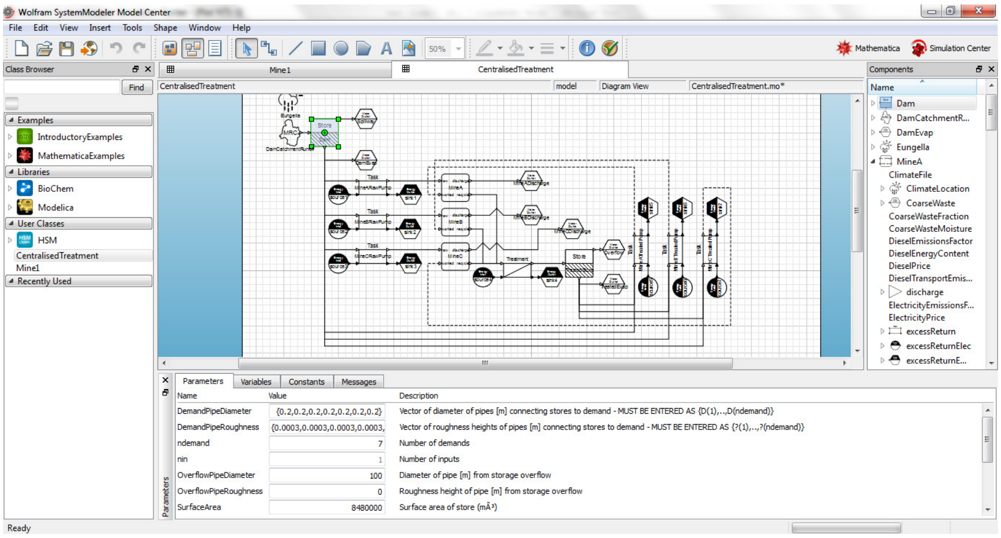
4 Modelling a Region

4.1 Loading a Region

1. As with Mines, Regions are usually stored as a single Modelica model file (*.mo). Once again the file can be loaded either by double clicking on the file in explorer or by choosing **"File ->Open"** from the SystemModeller menu. Here, the user selects "CentralisedTreatment.mo", one of the case study used throughout the report for ACARP Project C21033.

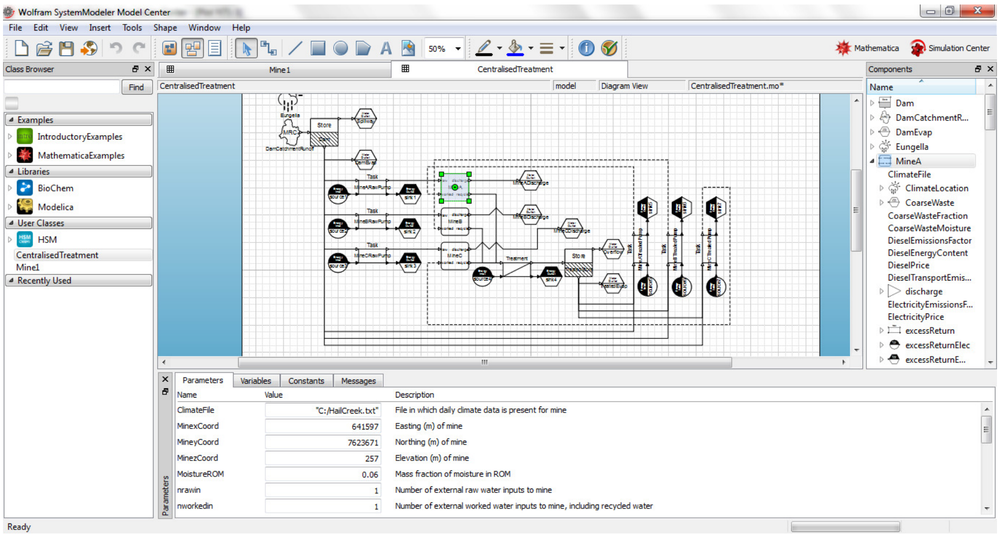
4.2 Exploring the Region

1. This case study contains three Mines that share a centralised treatment plant and a Regional Dam, which is represented as a Store. As before, it is possible to click on the Dam and explore its attributes in the information box.



Name	Value	Description
DemandPipeDiameter	{0.2,0.2,0.2,0.2,0.2,0.2,0.2}	Vector of diameter of pipes [m] connecting stores to demand - MUST BE ENTERED AS {D(1),..,D(ndemand)}
DemandPipeRoughness	{0.0003,0.0003,0.0003,0.0003,	Vector of roughness heights of pipes [m] connecting stores to demand - MUST BE ENTERED AS {?(1),..,?(ndemand)}
ndemand	7	Number of demands
nin	1	Number of inputs
OverflowPipeDiameter	100	Diameter of pipe [m] from storage overflow
OverflowPipeRoughness	0	Roughness height of pipe [m] from storage overflow
SurfaceArea	8480000	Surface area of store (mÂ³)

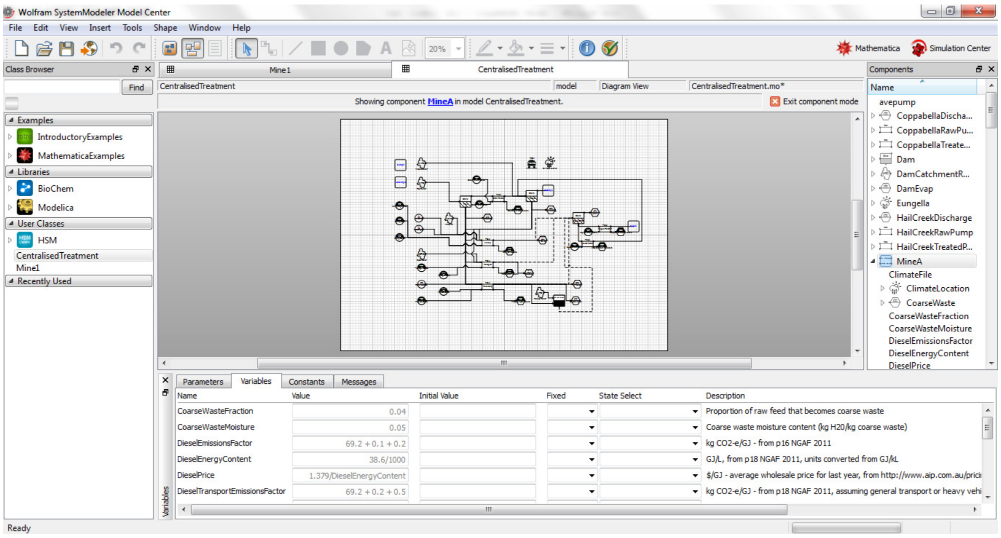
Figure 4-1 –Multiple Mines sharing a Regional Dam



Name	Value	Description
ClimateFile	"C:/HailCreek.txt"	File in which daily climate data is present for mine
MinexCoord	641597	Easting (m) of mine
MineyCoord	7623671	Northing (m) of mine
MinezCoord	257	Elevation (m) of mine
MoistureROM	0.06	Mass fraction of moisture in ROM
nrawin	1	Number of external raw water inputs to mine
nworkedin	1	Number of external worked water inputs to mine, including recycled water

Figure 4-2 – User clicks on Mine A in the Region

2. The Mine components can also be explored. A single click lists the attributes of a Mine and a double click enters a Mine allowing the user to explore each of the Mine subcomponents. Here, the user clicks on "Mine A", an open cut Mine with a similar configuration to the Mine shown in the previous chapter.



Showing component MineA in model CentralisedTreatment.

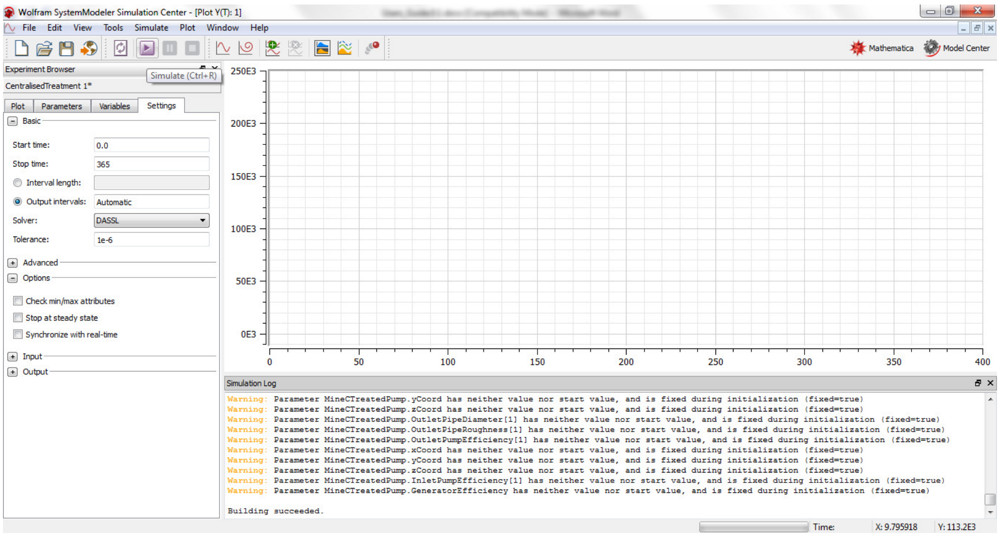
Name	Value	Initial Value	Fixed	State Select	Description
CoarseWasteFraction	0.04				Proportion of raw feed that becomes coarse waste
CoarseWasteMoisture	0.05				Coarse waste moisture content (kg H20/kg coarse waste)
DieselEmissionsFactor	69.2 + 0.1 + 0.2				kg CO2-e/GJ - from p16 NGAF 2011
DieselEnergyContent	38.6/1000				GJ/L, from p18 NGAF 2011, units converted from GJ/kL
DieselPrice	1.379/DieselEnergyContent				$/GJ - average wholesale price for last year, from http://www.aip.com.au/prici
DieselTransportEmissionsFactor	69.2 + 0.2 + 0.5				kg CO2-e/GJ - from p18 NGAF 2011, assuming general transport or heavy vehi

Figure 4-3 –Inside the model of Mine A

3. As before, the user can click on any of Mine A's components to explore them. As before, the user should click the "**Exit Component Model**" button when finished exploring the subcomponents.

4.3 Executing a Simulation

1. As before, the user can run a simulation (this time on the entire Region) by following the same steps as above (clicking on the "**Simulation Centre**" button, specifying a start and end day and clicking "**Run Simulation**"). Due to the inherent extra complexity of a Region, it will often take longer to run than an individual Mine.



Start time: 0.0
Stop time: 365
○ Interval length:
● Output intervals: Automatic
Solver: DASSL
Tolerance: 1e-6

☐ Check min/max attributes
☐ Stop at steady state
☐ Synchronize with real-time

```
Warning: Parameter MineCTreatedPump.yCoord has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter MineCTreatedPump.zCoord has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter MineCTreatedPump.OutletPipeDiameter[1] has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter MineCTreatedPump.OutletPipeRoughness[1] has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter MineCTreatedPump.OutletPumpEfficiency[1] has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter MineCTreatedPump.xCoord has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter MineCTreatedPump.yCoord has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter MineCTreatedPump.zCoord has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter MineCTreatedPump.InletPumpEfficiency[1] has neither value nor start value, and is fixed during initialization (fixed=true)
Warning: Parameter MineCTreatedPump.GeneratorEfficiency has neither value nor start value, and is fixed during initialization (fixed=true)

Building succeeded.
```

Time: X: 9.795918 Y: 113.2E3

Figure 4-4 –Simulating a Region

4.4 Plotting Results

1. As before, the user can plot of the results of the simulation by selecting the appropriate attribute. Here, the user plots the volume of water in the Regional Dam by selecting the "**V**" attribute from the "**Dam**" component.

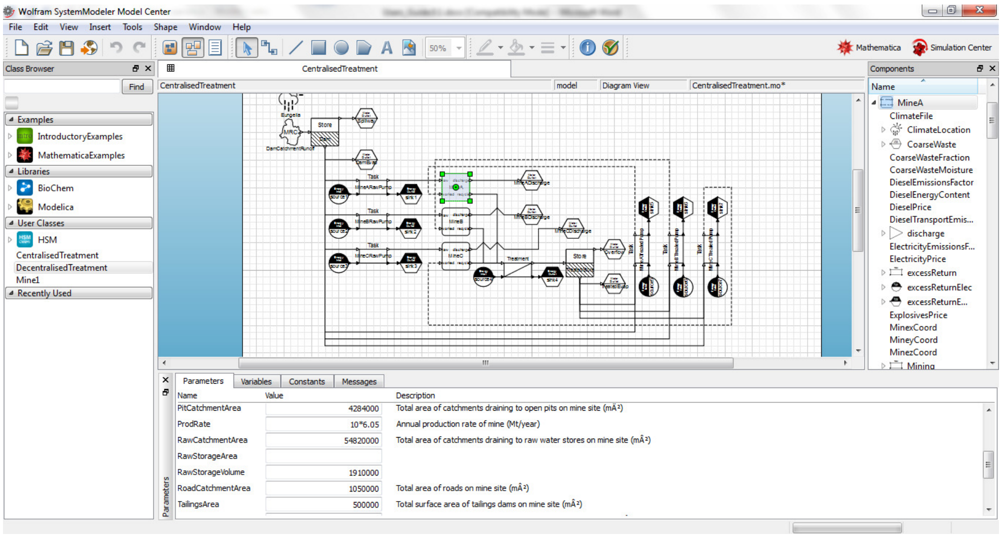
Name	Unit	Description
☐ DemandPipeRou...		Vector of rou...
☐ DemandPipeRou...		Vector of rou...
☐ DemandPipeRou...		Vector of rou...
☐ DemandPipeRou...		Vector of rou...
☐ DemandPipeRou...		Vector of rou...
☐ DemandPipeRou...		Vector of rou...
☐ DemandPipeRou...		Vector of rou...
☐ der(C)		Derivative of ...
☐ der(V)		Derivative of ...
☐ ndemand		Number of d...
☐ nin		Number of i...
☐ OverflowPipeDia...		Diameter of ...
☐ OverflowPipeRou...		Roughness h...
☐ SurfaceArea		Surface area ...
☑ V		Volume in st...
☐ Vmin		Minimum o...
☐ Vtol		Tolerance be...
☐ Vtot		Total volume...
☐ xCoord		x coordinate ...
☐ yCoord		y coordinate ...
☐ zCoord		z coordinate ...

```
Expected a Real number Syntax error at character 59 of
... mmyyyy) (oC) () (oC) () (mm) () (mm) () (MJ/m2) ...
*
Expected a Real number Syntax error at character 38 of
(yyyymmdd) () (ddmmyyyy) (oC) () (oC) () (mm) () (m ...
*
Expected a Real number Syntax error at character 1 of
(yyyymmdd) () (ddmmyyyy) (oC) () (oC) () (mm) () (m ...
*
Expected an Integer number
Simulation exited at 00:42:32
```

Figure 4-5 –Regional Dam volume

4.5 Defining Behaviour

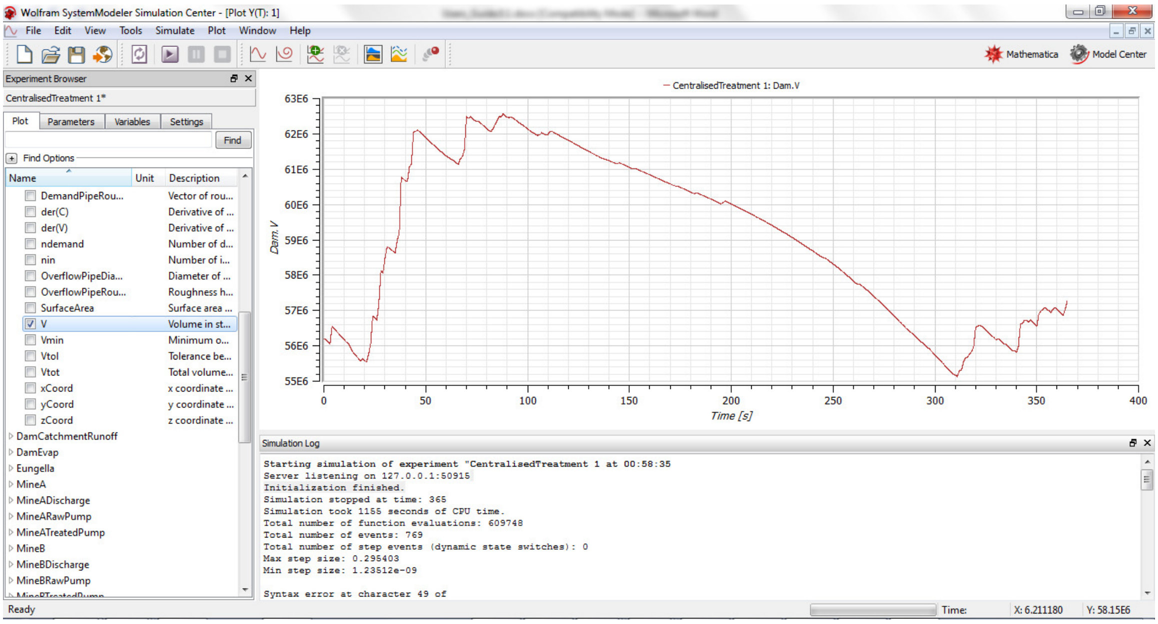
1. As before, the user can define the behaviour of the Region by changing the attributes of its components. Here, the user decides to double the production rate Mine A. The user returns to the Simulation Centre, clicks on Mine A from the Region's grid and changes its ProdRate value from 6.05 to 10 * 6.05.



Name	Value	Description
PitCatchmentArea	4284000	Total area of catchments draining to open pits on mine site (mÂ²)
ProdRate	10*6.05	Annual production rate of mine (Mt/year)
RawCatchmentArea	54820000	Total area of catchments draining to raw water stores on mine site (mÂ²)
RawStorageArea		
RawStorageVolume	1910000	
RoadCatchmentArea	1050000	Total area of roads on mine site (mÂ²)
TailingsArea	500000	Total surface area of tailings dams on mine site (mÂ²)

Figure 4-6 – Changing the production rate for Mine A

2. Now the user can perform another simulation and see how the change in production Rate has affected water volume in the Regional Dam.



Name	Unit	Description
☐ DemandPipeRou...		Vector of rou...
☐ der(C)		Derivative of ...
☐ der(V)		Derivative of ...
☐ ndemand		Number of d...
☐ nin		Number of i...
☐ OverflowPipeDia...		Diameter of ...
☐ OverflowPipeRou...		Roughness h...
☐ SurfaceArea		Surface area ...
☑ V		Volume in st...
☐ Vmin		Minimum o...
☐ Vtol		Tolerance be...
☐ Vtot		Total volume...
☐ xCoord		x coordinate ...
☐ yCoord		y coordinate ...
☐ zCoord		z coordinate ...

- DamCatchmentRunoff
- DamEvap
- Eungella
- MineA
- MineADischarge
- MineARawPump
- MineATreatedPump
- MineB
- MineBDischarge
- MineBRawPump

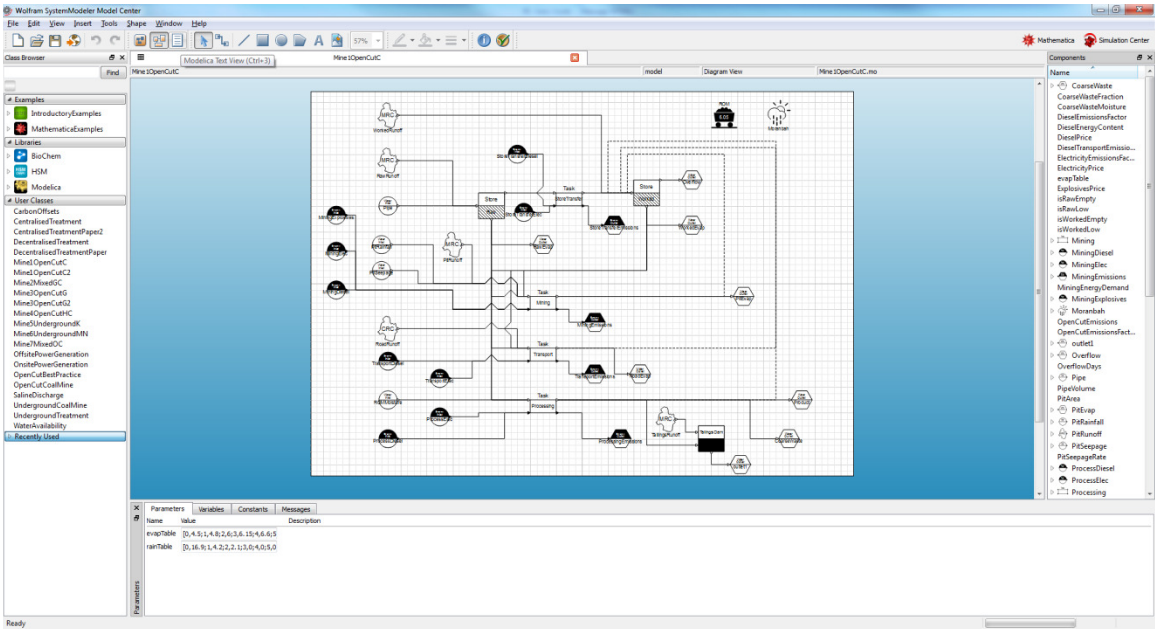
```
Starting simulation of experiment "CentralisedTreatment 1 at 00:58:35
Server listening on 127.0.0.1:50915
Initialization finished.
Simulation stopped at time: 365
Simulation took 1155 seconds of CPU time.
Total number of function evaluations: 609748
Total number of events: 769
Total number of step events (dynamic state switches): 0
Max step size: 0.295403
Min step size: 1.23512e-09

Syntax error at character 49 of
```

Figure 4-7 –Regional dam volume following production increase to MineA

5 Viewing Model Code Directly (Advanced Use)

The previous sections have described the use of the model via the graphical user interface only. Additional customisation for advanced users is available by directly examining and editing the model code. All model code is stored as plain text in *.mo files, which can be edited in a text editor of choice, or directly within the IDE as well by clicking the ‘Modelica Text View’ button in the upper left toolbar (shown below in Figure 5-1)

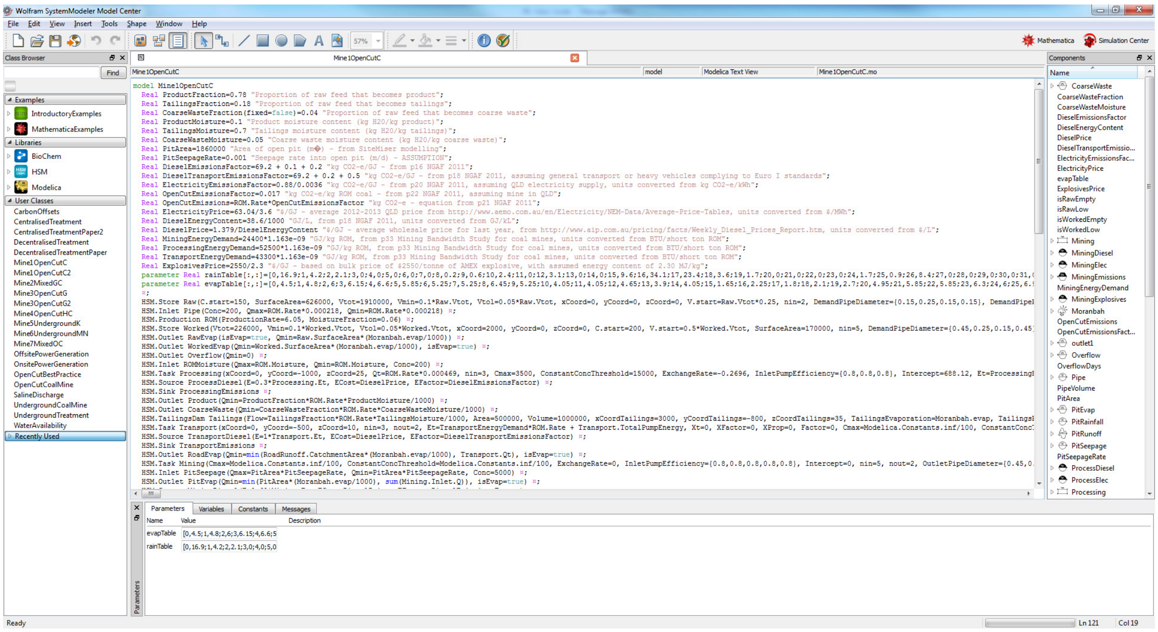


Name	Value	Description
evapTable	[0,4.5;1,4.8;2,6;3,6.15;4,6.6;5	
rainTable	[0,16.9;1,4.2;2,2.1;3,0;4,0;5,0	

Figure 5-1 –Accessing ‘Modelica Text View’ mode in IDE

This displays a textual view of the code that describes the model laid out in the graphical view, as shown in Figure 5-2. This may be useful to add additional equations to define advanced model behaviour, or to rapidly edit large portions of the model. This can be performed both for individual models, as well as components of the HSM itself.

While a significant effort has been made to comment all code in the HSM project, the developers note that this facility is intended for advanced users, and indiscriminate editing can easily result in models that do not respect the equality and assignment rules of Modelica (in simple terms, each model must contain exactly the same number of equations and unknowns, that is, the system must not be over-determined or under-determined), and hence fail to compile and run.



```
model Mine1OpenCutC
  Real ProductFraction=0.78 "Proportion of raw feed that becomes product";
  Real TailingsFraction=0.18 "Proportion of raw feed that becomes tailings";
  Real CoarseWasteFraction(fixed=false)=0.04 "Proportion of raw feed that becomes coarse waste";
  Real ProductMoisture=0.1 "Product moisture content (kg H20/kg product)";
  Real TailingsMoisture=0.7 "Tailings moisture content (kg H20/kg tailings)";
  Real CoarseWasteMoisture=0.05 "Coarse waste moisture content (kg H20/kg coarse waste)";
  Real PitArea=1860000 "Area of open pit (m�) - from SiteMiser modelling";
  Real PitSeepageRate=0.001 "Seepage rate into open pit (m/d) - ASSUMPTION";
  Real DieselEmissionsFactor=69.2 + 0.1 + 0.2 "kg CO2-e/GJ - from p16 NGAF 2011";
  Real DieselTransportEmissionsFactor=69.2 + 0.2 + 0.5 "kg CO2-e/GJ - from p18 NGAF 2011, assuming general transport or heavy vehicles complying to Euro I standards";
  Real ElectricityEmissionsFactor=0.88/0.0036 "kg CO2-e/GJ - from p20 NGAF 2011, assuming QLD electricity supply, units converted from kg CO2-e/kWh";
  Real OpenCutEmissionsFactor=0.017 "kg CO2-e/kg ROM coal - from p22 NGAF 2011, assuming mine in QLD";
  Real OpenCutEmissions=ROM.Rate*OpenCutEmissionsFactor "kg CO2-e - equation from p21 NGAF 2011";
  Real ElectricityPrice=63.04/3.6 "$/GJ - average 2012-2013 QLD price from http://www.aemo.com.au/en/Electricity/NEM-Data/Average-Price-Tables, units converted from $/MWh";
  Real DieselEnergyContent=38.6/1000 "GJ/L, from p18 NGAF 2011, units converted from GJ/kL";
  Real DieselPrice=1.379/DieselEnergyContent "$/GJ - average wholesale price for last year, from http://www.aip.com.au/pricing/facts/Weekly_Diesel_Prices_Report.htm, units converted from $/L";
  Real MiningEnergyDemand=24400*1.163e-09 "GJ/kg ROM, from p33 Mining Bandwidth Study for coal mines, units converted from BTU/short ton ROM";
  Real ProcessingEnergyDemand=52500*1.163e-09 "GJ/kg ROM, from p33 Mining Bandwidth Study for coal mines, units converted from BTU/short ton ROM";
  Real TransportEnergyDemand=43300*1.163e-09 "GJ/kg ROM, from p33 Mining Bandwidth Study for coal mines, units converted from BTU/short ton ROM";
  Real ExplosivesPrice=2550/2.3 "$/GJ - based on bulk price of $2550/tonne of AMEX explosive, with assumed energy content of 2.30 MJ/kg";
  parameter Real rainTable[:,:]=[0,16.9;1,4.2;2,2.1;3,0;4,0;5,0;6,0;7,0;8,0.2;9,0.6;10,2.4;11,0;12,3.1;13,0;14,0;15,9.6;16,34.1;17,23.4;18,3.6;19,1.7;20,0;21,0;22,0;23,0;24,1.7;25,0.9;26,8.4;27,0;28,0;29,0;30,0;31,
  parameter Real evapTable[:,:]=[0,4.5;1,4.8;2,6;3,6.15;4,6.6;5,5.85;6,5.25;7,5.25;8,6.45;9,5.25;10,4.05;11,4.05;12,4.65;13,3.9;14,4.05;15,1.65;16,2.25;17,1.8;18,2.1;19,2.7;20,4.95;21,5.85;22,5.85;23,6.3;24,6;25,6.
  ¤;
  HSM.Store Raw(C.start=150, SurfaceArea=626000, Vtot=1910000, Vmin=0.1*Raw.Vtot, Vtol=0.05*Raw.Vtot, xCoord=0, yCoord=0, zCoord=0, V.start=Raw.Vtot*0.25, nin=2, DemandPipeDiameter={0.15,0.25,0.15,0.15}, DemandPipe
  HSM.Inlet Pipe(Conc=200, Qmax=ROM.Rate*0.000218, Qmin=ROM.Rate*0.000218) ¤;
  HSM.Production ROM(ProductionRate=6.05, MoistureFraction=0.06) ¤;
  HSM.Store Worked(Vtot=226000, Vmin=0.1*Worked.Vtot, Vtol=0.05*Worked.Vtot, xCoord=2000, yCoord=0, zCoord=0, C.start=200, V.start=0.5*Worked.Vtot, SurfaceArea=170000, nin=5, DemandPipeDiameter={0.45,0.25,0.15,0.45
  HSM.Outlet RawEvap(isEvap=true, Qmin=Raw.SurfaceArea*(Moranbah.evap/1000)) ¤;
  HSM.Outlet WorkedEvap(Qmin=Worked.SurfaceArea*(Moranbah.evap/1000), isEvap=true) ¤;
  HSM.Outlet Overflow(Qmin=0) ¤;
  HSM.Inlet ROMMoisture(Qmax=ROM.Moisture, Qmin=ROM.Moisture, Conc=200) ¤;
  HSM.Task Processing(xCoord=0, yCoord=-1000, zCoord=25, Qt=ROM.Rate*0.000469, nin=3, Cmax=3500, ConstantConcThreshold=15000, ExchangeRate=-0.2696, InletPumpEfficiency={0.8,0.8,0.8}, Intercept=688.12, Et=Processing
  HSM.Source ProcessDiesel(E=0.3*Processing.Et, ECost=DieselPrice, EFactor=DieselEmissionsFactor) ¤;
  HSM.Sink ProcessingEmissions ¤;
  HSM.Outlet Product(Qmin=ProductFraction*ROM.Rate*ProductMoisture/1000) ¤;
  HSM.Outlet CoarseWaste(Qmin=CoarseWasteFraction*ROM.Rate*CoarseWasteMoisture/1000) ¤;
  HSM.TailingsDam Tailings(Flow=TailingsFraction*ROM.Rate*TailingsMoisture/1000, Area=500000, Volume=1000000, xCoordTailings=3000, yCoordTailings=-800, zCoordTailings=35, TailingsEvaporation=Moranbah.evap, Tailings
  HSM.Task Transport(xCoord=0, yCoord=-500, zCoord=10, nin=3, nout=2, Et=TransportEnergyDemand*ROM.Rate + Transport.TotalPumpEnergy, Xt=0, XFactor=0, XProp=0, Factor=0, Cmax=Modelica.Constants.inf/100, ConstantConc
  HSM.Source TransportDiesel(E=1*Transport.Et, ECost=DieselPrice, EFactor=DieselTransportEmissionsFactor) ¤;
  HSM.Sink TransportEmissions ¤;
  HSM.Outlet RoadEvap(Qmin=min(RoadRunoff.CatchmentArea*(Moranbah.evap/1000), Transport.Qt), isEvap=true) ¤;
  HSM.Task Mining(Cmax=Modelica.Constants.inf/100, ConstantConcThreshold=Modelica.Constants.inf/100, ExchangeRate=0, InletPumpEfficiency={0.8,0.8,0.8,0.8,0.8}, Intercept=0, nin=5, nout=2, OutletPipeDiameter={0.45,0.
  HSM.Inlet PitSeepage(Qmax=PitArea*PitSeepageRate, Qmin=PitArea*PitSeepageRate, Conc=5000) ¤;
  HSM.Outlet PitEvap(Qmin=min(PitArea*(Moranbah.evap/1000), sum(Mining.Inlet.Q)), isEvap=true) ¤;
```

Name	Value	Description
evapTable	[0,4.5;1,4.8;2,6;3,6.15;4,6.6;5	
rainTable	[0,16.9;1,4.2;2,2.1;3,0;4,0;5,0	

Figure 5-2 –Example of ‘Modelica Text View’ mode in IDE

6 Conclusion

This user guide has described how to explore, simulate and plot the results of models developed using the CWiMI HSM. Both Mine and Region examples have been given using the graphical interface of the Wolfram SystemModeler IDE, with a brief discussion of directly editing model code for advanced users.

For a more thorough description of the HSM or a better description of how to execute the models please refer to the “Further Readings” chapter or contact Dr. Greg Keir (g.keir1@uq.edu.au).

7 Further Readings

7.1 Water Systems Modelling

MORAN, C., CÔTE, C., MCINTOSH, J., HEDEMANN, C. & SILVERSTER, N. 2006. Northern Bowen Basin water and salt management practices. ACARP Research Report C15001.

CÔTE, C., MORAN, C., GOZZARD, E., CRAVEN, A. & SHIH, J. 2009. Understanding leading practice in water management. ACARP Research Report C16035.

CÔTE, C. M., MORAN, C. J., HEDEMANN, C. J. & KOCH, C. 2010. Systems modelling for effective mine water management. *Environmental Modelling & Software,* 25**,** 1664-1671.

KUNZ, N. C., MORAN, C. J. & KASTELLEC, T. 2013. Implementing an integrated approach to water management by matching problem complexity with management responses: a case study of a mine site water committee. *Journal of Cleaner Production,* 52**,** 362-373.

7.2 Water and Energy Hierarchical Systems Modelling

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7.3 Modelica

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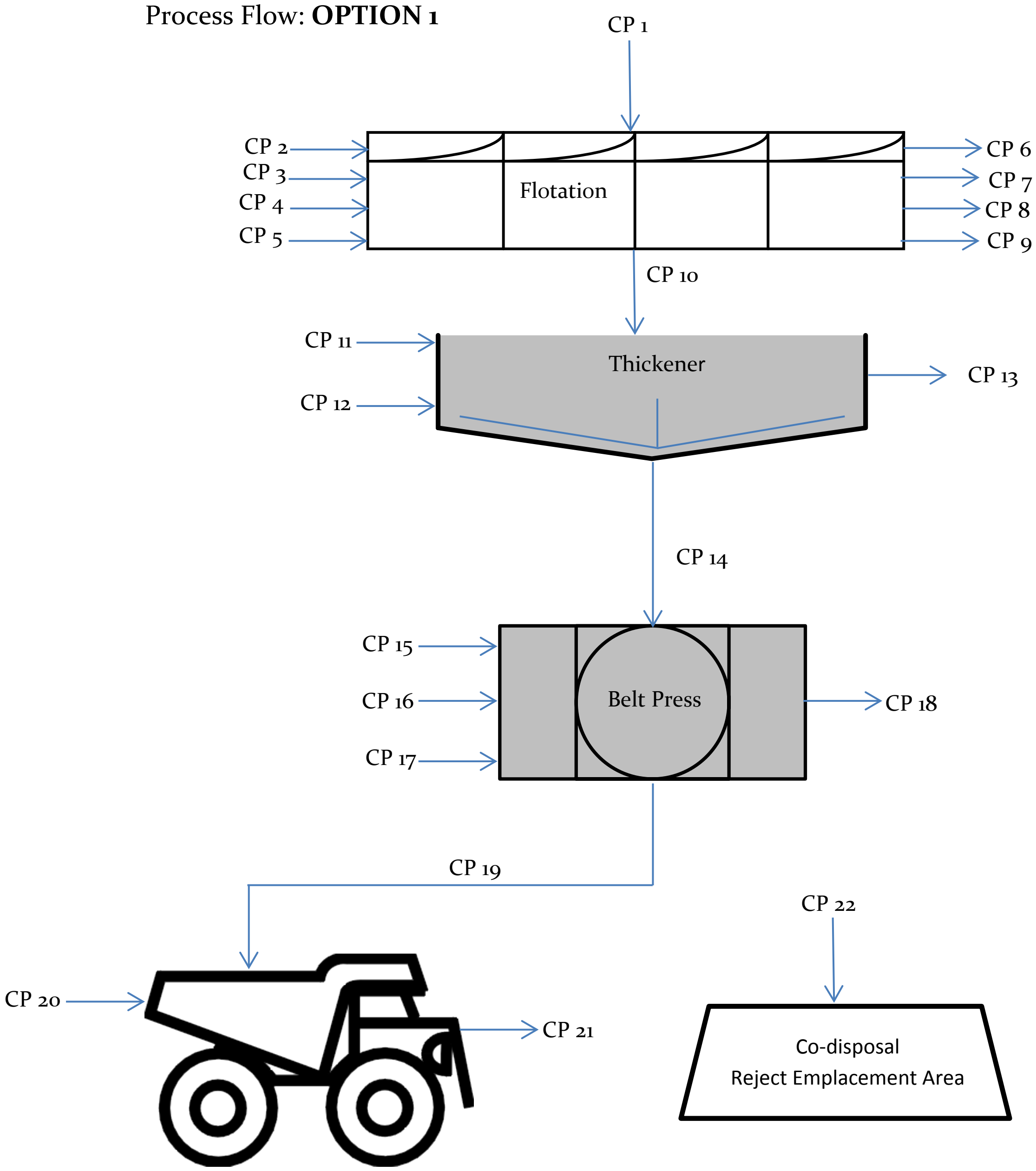
Life Cycle Inventory dataset

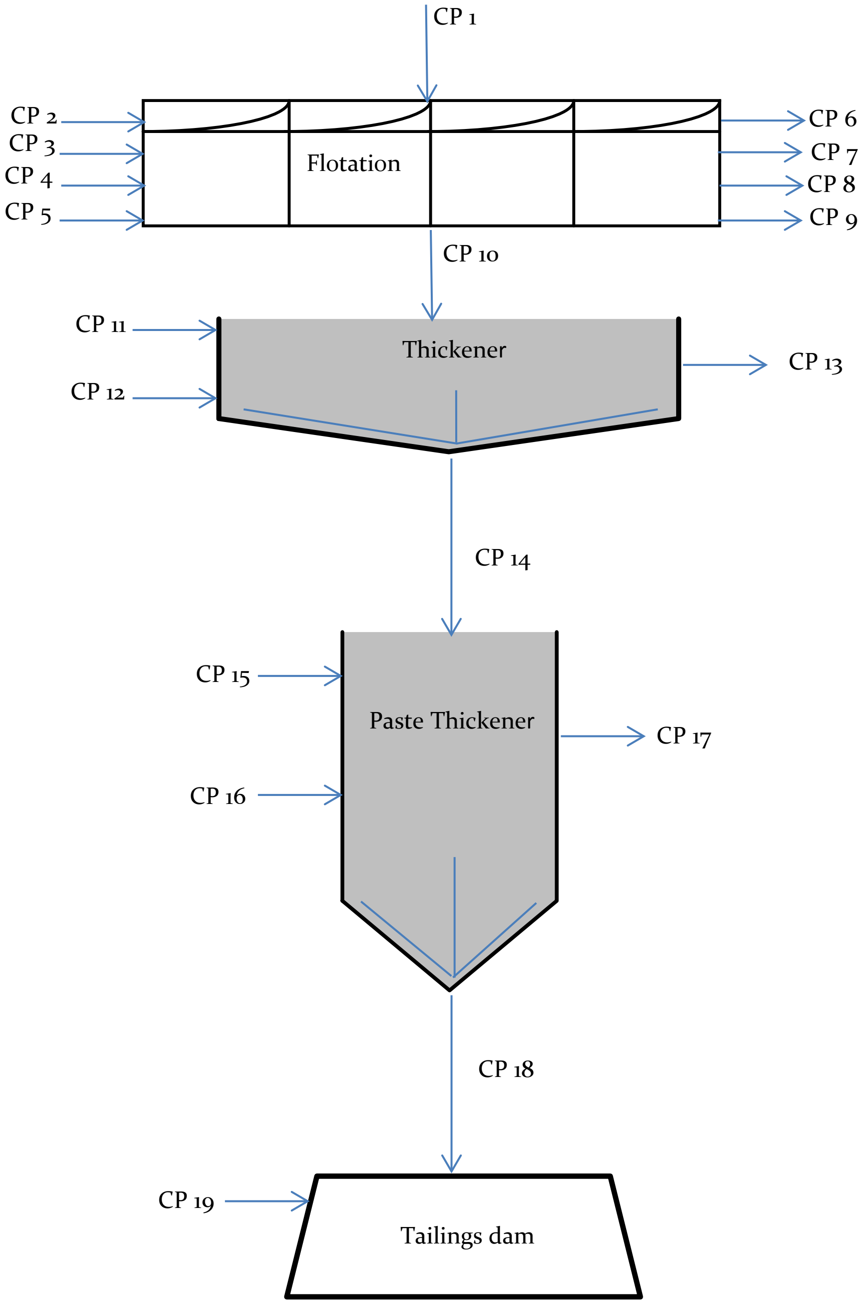
Methods/Options	Data		Code	Remarks
	Quantity	Unit		
Materials INPUT				
Fine coal slurry	50.86	t	CP1+CP2	10% solids w/w
Filtered tailings				
INPUT				
Electricity for flotation operations	864.54	kWh	CP3	
Electricity for thickener operations	20.75	kWh	CP11	
Electricity for underflow pumping	0.19	kWh	CP11	
Electricity for belt press operations	32.85	kWh	CP15	
Methyl Isobutyl Carbinol (MIBC)	0.05	Kg	CP4	Flotation
Diesel Oil	4.58	Kg	CP5	Flotation
Anionic Floc – Sodium Acrylate	1.22	Kg	CP12	Thickener
Anionic Floc – Sodium Acrylate	6.84	Kg	CP16	Belt Press
Cationic Floc - Polyethylemine	3.42	Kg	CP16	Belt Press
Water	34.00	t	CP17	Belt Press
Fuel – Transporting truck	9.54	lt	CP20	
Fuel – Reject Emplacement Area	39.74	lt	CP22	Dozer
OUTPUT				
Fine coal concentrate	1	t	CP6	
Water	0.25	t	CP7	Flotation
Tailings underflow	50.60	t	CP10	
MIBC	0.00005	t	CP8	In water
Diesel Oil	0.005	t	CP9	Attached in coal
Water overflow	10.12	t	CP13	Thickener
Tailings underflow	40.48	t	CP14	30% solids
Water reclaimed from belt press operations	48.17	t	CP18	
Tailings cake	26.32	t	CP19	65% solids
Trucking tailings cake	52.65	tkm	CP21	
Paste tailings				
INPUT				
Electricity for flotation operations	864.54	kWh	CP3	
Electricity for thickener operations	20.75	kWh	CP11	
Electricity for underflow pumping	0.19	kWh	CP11	
Electricity for paste thickener operations	131.17	kWh	CP15	Paste thickener
Electricity for pumping paste tailings to disposal area	113.76	kWh	CP19	Transporting tailings
Methyl Isobutyl Carbinol (MIBC)	0.05	Kg	CP4	Flotation
Diesel Oil	4.58	Kg	CP5	Flotation
Anionic Floc – Sodium Acrylate	1.22	Kg	CP12	Thickener

Anionic Floc – Sodium Acrylate	2.43	Kg	CP16	Paste thickener
OUTPUT				
Fine coal concentrate	1	t	CP6	
Water	0.25	t	CP7	Flotation
Tailings underflow	50.60	t	CP10	
MIBC	0.00005	t	CP8	In water
Diesel Oil	0.005	t	CP9	Attached in coal
Water overflow	10.12	t	CP13	Thickener
Tailings underflow	40.48	t	CP14	30% solids
Water overflow	8.09	t	CP18	Paste thickener
Tailings paste	32.39	t	CP19	50% solids
Thickened tailings				
INPUT				
Electricity for flotation operations	864.54	kWh	CP3	
Electricity for thickener operations	20.75	kWh	CP11	
Electricity for pumping tailings to disposal area	1.87	kWh	CP15	
Methyl Isobutyl Carbinol (MIBC)	0.05	Kg	CP4	Flotation
Diesel Oil	4.58	Kg	CP5	Flotation
Anionic Floc – Sodium Acrylate	1.22	Kg	CP12	Thickener
OUTPUT				
Fine coal concentrate	1	t	CP6	
Water	0.25	t	CP7	Flotation
Tailings underflow	50.60	t	CP10	
MIBC	0.00005	t	CP8	In water
Diesel Oil	0.005	t	CP9	Attached in coal
Water overflow	10.12	t	CP13	Thickener
Thickened tailings	40.48	t	CP14	30% solids

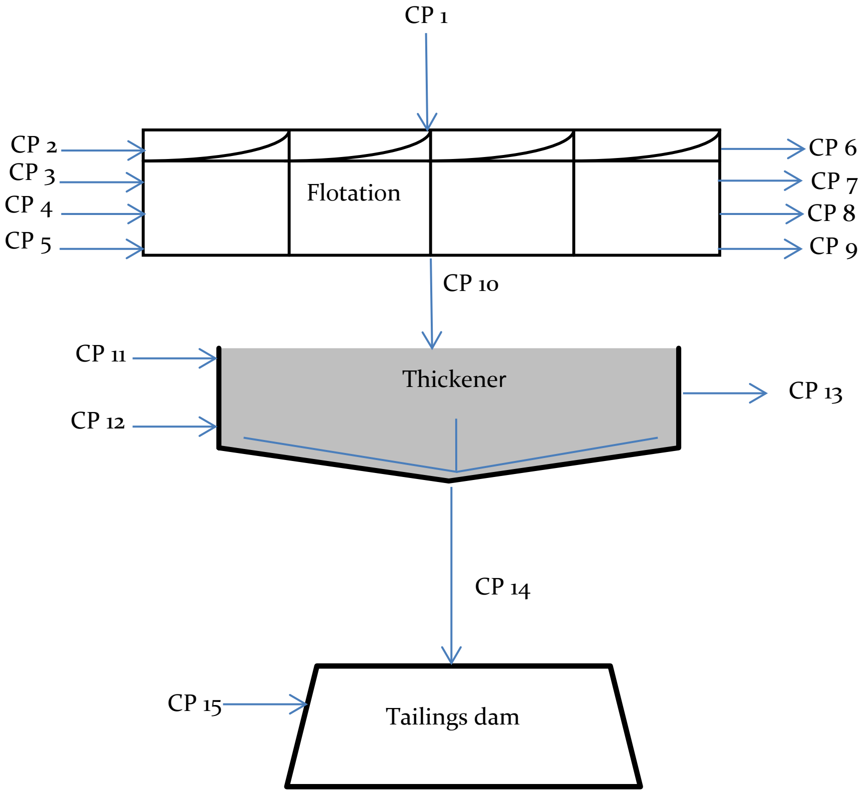
Process Flow: **OPTION 1**



OPTION 2


CP 1
CP 2
CP 3
CP 4
CP 5
Flotation
CP 6
CP 7
CP 8
CP 9
CP 10
CP 11
CP 12
Thickener
CP 13
CP 14
CP 15
Paste Thickener
CP 16
CP 17
CP 18
CP 19
Tailings dam

OPTION 3


CP 1
CP 2
CP 3
CP 4
CP 5
Flotation
CP 6
CP 7
CP 8
CP 9
CP 10
CP 11
CP 12
Thickener
CP 13
CP 14
CP 15
Tailings dam

Impact Characterisations

Options	Global Warming	Eutopication	Land use	Water use	Solid waste	Commulative energy demand	Fresh water aquatic ecotoxicity
	Kg CO_2	Kg PO_4	Ha	M^3	Kg	MJ	DAY
OPT 1	919.50	0.32	0.005	2.22	56.43	10418	5.40E-11
OPT 1A	523.19	0.19	0.003	1.63	31.57	6070	3.80E-11
OPT 1B	30.72	0.02	0.0001	0.89	0.68	2501	1.82E-11
OPT 1C	473.94	0.17	0.002	1.56	28.48	5713	3.60E-11
OPT 1D	30.83	0.02	0.0001	0.89	0.70	2503	1.83E-11
OPT 1E	473.95	0.17	0.002	1.56	28.48	5714	3.60E-11
OPT 2	1104	0.38	0.006	1.93	68.87	12363	4.92E-11
OPT 3	865	0.30	0.005	1.39	53.96	9719	3.68E-11

Note:

OPT 1= tailings cake with belt press, OPT 1A= tailings cake belt press with stack cell flotation, OPT 1B= tailings cake belt press with stack cell flotation and 100% solar energy, OPT 1C= tailings cake belt press with stack cell flotation and 10% solar energy, OPT 1D= tailings cake belt press with stack cell flotation and 100% wind energy, OPT 1E= tailings cake belt press with stack cell flotation and 10% wind energy, OPT 2= tailings paste with paste thickener, OPT 3= thickened tailings with thickener.

Item	**OPT 1**	**OPT 1A**	**OPT 1B**	**OPT 1C**	**OPT 2**	**OPT 3**
CAPITAL COST ($)						
Column flotation	1,561,218	-	-	-	1,561,218	1,561,218
Stackcell flotation	-	1,561,218	1,561,218	1,561,218	-	-
Thickener	2,683,168	2,683,168	2,683,168	2,683,168	2,683,168	2,683,168
Paste Thickener	-	-	-	-	939,109	-
Belt press	469,554	469,554	469,554	469,554	-	-
Tailings dam	-	-	-	-	20,745,849	20,745,849
Co-disposal	3,378,805	3,378,805	3,378,805	3,378,805	-	-
Wind energy	-	-	-	4,415	-	-
Solar energy	-	-	5,565	-	-	-
OPERATIONAL COST ($)						
Anionioc Floc	37.96	37.96	37.96	37.96	17.16	5.72
Cationic Floc	16.12	16.12	16.12	16.12	-	-
Electricity	47.39	47.39	47.39	47.39	52.46	45.78
Reject&trucking	41.33	41.33	41.33	41.33	-	-
Co-disposal	10.53	10.53	10.53	10.53	-	-
Maintenance	66,765	66,765	66,765	66,765	213,917	206,169
BENEFIT VALUES ($)						
Saleable coal	902E+6	902E+6	902E+6	902E+6	902E+6	902E+6
Water conserv	89,786E+3	89,786E+3	89,786E+3	89,786E+3	28,057E+3	15,587E+3
Land conserv	3,055E+3	3,055E+3	2,989E+3	3,028E+3	1,594E+3	0
GHG reduction	-426	2,646	3,028	3,028	-1,859	0

Note:

OPT 1= tailings cake belt press with column flotation, OPT 1A= tailings cake belt press with stack cell flotation, OPT 1B= tailings cake belt press with stack cell flotation and 10% solar energy, OPT 1C= tailings cake belt press with stack cell flotation and 10% wind energy, OPT 2= tailings paste with paste thickener and column flotation, OPT 3= thickened tailings with thickener and column flotation.

Benefit values of land conservation and GHG reduction based reference is OPT 3.