Early-stage design and development of mine waste valorisation technologies with expert input: A case study of South African sulfide-enriched coal waste

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Abstract

Mining and minerals beneficiation typically result in the production of both valuable products and large bodies of waste, which are traditionally disposed of on land and carry environmental and social risks. Circular economy and resource efficiency trends have shifted the focus from disposal to waste reuse and recycling. Despite the benefits of the circular economy approach, development and implementation of waste reuse technologies in the mining industry is fraught with challenges and has thus far been limited.

When designing processes for the application of large-volume mine waste, information deficits are encountered. This is largely because the characteristics of mine waste tend to be poorly understood or unknown as well as highly complex due to residual target minerals and processing chemicals present in the gangue components. Furthermore, whilst the technologies used may not be novel, their application in the processing of wastes is generally untested or inadequately researched. Working within such a context, with many unknowns, makes selection of appropriate technologies difficult. Another potential difficulty associated with designing and developing technologies for waste reuse is that unsolicited novel technologies by universities and research institutions can face opposition upon implementation. When designed and developed processes remain unimplemented, research resources are wasted and an opportunity to effect much-needed change is missed.

It is these challenges that this study seeks to address through the development of a generalised systematic approach for the early-stage design and development of technologies for the reuse of mineral beneficiation waste that addresses both technology transfer and information deficit issues. The approach is based on three key premises: firstly, that technology transfer issues should be identified and integrated into technology selection and development from the early design and development stages. Secondly, that expert interviews and surveys can provide data that is useful not only in social sciences, but also in technical development and decision making to address data gaps. The third premise is that pre-feasibility studies, usually used to assess the techno-economics of relatively mature technologies, can be valuable for both technical information gathering and identifying technology transfer issues within the context of early-stage mineral processing waste reuse design and development. The application of this approach has been demonstrated in a case study on the downstream utilisation of South African sulfide-enriched fine coal processing waste.

The premises identified above were studied in turn. Firstly, technology transfer issues were investigated using interviews with South African coal industry participants and the transcripts were analysed using thematic analysis. Secondly, the use of surveys and expert interviews to overcome data gaps in decision support for technology selection was investigated using a value theory multi-criteria decision analysis approach, and the data quality was assessed using distinguishability analysis. Lastly, the pre-feasibility study was conducted to assess the selected technology based on local contextual factors identified during the technology transfer interviews.

The results of the study showed that exploring technology transfer issues in the early stages of technology development can support technology development by identifying aspects of key importance to the receiving industry. In terms of the case study, aspects such as the continued pre-eminence of techno-economic considerations in technology investment decisions and industry preference for mature technologies were identified. It was also highlighted that the South African mining industry is structured to focus on core business-related activities, making them unlikely to become technology development partners. Original equipment manufacturers and boutique waste processors, as opposed to mining companies, were considered appropriate commercial partners for universities and research institutions developing mine waste valorisation technologies.

The study also showed that using expert judgement inputs as data for decision support must be done with caution. The case study data showed a high degree of dispersion to the point where the performance of technology alternatives on different criteria could not be meaningfully distinguished. Distinguishability improved with a more careful selection of "high-quality" experts and again when interviews were conducted with these experts, but not to the point of enabling defensible decision support. Analysis of the interview transcripts also showed that much of the variability could be attributed to uncertainty inherent in the decision problem as well as disagreement between experts. This indicated that some measure of variability in the data is inherent. Experts did, however, provide information that is useful for future technology development as well as indications of what research questions were still unanswered. Expert interviews for eliciting technical information therefore have value for providing background information for further development. Despite the uncertainties in the data, the option of using the sulfide-enriched coal processing waste as a soil ameliorant was consistently highly ranked and was therefore explored in the pre-feasibility study.

The study also showed that technology viability can be assessed relatively efficiently using a pre-feasibility study that incorporates consideration of technology transfer issues and local contextual issues. For the specific case study of application of sulfide-enriched fine coal processing waste as a soil ameliorant within the South African context, several issues were investigated: potential markets were identified; the transport costing of the product compared with the current market alternative was calculated; technical viability was assessed through a literature study; and health and safety risks were identified. This showed that while the technology is likely to be technically viable, the commercial viability is affected by high transport costs. The business case for the solution is therefore dependent on the avoided disposal costs for mines as well as the propensity of the material to slow-release acidity and thereby avoid repeated applications of the competitor product.

In conclusion, this study demonstrated that a systematic and integrated approach for the early-stage design and development of waste valorisation technologies can help universities and research institutions structure the technology development process aiming at implementation of technologies. Ultimately, it is postulated that such an approach will facilitate the sustainable management of large-volume mineral beneficiation waste in line with the principles of industrial ecology and circular economy.

Due to the difficulty with obtaining high-quality data for technology selection, it is recommended that improved approaches for early-stage technology selection must be investigated. Future work should furthermore include a more detailed investigation to clarify the cut-off distinguishability index values needed for different decision-analysis scenarios. Improved approaches for alternative identification in a mine waste valorisation context must also be investigated. Lastly, the role and approach of technical interviews, other technology transfer activities, and commercial partner identification must receive future research attention to investigate to what extent these can be combined to reduce resource requirements.

Plagiarism declaration

I, Helene-Marie Stander, declare that the work in this document is my own, save for that which has been properly acknowledged. The three papers and book chapter incorporated in this thesis are all comprised of work that I have performed as part of the scope of my PhD. This was conducted under the supervision of A/Professor Jennifer Broadhurst and Professor Susan Harrison. All work that was conducted by others was cited or acknowledged appropriately and does not compromise the originality of this thesis. The contributions made by co-authors to the jointly authored works are listed in the relevant chapters.

Stander

Helene-Marie Stander 8 August 2023

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Publication type	**Date**	**Title**	**Chapter**	**Publication**	**Authors**
Peer-reviewed book chapter	July 2019	Reflections on method of expert interviews for research on sustainable development of mineral resources in Africa	Chapter 3	Sustainable Development in Africa: Concepts and Methodological Approaches (Book)	Helene-Marie Stander Jennifer L. Broadhurst
Peer-reviewed journal article	April 2021	Understanding the Opportunities, Barriers and Enablers for the Commercialisation and Transfer of Technologies for Mine Waste Valorisation: A Case Study of Coal Processing Wastes in South Africa	Chapter 4	Resources (Journal)	Helene-Marie Stander Jennifer L. Broadhurst
Peer-reviewed journal article	June 2023	Selecting technologies for sustainable processing and reuse of pyrite-enriched coal waste using expert input: Questionnaires and interviews	Chapter 5	Journal of Cleaner Production (Journal)	Helene-Marie Stander, Brett Cohen, Susan T.L. Harrison, Jennifer L. Broadhurst
Peer-reviewed journal article	April 2022	Using South African sulfide-enriched fine coal waste for amelioration of calcareous soil: pre-feasibility study	Chapter 6	Minerals Engineering (Journal)	Helene-Marie Stander, Susan T.L. Harrison, Jennifer L. Broadhurst

Conference proceedings

The following paper was also published as part of ICARD|IMWA|MWD conference proceedings:

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This thesis is for my Lord and Saviour, who cares deeply for the people living in mining affected areas and who honours mortals like me by using our contributions towards solutions.

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Glossary

ARD	Acid rock drainage (also known as acid and metalliferous drainage or acid mine drainage), AMD refers to high sulfate, metal-rich acidic seepage from mines and mine wastes, which is generated when sulfidic minerals, such as pyrite, pyrrhotite, and chalcopyrite are oxidised. Although this process does happen spontaneously when purely chemical oxidation takes place, it is most often mediated by micro-organisms that increase the rate of oxidation dramatically and transforms this into a serious environmental problem.
Base case flow sheet	A flow sheet of the basic operations that are needed for converting a feedstock to a product. These are often high-level descriptive unit operations such as ‘roasting’ and ‘separation’, without specifications as to the particular type of equipment needed.
Capital expenditure (CAPEX)	The expenses incurred to procure or maintain fixed assets such as chemical processing equipment.
Design	See process design
Development	Technology development
Flotation	Physical separation process whereby hydrophobic mineral particles are separated from hydrophilic mineral particles by using air bubbled through an aqueous slurry.
Flotation chemicals	Chemicals that are added to a slurry prior to flotation to improve bubble formation and mineral recovery selectivity.
Gangue	The low-value mineral material that is associated with target elements or minerals. This is typically separated from target elements or minerals and then discarded as waste.
Heap Leach Spent Ore	Rock remaining after recovery of metals and some soluble constituents through heap leaching and heap rinsing of ores.
Internal rate of return (IRR)	A measure of a project’s projected profitability. It uses the projected cash flows to calculate what percentage return can be expected on capital investments.
Legacy/historical mines	Mines that are closed, and normally have been for many years, but where no company or person can be identified for taking responsibility for rehabilitation or management. These tasks often devolve to government.
Life cycle assessment (LCA)	Life cycle assessments measure the impacts of a product or process on the environment using several indicators, such as greenhouse gas emissions and eutrophication.
Low Grade Ore Stockpiles	Rock that has been mined and stockpiled with sufficient value to warrant processing, either when blended with higher-grade rock or after higher-grade ore is exhausted, but often left as ‘waste’.
Market pull	Technology development based on customer needs.
Mineralogy	Group of characteristics characterising mineral matter, including chemical composition, crystal structure and distribution of components.
Minor and trace elements	Elements that are present in an ore body at very low concentrations.

Multicriteria decision analysis (MCDA)	The comprehensive group of decision analysis tools that incorporates decision support with the consideration of multiple criteria. This includes methods for supporting discrete decision support as well as continuous decision support.
Mulitattribute decision analysis (MADA)	A group of decision analysis tools appropriate for discrete decision problems, such as selecting a preferred processing technology.
Operational expenditure (OPEX)	OPEX refers to expenses that a company has to incur in order to run the operation on a day-to-day basis
Overburden	The rock above the mineral resource that must be removed in order to mine the mineral resource.
Pre-feasibility study	An analysis that aims at assessing the profitability of an investment on a preliminary basis.
Process design	Chemical process design is the series of tasks undertaken to progress from opportunity identification or a client brief to a fully specified set of design documents that can be used to construct a functioning chemical or minerals processing facility.
Pugh matrix	A decision support tool that uses multiple criteria and scoring to select between several potential alternatives. It also includes a weighting step. Practitioners often does not attempt to ground either the weights or the ratings on quantitative or pre-defined qualitative ranges.
Pyrite	An iron-sulfide mineral that is often associated with coal, gold and copper minerals. It is the main cause of ARD in South African coal and gold mining contexts.
Quality function deployment	A more advanced version of a Pugh matrix, which includes competitor comparisons and grounds selection criteria on the customer requirements (voice of the customer). It also includes aspects such as technical difficulty, benchmarks and target values.
Reprocessing	Processing mine waste for the purpose of extracting residual mineral value. This often includes re-grinding as well as treatment steps.
Reuse	Beneficially using a specific mine waste fraction, whether it be hazardous, specialised or bulk waste.
Risk	An adverse outcome with some probability of happening.
Run of mine (ROM)	Unprocessed ore that is excavated from the mine. The target mineral is extracted from the run of mine material, which often still contains a significant gangue component.
Separation/partitioning of waste	The separation of mine waste into different streams with distinct characteristics. Often with the aim to use the streams for specific purposes.
Spontaneous combustion	The spontaneous oxidation of coal when exposed to air. It can be accelerated by the oxidation of pyrite associate with the coal and can lead to high-temperature fires in mines.
Sulfide minerals	Minerals that contain
Stakeholders	Persons or entities that are involved with or affected by a project, operation or change made.
Tailings	The solid product of the treatment and mineral concentration process that are considered too low grade to be treated further. Tailings are the finely

	ground host rock materials from which the desired mineral values have been largely extracted.
Target mineral(s)	The mineral(s) that a mine and processing plants are designed to extract.
Technology development	The process of moving from an idea to a commercial technology.
Technology transfer	The process of transferring a technology (including technology objects, codified knowledge (such as safe operating procedures and design documents) and know-how) from one organisation to another. It is considered complete when the receiving organisation shows strong commitment to a technology’s continual use.
Valorisation	The general approach of adding value and reusing mine waste, including separation and processing.
Value theory	A MCDA tool for selecting between discrete alternatives. The performance of alternatives are related to decision-maker values using value functions. The criteria are weighted and aggregated and the outcomes tested with decision-makers for validity using sensitivity analysis.
Waste Rock	Barren or uneconomic mineralised rock that has been mined, but is not of sufficient value to warrant treatment and is therefore removed ahead of processing.
Technology push	Technology development based on an institution’s technical competence.

Chapter one – Introduction

Mining and mineral beneficiation is critical to sustaining energy security and living standards across the globe (Valero et al., 2018; Walton and Anderson, 2021; Wang et al., 2019; Watari et al., 2019). These activities, however, produce large volumes of waste which can be harmful to human health as well as the environment (Broadhurst et al., 2019; Martin et al., 2002; Owen et al., 2020; Politis et al., 2017) and also represent a waste of natural resources. To address this problem, waste can be processed to recover inherent minerals (Bellenfant et al., 2013; Blasenbauer et al., 2020; Riina et al., 2014; Suppes and Heuss-Aßbichler, 2021) or be used in other applications (Acordi et al., 2023; Li and Hitch, 2016; Meyer et al., 2014; Segui et al., 2023; Veiga Simão et al., 2022). However, whilst many of these technologies are not novel, their application in the processing of wastes is generally unproven. This is aggravated by the fact that the compositions of large-volume mineral wastes are complex and varied and poorly characterised, so a technology that works well on one waste may not be applicable to another (Broadhurst and Harrison, 2015; Petrie et al., 2007; Segura-Salazar et al., 2019; Žibret et al., 2020). Furthermore, examples of commercial technologies remain few (Larkin, 2023; Qi and Fourie, 2019). This is because of the number of both technical and non-technical factors that may influence the performance and broader feasibility of mine waste valorisation[1] technologies in practice (ICMM, 2022). Working within such a complex context, with many unknowns, makes the selection of appropriate technologies difficult. A structured approach to the early-stage design and development of mine waste valorisation technologies is therefore needed that can address data scarcity and technology transfer.

This chapter elaborates on the background of the problem of mine waste management. It then states the problem that the thesis aims to address and its objective and scope. Lastly, the thesis lay-out is discussed.

1.1 Background

Increased volumes of stored mine waste are likely to have detrimental consequences for communities living near mines as well as the local environment (Ayers et al., 2009; Bian et al., 2010; Broadhurst et al., 2019; Mpanza et al., 2020; Owen et al., 2020). This section investigates the source of mining wastes, management methods, problems associated with waste and novel approaches to waste handling that attempt to improve outcomes. It should be noted that only land-based disposal of large-volume mineral wastes from the extraction and early beneficiation stages is discussed. These are most relevant within the South African context but in other countries riverine- and marine-based disposal may also be relevant (IIED, 2002).

1.1.1 Mine waste risks and their management

Ores mined for mineral extraction are rarely pure and, in most cases, contain orders of magnitude more than the target mineral of other, unwanted (gangue) minerals. Mine wastes are these unused by-products of mining and primary mineral beneficiation processes and are often found in rock or slurry form (Harrison et al., 2010; Martin et al., 2002; Van Zyl et al., 2002). For slurry waste (tailings), conventional disposal is in purpose-built dams (ICMM, 2022; Morrill et al., 2022). Coarse mine waste, such as overburden, waste rock, spent heap leach material and soil, has traditionally been stockpiled for later use or disposal (Harrison et

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[1] The general approach of adding value and reusing mine waste, including separation and processing

al., 2010; Van Zyl et al., 2002). Historically, gold, coal and platinum group metals have accounted for most of the mine waste produced in South Africa (Harrison et al., 2010). In the South African coal industry, four types of wastes are generally produced: overburden, that is removed to expose coal seams; waste rock, which is material screened out of the run-of-mine coal; discards, which is low-grade coarse coal rejected from coal washing operations; and tailings, which is the slurry waste of coal washing operations (SACRSC 2011).

Mine wastes, having been disposed of in tailings dams or stockpiles, are not, however, environmentally or socially neutral. After mining and comminution, the newly exposed minerals are free to interact with their surroundings (García et al., 2005; Johnson, 2003). In many cases, the reduced particle sizes of the waste also enables it to be distributed into the surrounding environment (Blight, 2012; Khalil et al., 2023; Mpanza et al., 2020; Owen et al., 2020). Risks associated with mine waste are a mixture of chemical and physical. Chemical risks are associated with the composition of materials, which can be hazardous, while physical risks are associated with the failure of waste containment. A key challenge of land-based mine waste management is therefore to prevent mine waste from dispersing into, and interacting with, the environment. As the following section will show, when this containment fails, nearby communities, plants, and animals are negatively affected.

Mine waste can be dispersed into the environment in various ways by water from precipitation, natural water courses (rivers and subterranean water courses) and mine process water (Ayers et al., 2009). Dispersion can happen through either entrainment in water (Blight, 2012; Morrill et al., 2022), reaction with water (for example during the formation of acid rock drainage (ARD)) (Ayers et al., 2009), and/or dissolution into water (Ayers et al., 2009). The next three paragraphs will consider the various modes of water dispersion.

When sulfide minerals, such as pyrite (FeS_2), are present in the host rock, acid generation is often a problem in the attendant mine cavities and mine waste, depending on the availability of neutralising minerals (Ayers et al., 2009; Johnson, 2003; Park et al., 2019). Sulfide minerals oxidise in the presence of air and water in a series of reactions that lead to sulfuric acid formation (Ayers et al., 2009; Schippers et al., 1996; Schippers and Sand, 1999; Tao and Dongwei, 2014). These reactions are catalysed by micro-organisms that use the oxidation of mineral sulfides in their metabolic processes (Ayers et al., 2009; Leathen et al., 1953a, 1953b; Schippers et al., 1996; Schippers and Sand, 1999). The acidic and oxidative environment leads to increased metal leaching from the waste material and the resultant liquid, typically referred to as acid mine drainage (AMD) or acid rock drainage (ARD), can be highly acidic (as low as pH 2 and even lower, in some cases) and contain high metal and sulfate loads (McCarthy and Pretorius, 2009; Nordstrom et al., 2000). ARD is one of the most serious environmental impacts associated with sulfide-bearing mine waste as it is harmful to humans and animals, toxic to aquatic environments, and leads to soil sterilisation (Geldenhuis and Bell, 1998; McCarthy and Pretorius, 2009). Sulfide minerals are associated with various mineral commodities in South Africa, notably coal and gold (Geldenhuis and Bell, 1998; McCarthy, 2011; Nengovhela et al., 2006). The pyrite-bearing wastes that are generated in these industries are therefore one of the sources of ARD generation, along with mine workings. In the South African coal industry, both discards and ultra-fine slurries from coal processing are pyrite-bearing and therefore acid generating (Kazadi Mbamba et al., 2012; Moyo et al., 2019).

A serious physical water dispersion problem associated with tailings storage facilities is dam wall failures, which allow tailings (fine and ultrafine mine waste particles mixed with water) to spill uncontrolled into the surrounding environment (Morrill et al., 2022; Owen et al., 2020). When tailings dams fail, fatalities, infrastructure damage, and serious harm to the surrounding environments are some of the consequences (Barrie et al., 2019; Owen et al., 2020). In the recent Jagersfontein tailings disaster, for example, tailings released during a tailings dam failure killed at least one person, destroyed parts of the town, and travelled around 56km down the nearby rivers to the Kalkfontein dam, polluting water resources (Parker, 2022; Torres-Cruz and O'Donovan, 2023). A number of tailings dam failures have occurred since 2010, including the catastrophic 2019 Brumadinho tailings disaster in Brazil, in which 320 people are confirmed to have died (Owen et al., 2020). This disaster led to increased scrutiny of tailings dam management and tailings disposal practices (Minerals Council of South Africa, 2020). Some of the causes of tailings dam failures include poor design, poor maintenance, high water balance in tailings, erosion, and seismic activity at the facility's site (Martin et al., 2002; Owen et al., 2020).

Less cataclysmic, but still potentially problematic, is water erosion of mine waste facilities. This spreads potentially hazardous material into the environment and can lead to long-term risks to domestic water supplies, for example increased metal loads (Jarsjö et al., 2017; Pietroń et al., 2017). Water erosion has been observed on coal stockpiles in Mpumalanga (Centre for Environmental Rights 2019: 75), gold tailings facilities in Gauteng (Blight, 2012) and the Jagersfontein tailings facility prior to failure (Torres-Cruz and O'Donovan, 2023).

Small particle size mine waste is especially prone to wind dispersion into the surrounding environment and communities (Blight, 2012). Of particular concern are respirable particles (<5µm (Brown et al., 2013)), which can have serious impacts on lung health. Dust creation is normally a problem in arid areas during times of elevated wind speeds (>13 m/s for gold tailings (Blight, 2012)), where tailings heaps are easily dewatered and dust is blown to the area surrounding the facility (Blight 2007; Khalil et al. 2023; T. E. Martin et al. 2002; Mpanza et al. 2020). This problem is conventionally addressed by spraying moisture onto tailings, which presents a competing water use in already arid areas (Van Zyl et al., 2002).

In the case of coal spoils, slow chemical oxidation of low-grade coal and pyrite can heat up spoils heaps to a sufficient degree that they spontaneously smoulder (Lu et al., 2022; Mistry, 2005). These smouldering fires are difficult to prevent and control and release air pollution in the form of CO, H_2S, SO_x and NO_x emissions (Bian et al., 2010; Lu et al., 2022; York, 2017).

Mine waste can also be dispersed by people or animals tracking mine waste from the mining facilities to the surrounding environment. At legacy and poorly closed mines, informal miners can often gain entry to the mine site to re-mine either the mines themselves or the waste to extract residual target minerals (Van Wyk, 2014). South African examples of re-mining by informal miners include coal waste dumps and defunct coal mines (Van Wyk, 2014). When these mine waste facilities are close to residential areas, children may play in the 'sand' and water at the facility (Bega, 2022). This poses health and safety risks to both the informal miners and children involved (Bega, 2022; Van Wyk, 2014), as well as dispersing the material into the residential areas and surrounding environment, again presenting long-term risks.

In addition to leading to environmental and social risks, mine waste also incapacitates useful resources. These include the land used for surface disposal, water used in dust prevention and in storing waste, biodiversity when wildlife corridors are blocked or sensitive environments impacted, and economic resources for waste management (Andersen et al., 2014; Barati et al., 2020; Broadhurst et al., 2019; Simpson et al., 2019; Van Zyl et al., 2002; Warhurst and Noronha, 2000; Watson et al., 2010; Yıldız, 2020). An example of this is the gold tailings that are located on around 320m^2 of land area within and around the Johannesburg metropolitan area (Bobbins, 2013). Much of this is located near high-value land and it is reasonable to believe that it would likewise be high-value land if it was available for other uses.

1.1.2 Improved mine waste containment methods

Given the serious impacts that mining waste can have on its environment, it became clear in the early 2000's that improved mine waste management methods were needed (Martin et al., 2002). Several methods have been pioneered to improve the containment, reduce the risk of chemical interaction with the environment, and reduce the land footprint of mine waste facilities. Despite improvements in the environmental and social impacts of mine waste resulting from these interventions, this section will show that none of these guarantee that mine waste will be safe and environmentally benign. In fact, the recent *Safety First* guidelines on tailings management, co-sponsored by Earthworks, MiningWatch Canada and the London Mining Network (Morrill et al., 2022) noted that, "the safest tailings facility is one that is not built."

One of the oldest approaches to improving containment of mine waste post-closure is to provide barriers between waste bodies and the environment. Waste bodies can be covered at the end of the life of mine, preventing precipitation and air from entering waste bodies and reacting with reactive waste (Department of Minerals and Energy, 2002; Martin et al., 2002). Liners at the base of tailings facilities prevent seepage from entering soil and water courses and, in South Africa, it is legislated that new mine waste storage facilities be lined, and seepage diverted and treated (Department of Environmental Affairs, 2015, 2013). Covers and liners require complex engineering to be effective, however, and it was already becoming evident in the early 2000's that these are not dependable in isolating mine wastes since they are subject to cracking, erosion, excavation, and seepage (Karlsson et al., 2010; Limpitlaw et al., 2005; Martin et al., 2002; Timms et al., 2003; Villain et al., 2013).

In contrast to covers, which can only be used at the end of the life of mine, the ingress of oxygen and precipitation during mine operation is reduced by compacting and/or co-disposing mine waste (Bell et al., 2001; Bian et al., 2010; Department of Minerals and Energy, 2002; Mjonono et al., 2019; Politis et al., 2017; York, 2017). Co-disposal involves combining waste with different characteristics, such as tailings and discards, when constructing waste facilities (Kotsiopoulos and Harrison, 2018; Mjonono et al., 2019; Politis et al., 2017). This reduces seepage generation and incidences of spontaneous combustion in coal waste (Bell et al., 2001; Bian et al., 2010; Kotsiopoulos and Harrison, 2018; Politis et al., 2017; York, 2017), and improves the geotechnical stability of tailings (Mjonono et al., 2019; Morrill et al., 2022; Politis et al., 2017). Seepage, spontaneous combustion, and instability is, however, not eliminated by compaction and co-disposal (Behum et al., 2018; Kotsiopoulos and Harrison, 2017; York, 2017). Monitoring, intervention, and eventual rehabilitation requirements therefore remain.

Dry stacking of tailings is an increasingly popular solution aimed at recovering the water retained in tailings, reducing the risk of catastrophic tailings dam failures, and reducing land footprint (Adiansyah et al., 2017; Franks et al., 2011; Martin et al., 2002; Morrill et al., 2022). For dry stacking, tailings are normally dewatered to a water content of less than 20% (Adiansyah et al., 2017; Watson et al., 2010). Dust is a problem for dewatered tailings, however, requiring spraying with water, installing wind breaks, and other measures to prevent dust mobilisation. Water spraying represents a competing water use in already dry areas (Blight, 2007; Van Zyl et al., 2002). Seepage is, furthermore, not prevented by this method (Watson et al., 2010) and, along with wind and human dispersion, creates long-term risks for the surrounding environment and communities. Maintenance of the tailings infrastructure, even after rehabilitation, must continue until failure is a near impossibility and this is likely to be a long-term or indefinite liability (Morrill et al., 2022).

Backfilling is another increasingly popular approach to preventing catastrophic tailings facility failures as well as reduce disposal footprints involving disposal of mine waste in old mine voids (Bian et al., 2010; Politis et al., 2017; Zhang et al., 2019a). Backfilling also improves the structural stability of underground mines (Bian et al., 2010; Politis et al., 2017). Only about 60% of the originally mined material can be backfilled in the mining void, however, because the host rock has been broken up, reducing the packing density (Fu et al., 2015). Backfilling mine waste also carries long-term risks, since ARD or other seepage can still emanate from the waste, potentially polluting subterranean water courses and river systems (Villain et al., 2013).

Since the chemical reactivity of mine wastes represent an important component of the inherent risk of the waste, the idea of generating chemically benign wastes has been put forward by several authors (Cooling, 2007; Freeman et al., 1992; Hesketh et al., 2010; Kazadi Mbamba et al., 2012; Kinnunen et al., 2021; Zhou et al., 2019). These approaches range from separating out or chemically reacting hazardous components through barrier methods such as microencapsulation (Hesketh et al., 2010; Kinnunen et al., 2021; Park et al., 2019; Politis et al., 2017; Zhou et al., 2019). Creating benign waste may, however, require the use of large volumes of aggressive chemicals, which adds risk to the operation (Park et al., 2019) and still requires geotechnically stable disposal (Bellenfant et al., 2013). Current mine waste containment methods do not completely remove risk and the associated liability, but rather postpones or reduces it.

1.1.3 Approaches to reducing land-based disposal of mine waste

The previous section shows that there are no permanent solutions to the problem of reactive mining and mineral waste when these are stored. A growing body of literature asserts that mineral waste management should aim at zero harm (Franks et al., 2011; Harrison et al., 2020; ICMM, 2022; Morrill et al., 2022). An important approach to doing this, advocated by the International Council on Mining and metals (ICMM), is to reduce the volume of mine waste produced through improved mine design, mining, processing, and separation methods (ICMM, 2022). These methods are helpful to reduce the volumes of waste produced and are likely to have great impact (Lèbre et al., 2017), but will not be able to completely prevent the production of mine waste, due to the mixed-mineral nature of most ores.

An important line of enquiry that is growing in popularity is that of processing the mine waste to extract secondary target minerals (Bellenfant et al., 2013; Blasenbauer et al., 2020; Parbhakar-Fox et al., 2022; Suppes and Heuss-Aßbichler, 2021). This approach increases resource efficiency and potentially avoids or postpones development of virgin resources (Parbhakar-Fox et al., 2022) in addition to improving certain regions' feedstock supply security (Suppes and Heuss-Aßbichler, 2021). It does not, however, solve the problems associated with land-disposal of bulk wastes, since only a small proportion of the waste is extracted during reprocessing.

A growing body of literature demonstrates on a laboratory scale that the bulk portion of mine wastes - consisting predominantly of silicates with possibly minor quantities of oxide, carbonate and sulfide minerals - can be beneficially used in construction, construction-adjacent, mining, and industrial applications (Acordi et al., 2023; Barati et al., 2020; Binnemans et al., 2015; Chugh, 1992; Harrison et al., 2020; Li and Han, 2006; Pereira, 2006; Stolboushkin et al., 2016; Taha et al., 2022; Zhang et al., 2014). For example, Pereira (2006) has worked on creating a method for assessing industrial and mine wastes for their applicability in a few pre-defined construction-related use cases. His process includes considering the waste category according to law, and subsequently the waste's physical and chemical characteristics, as well as the volumes of waste created (Pereira, 2006). The method, however, explicitly excludes the consideration of any form of hazardous waste (Pereira, 2006), which is the waste type where the most can be gained by reuse as opposed to disposal.

To effectively reduce the problems associated with mine waste management, a variety of technology alternatives for beneficially using mine waste must be developed and brought to market. To date, research into technologies for the beneficial use of mine waste have been developed predominantly at universities and other research institutions (see 8Appendix A) and only a few examples of commercial technologies are known (Larkin, 2023; Qi and Fourie, 2019). Some difficulties for technology development and implementation include the varying compositions of mine wastes (Abdellatif et al., 2019; Acordi et al., 2023; Johnson, 2003; Suppes and Heuss-Aßbichler, 2021; Taha et al., 2022; Žibret et al., 2020) and their generally poor characterisation (Broadhurst et al., 2007). These data limitations and uncertainties constrain selection of appropriate technology alternatives to process and use mine waste.

Furthermore, universities and research institutions can face difficulty with successfully transferring developed technologies (Greiner and Franza, 2003; Lai, 2011). There are several reasons for this, including technical risk, differing cultures between universities and industry, as well as regulatory issues related to technology novelty (Greiner and Franza, 2003). Technologies for the beneficial use of mine waste must, however, be implemented commercially to have the desired impact. Also, failure to do so, when not due to technology failure, is a waste of resources.

Several frameworks have been developed to assist in the systematic identification, development and implementation of technologies and engineering processes (Cano-Ruiz and McRae, 1998; Cooper, 1990; Lind, 2006; Schulz et al., 2000; Towler and Sinnott, 2008; Whitney, 2007; Yapps Cohen et al., 1998), all of which entail a sequence of development steps and associated decision points from early-stage design to implementation. Process design and technology development literature, furthermore, shows that the early-stage identification and selection of alternatives are particularly important steps in the design and development of technologies and processes (Clark and Wheelwright, 1992; Dym et al., 2009; Stewart et al., 2003; Towler and Sinnott, 2008). It is in these early stages that decisions are made that have the biggest impacts on subsequent design and development outcomes (Basson and Petrie, 2001; Stewart et al., 2003; Ullman et al., 1988). To date, however, neither process design nor technology development theory have been applied to facilitate the design and development of technologies for mine waste reuse and address the particular challenges involved.

1.2 Problem statement

Mining and minerals beneficiation typically result in the production of both valuable products and large bodies of waste, which are traditionally disposed of on land and carry environmental and social risks. Circular economy and resource efficiency trends have shifted the focus from disposal to waste reuse and recycling. Despite the benefits of the circular economy approach, development and implementation of waste reuse technologies in the mining industry is fraught with challenges and has thus far been limited.

When designing processes for the application of large-volume mine waste, information deficits are encountered. This is largely because the characteristics of mine waste tend to be poorly understood or unknown as well as highly complex due to residual target minerals and processing chemicals present in the gangue components. Furthermore, whilst the technologies used may not be novel, their application in the processing of wastes is generally untested or inadequately researched. Working within such a context, with many unknowns, makes selection of appropriate technologies difficult. Another potential difficulty associated with designing/developing for waste reuse is that unsolicited novel technologies by research institutions can face opposition upon implementation. When designed and developed processes remain unimplemented, research resources are wasted and an opportunity to effect much-needed change is missed.

1.3 Aim and scope

The overarching aim of this thesis is to develop and explore application of a generalised approach to early-stage technology design and development for mine waste valorisation. The approach is synthesised based on process design, technology development and innovation literature to address both the problem of data deficiency at the early stages of design and development, and to incorporate a consideration of eventual technology transfer. It then explores application of this approach by applying it to the case study of South African sulfide-enriched fine coal processing waste. This waste stream was selected due to the relatively high environmental impacts associated with pyrite-bearing coal waste within South Africa, and the risks that this poses in terms of a just transition to a post-coal future within the country. This case study is, furthermore, of relevance to a programmatic study at the University of Cape Town which is focussing on the development of a multi-stage process for the valorisation of fine coal waste (see discussion in Section 3.1.1).

The study considers the important factors influencing implementation of mine waste valorisation technologies, the appropriateness of using expert judgement input in process selection for waste reuse technologies, as well as the use of pre-feasibility studies to inform process development. While these outcomes are specifically applicable to South African sulfide-enriched coal waste, the overarching insights derived from implementation of the generalised approach should be generalisable to other waste streams. Ultimately, it is envisaged that the generalised approach proposed in this study will assist in identifying technology options for the reuse of mine waste that are most likely to be commercially viable, and also serve to guide further developmental studies and technology transfer.

The study is based on qualitative data and literature, consistent with early-stage design. Primary data are in the form of expert interviews and questionnaires. No experimental work was conducted for this study.

While the entire technology design and development process is important, this work focuses on tailoring the early stages for mine waste valorisation. The early stages are particularly salient, since these are where small decisions can have large impacts (Basson and Petrie, 2001; Stewart et al., 2003; Ullman et al., 1988). Also, the early stages of design and development are particularly complex in terms of data availability. This thesis therefore focuses on problem structuring through development planning, as defined in the generalised early-stage technology design and development process proposed in Chapter 2.

Most studies on mine waste valorisation have to date been developed by universities and other research institutions. Increased technology successes at these institutions can therefore improve the output of useful technology alternatives for beneficial use of mine waste. This thesis therefore focuses on aspects of technology development that might be useful to universities and other research institutions, as opposed to other corporations. Design and development emanating from commercial design companies and mines themselves is explicitly excluded, as these will work with different starting assumptions. Examples are the presence of a client brief and well-defined commercialisation end-point, as well as different challenges with, for instance, data availability.

A related assumption is that this work will contemplate unsolicited technology development from research institutions. The thesis aims to support design and development work that is not the result of industrial partners approaching a research institution since it is known that technologies developed at universities can face obstacles to successful commercialisation. It is therefore contemplated to be useful in a context where no existing commercial partner and well-defined road to commercialisation is present.

While design for sustainability literature advocates including the entire value chain when assessing the sustainability performance of design alternatives (Petrie et al., 2007), it is excluded in this thesis. Data availability is problematic when designing for mineral applications, and this is exacerbated with mineral wastes. Since this thesis aims to overcome data deficiency, it was considered prudent to engage in a smaller, less complex 'pilot.'

1.4 Organisation of the thesis

This thesis consists of seven chapters. Chapter 1 provides the background of the study, while Chapter 2 provides a review of the pertinent literature, leading to a formulation of the generalised early-stage approach for design and development of technologies for mine waste valorisation. Chapter 3 introduces the methodology and contains the first publication included in the PhD, as shown in Table 1-1. The publication is a peer-reviewed book chapter from the published book *Sustainable Development in Africa: Concepts and Methodological Approaches* and concerns the method for expert interviews in the context of research on sustainable development of mineral resources. Chapter 3 also introduces the case study as well as the mine waste valorisation technology alternatives applicable to the case study. Chapters 4, 5 and 6 each consider a stage in the generalised early-stage technology design and development approach for technologies for mine waste valorisation and as such form a coherent interrogation of the approach. These chapters are presented in the form of three separate published journal papers (see Table 1-1). Chapter 7 synthesises the work and draws conclusions for future practice.

Table 1-1 Published peer-reviewed articles and articles under review included in the thesis.

Authors	Date	Title	Chapter	Publication
Helene-Marie Stander Jennifer L. Broadhurst	July 2019	*Reflections on method of expert interviews for research on sustainable development of mineral resources in Africa*	Chapter 3	Sustainable Development in Africa: Concepts and Methodological Approaches (Book chapter)
Helene-Marie Stander Jennifer L. Broadhurst	April 2021	*Understanding the Opportunities, Barriers and Enablers for the Commercialisation and Transfer of Technologies for Mine Waste Valorisation: A Case Study of Coal Processing Wastes in South Africa*	Chapter 4	Resources (Journal)
Helene-Marie Stander, Brett Cohen, Susan T.L. Harrison, Jennifer L. Broadhurst	June 2023	*Selecting technologies for sustainable processing and reuse of pyrite-enriched coal waste using expert input: Questionnaires and interviews*	Chapter 5	Journal of Cleaner Production (Journal)
Helene-Marie Stander, Susan T.L. Harrison, Jennifer L. Broadhurst	April 2022	*Using South African sulfide-enriched fine coal waste for amelioration of calcareous soil: pre-feasibility study*	Chapter 6	Minerals Engineering (Journal)

Chapter two - Conceptualising a structured approach for the early-stage design of technologies for the reuse of mine waste

The literature from several fields of enquiry is used in this study. To provide an overview of the topics covered, Table 2-1 shows the literature considered in various chapters of the thesis. This chapter reviews and assesses the status quo for beneficially using mine waste (Section 2.1) and current approaches to technology development and design (Section 2.2). The information and gaps identified leads to the creation of the generalised approach for early-stage design and development of mine waste valorisation technologies with a view to technology transfer (Section 2.3). The approach is then used as the basis for the hypotheses and key questions at the end of the chapter (Section 2.4).

Table 2-1 The literature examined in various chapters of the thesis.

	Ch 1	**Ch 2**	**Ch 3**	**Ch 4**	**Ch 5**	**Ch 6**
Mine waste production	X					
Mine waste management problems	X			X		X
Mine waste valorisation	X	X		X		X
Sustainability and circular economy		X				
Process design		X				
Technology development		X				
Innovation		X				
Technology transfer		X		X		
Decision support		X			X	
Data requirements		X			X	
Value theory					X	
Expert input		X	X	X	X	
Interviews		X	X	X		
Questionnaires			X			
Judgement aggregation					X	
Thematic analysis			X	X		
Scoping/pre-feasibility studies		X				
Soil amelioration using pyrite						X
Oxidation of pyrite						X
Backfilling	X	X				X

2.1 Approaches to using mine waste

Large volumes of mine waste are generated worldwide, which has negative environmental and social impacts, as discussed in Chapter 1. Chapter 1 also showed that there are no walk-away solutions to the problem of reactive mining and mineral waste when disposed on land. A growing body of literature asserts that mineral waste management should work towards achieving zero social and environmental harm in the long term (Franks et al., 2011; Harrison et al., 2020; Morrill et al., 2022; Warhurst and Noronha, 2000).

The circular economy approach is a useful conceptual lens for thinking about how to achieve this. It is an approach to designing and developing industrial, consumer and agricultural systems with the aim of decoupling human well-being (economic prosperity) from environmental harm (Bocken et al., 2016; Kirchherr et al., 2017; Stahel, 2016). Circular economy advocates promote the idea of reducing society's resource needs by, amongst other things, keeping items in use for longer, engineering out waste during production and making end-of-life items useful again (Bocken et al., 2016; Brady, 2016; Kirchherr et al., 2017). This has the two-pronged advantage of avoiding both waste disposal and, potentially, the extraction of virgin resources (Golev et al., 2022; United Nations Environment Programme, 2019) and their concomitant environmental impacts (Lèbre et al., 2017). Finding value in waste is therefore prominent in most treatments of circular economy (Bocken et al., 2016; Brady, 2016; Kirchherr et al., 2017; Pactwa et al., 2020). In terms of mine waste, the waste hierarchy suggested by Lèbre et al. (2017) provides an approach for operationalising circular economy ideals. They suggest that production of mine waste should be avoided as far as possible. For waste that cannot be avoided, all economically recoverable minerals must be extracted, bulk waste beneficially used (downcycled) and, as a last resort disposed of (Lèbre et al., 2017).

Mine waste reprocessing and reuse, in line with circular economy principles, has received attention as a solution for avoiding land disposal of mine waste (Akinwekomi et al., 2020; Amaral Filho et al., 2020; Broadhurst et al., 2002; Harrison et al., 2020; Kinnunen and Kaksonen, 2019; Pactwa et al., 2020). Using mine waste in a way that utilises, or at least neutralises, the characteristics or components associated with risks has the potential to create value in addition to removing risk and is consistent with circular economy principles.

2.1.1 Taxonomy for using mine waste

Before exploring alternatives to waste disposal, however, it is worthwhile to first consider definitions. There is currently no consistency in literature when describing the beneficial use of mine waste. The words 'reuse', 'valorisation', 'recycling', 'reprocessing', 're-mining' and 'recovery' are loosely and interchangeably used, despite Lottermoser's (2011) attempt at creating a standardised taxonomy. For instance, waste can be processed with the intention of extracting the residual original target mineral, which has variously been called 'reprocessing' (Bellenfant et al., 2013; Lahiri-Dutt et al., 2011; Lèbre et al., 2017), 'recovery' (Suppes and Heuss-Aßbichler, 2021; Taha et al., 2022; Zhou et al., 2019; Žibret et al., 2020), 're-mining' (Lottermoser, 2011; Maroušek et al., 2023) and 'valorisation' (Binnemans et al., 2015; Nwaila et al., 2021b; Suppes and Heuss-Aßbichler, 2021). Lottermoser (2011) distinguished between mine waste being processed to extract the original target mineral ('re-mining') and a secondary target mineral ('reprocessing'). Using the bulk mine waste has variously been called 'valorisation' (Acordi et al., 2023; Khaldoun et al., 2016; Kinnunen et al., 2021; Nzihou and Lifset, 2010), 'reuse' (Aznar-Sanchez et al., 2018; Barati et al., 2020; Brady, 2016; Politis et al., 2017), 'repurposing' (Broadhurst et al., 2019; Mjonono et al., 2019) 'recycling' (Barati et al., 2020), and 'downcycling' (Lèbre et al., 2017) or upcycling (Kinnunen et al., 2022). In some cases, these terms are used interchangeably (Taha et al., 2022).

Part of the taxonomy problem arises because of the complexity of reusing waste. Figure 2-1 shows a flowsheet of the approaches one can take for using mine waste productively. At the top of the figure there is the option of removing any target mineral components and resigning the bulk of the material to mine waste again. Then, at the bottom of the figure, there is the option to process and use the bulk mine waste. From either of these extremes, there is the option to process and then separate the bulk waste into useful fractions (Binnemans et al., 2015; Harrison et al., 2020; Lèbre et al., 2017). Alternatively, there is the option to separate mine waste into fractions: recover inherent mineral value and then separate the remaining material such as both benign bulk waste and other useful fractions are recovered. To achieve this, hazardous components must be separated out and reused or disposed of in specialised facilities or alternatively, waste with hazardous components must be processed to become benign. At each junction, there is the option to process the residual material for use or to resign it to waste.

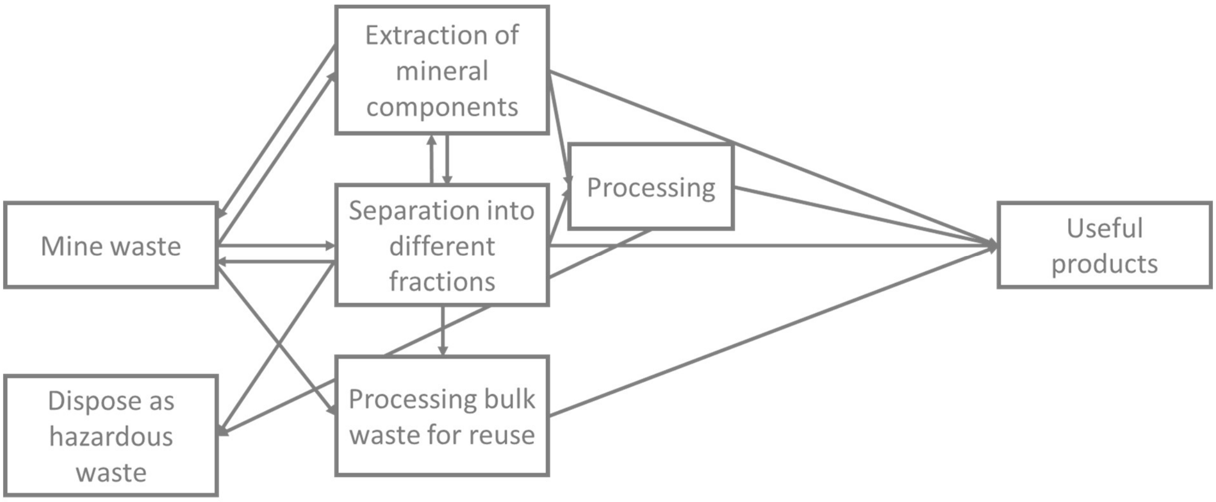

Figure 2-1 Approaches for converting mine waste into useful products.

For the remainder of this thesis the taxonomy shown in Table 2-2 below will be used. *Valorisation* means ascribing value to something or making something valuable (O'Shea and Waterhouse, 2022). This is therefore an appropriate word for describing the overall approach of considering mine waste useful and then acting to make it so. This study uses *re-mining* to describe the extraction of residual target mineral value from mine waste. *Re-mining* was selected over *reprocessing* and *recovery* since it avoids mistaken references to technical processing terminology. This study uses *reuse* to describe the utilisation of specific waste fractions. *Reuse* was chosen over *recycling, upcycling* and *downcycling* because these terms have specific connotations to end-of-life consumer goods. *Reuse* is also preferred to *repurposing* in this study, since *repurposing* is also used in the context of post-mining land use (Brock et al., 2019; Demirkan et al., 2022; ICMM, 2022). The prefix '*re*' was maintained in *reuse* (as opposed to just *use*) to emphasise the adding of value to a material stream that would otherwise have been idle or hazardous.

Table 2-2 The taxonomy that will be used in the remainder of the thesis to express creating value from mine waste.

Valorisation	The general approach of adding value and reusing mine waste, including separation and processing.
Re-mining	Processing mine waste for the purpose of extracting residual mineral value. This often includes re-grinding as well as treatment steps.
Reuse	Beneficially using a specific mine waste fraction, whether it be hazardous, specialised, or bulk waste.

2.1.2 Waste re-mining

Waste re-mining is traditionally done to recover mineral value from mine waste, often historical mine tailings (Bellenfant et al., 2013; Blasenbauer et al., 2020; Riina et al., 2014; Suppes and Heuss-Aßbichler, 2021). This may include the target minerals that were extracted by the original mines or minerals that have become economically interesting more recently. Examples include the re-mining of waste for inherent gold

(Lahiri-Dutt et al., 2011), coal (Kazadi Mbamba et al., 2013), rare earth metals (Binnemans et al., 2015) and critical raw materials (Suppes and Heuss-Aßbichler, 2021). In this paradigm, economic value is therefore still of prime importance.

Re-mined mine tailings are, however, often returned to tailings storage facilities (Banya, 2022; Fleming et al., 2010; James, 2020), perpetuating the environmental and social concerns raised in Chapter 1. In truth, re-mined mine tailings can have more severe environmental impacts than the original tailings, since particles are often finely milled (Binnemans et al., 2015; Fleming et al., 2010), which exposes previously unexposed minerals (Fleming et al., 2010). As shown in Chapter 1, this means that the tailings are likely to be more difficult to dewater, more chemically reactive, more likely to be mobilised by wind and water, and more likely to be in the respirable size range.

Experience has also shown that re-mined tailings, like all tailing facilities, can be poorly managed (Banya, 2022). When re-mined tailings are stored, de-risking becomes less likely into the future, because much of the residual mineral value which could have helped pay for waste management have been removed. Such instances are disappointing since excavating and re-mining represents a unique opportunity for achieving an improved risk and liability profile while still affording the mining company an opportunity to make profit (Fleming et al., 2010; Riina et al., 2014). This can be done by removing hazardous components and ensuring proper disposal through re-engineering storage facilities or preferably through reallocating the bulk material as feedstock for other uses. Re-mining activities should not proceed without considering environmental and social liabilities and these may indeed form part of the motivation to do so (Bellenfant et al., 2013; Kazadi Mbamba et al., 2013; Kinnunen et al., 2021).

Re-mining-and-disposal also negates the value of the bulk waste that is left behind. Binnemans et al. (2015), for instance, considered it as the starting point for working towards zero mine waste. Harrison et al. (2020) envisioned waste re-mining as a starting point for achieving both zero risk and zero waste.

2.1.3 Bulk waste reuse

The low-hanging fruit for mine waste valorisation is the bulk reuse of relatively benign waste. Common uses include road fill, building fill, brick making, cement production, ceramics production and as a soil conditioner (Acordi et al., 2023; Barati et al., 2020; Benahsina et al., 2022a; Binnemans et al., 2015; Brady, 2016; Haibin and Zhenling, 2010; Lahiri-Dutt et al., 2011; Li and Han, 2006; Pereira, 2006; Segui et al., 2023; Stolboushkin et al., 2016; Veiga Simão et al., 2022; Zhang et al., 2014). Additionally, bulk mine waste is used to backfill mine voids to stabilise underground mine stopes during operation and rehabilitation (Dudeney et al., 2013; Haibin and Zhenling, 2010; Khaldoun et al., 2016). Research has also been conducted into using serpentine-rich mine waste for carbon sequestration (Li and Hitch, 2016; Meyer et al., 2014; Veetil et al., 2015). In some circumstances coal tailings have been used as low-grade fuel for electricity generation (Bian et al., 2010; Lahiri-Dutt et al., 2011) (also see Table A 1 in Appendix A).

These bulk waste applications place the waste in intimate contact with people and/or the environment. It is therefore important that the waste be tested for both chemical stability and desirable material properties so as to avoid pollution and harm to the community (Li and Han, 2006; Pereira, 2006). Even when waste can be safely reused in bulk, separation might create certain fractions with higher-value applications thus maximising the value obtained from a waste stream (Acordi et al., 2023).

2.1.4 Waste separation and reuse

Several authors suggested waste partitioning as a way to improve product characteristics, reuse specific waste fractions or even achieve ‘zero waste’ (Acordi et al., 2023; Amaral Filho et al., 2010; Binnemans et al., 2015; Harrison et al., 2020; Taha et al., 2022). This approach incorporates both the bulk waste reuse and waste re-mining paradigms and consequently addresses the criticisms against both approaches since it maximises the value to be obtained while minimising environmental harm. Separating waste into fractions with different inherent properties opens possibilities of widely diverging uses for components within the same waste stream.

For example, Binnemans et al. (2015) explored examples of how two rare-earth metal containing mine wastes might be processed to recover the rare-earth metals in addition to other minerals and metals while finding uses for the demineralised fractions as well. Fleming et al. (2010) suggested separating gold, uranium and pyrite from gold tailings in an effort to recover mineral value and reduce the tailings-associated risk. They did not, however, consider application options for the bulk benign waste. Allard et al. (2022) studied the recovery of gold from the concentrate of desulfurised tailings. They recommended the use of the desulfurised component in road construction and AMD management as well as the use of the sulfide component remaining after gold recovery for cemented paste backfill. The long-term strength, safety and environmental impacts of such cemented paste backfill remains to be confirmed, however. Helser et al. (2022) separated out hazardous material before applying the residual benign materials in construction applications. This study did not, however, attempt to make use of the hazardous components. Taha et al. (2022) also demonstrated this approach by crushing coal waste rock and separating it into fractions that can be used as fuel, in fired brick production and in concrete and construction applications. The waste they used was identified as potentially acid generating, however, and this may render some of their options infeasible without sulfide separation.

Amaral Filho et al. (2010) gravimetrically separated Brazilian coal mine waste with the aim of re-mining residual coal and using the benign and sulfide-rich components in other applications. Kazadi Mbamba et al. (2012) also separated coal waste into a residual coal, benign and sulfide-enriched stream with the aim of valorisation, while Hesketh et al. (2010) did the same with copper sulfide tailings. In further research on the downstream applications of pre-separated coal mine waste, the benign fraction has been used to produce a fabricated soil for mine rehabilitation purposes (Amaral Filho et al., 2020) and production of concrete paving (Santos et al., 2013). Related studies have illustrated the use of the potentially valuable but hazardous sulfide-enriched component (Colling et al., 2011; Menezes et al., 2017; Vigânico et al., 2011). Two of these studies used the sulfide-enriched concentrate to produce ferric sulfate (Colling et al., 2011) and ferrous sulfate heptahydrate (Vigânico et al., 2011). Another study illustrated that higher purity pyrite concentrate produces higher quality ferric sulfate (Menezes et al., 2017). Fleming et al. (2010) considered producing acid from the pyrite isolated from gold tailings. Politis et al. (2017), likewise, report on a case where the environmentally hazardous levels of alkalinity associated with bauxite waste was isolated and used as a soil amendment or neutralising chemical. Combining hazardous and bulk mine waste reuse has been recommended by Harrison et al. (2020).

Another example of waste partitioning, where the aim is that both the bulk waste and the target minerals be used, is at Vale’s operations at Carajás in Brazil, where iron ore tailings are re-mined to recover residual iron ore (Larkin, 2023). The further separation of the residual material for use as sand substitute in construction is being studied (Golev et al., 2022; Larkin, 2023). Early indications are that this approach will be technically feasible for both this separated iron ore tailings and for copper/gold waste (Benahsina et al., 2022b; Golev et al., 2022; Segura-Salazar and Franks, 2023). The approach should also be environmentally beneficial since it avoids exploitation of virgin sand resources (Golev et al., 2022; United Nations Environment Programme, 2019).

Partitioning and reusing mine waste has the potential to reduce or completely remove mine waste by using it in appropriate applications, thereby creating economic value and removing environmental and social risk (Binnemans et al., 2015; Harrison et al., 2020). Despite this promising start, relatively little work has, however, focussed on reusing potentially hazardous components in waste, such as the pyrite inherent in South African coal and gold ores. This is an important gap in reducing the risks associated with mine waste. Several difficulties also remain with implementing waste partitioning and reuse.

2.1.5 Identifying and assessing mine waste valorisation options

The first step towards identifying and developing mine waste valorisation options is understanding what the composition and other characteristics of the feed stream are likely to be (Pereira, 2006). Work on finding ways to screen and build databases of mine waste facilities to aid mine waste valorisation has been ongoing (Bellenfant et al., 2013; Blasenbauer et al., 2020; Broadhurst, 2007; Maroušek et al., 2023; Suppes and Heuss-Aßbichler, 2021; Žibret et al., 2020). Žibret et al. (2020), however, found that national mine waste registries did not contain enough data on the mine waste facilities to be useful in assessing resources for valorisation. Nwaila et al. (2021a, 2021b) developed a sampling and modelling protocol for assessing the resources inherent in existing tailings facilities as well as their distribution with a view to valorisation. They recommend considering geo-spacial aspects in addition to chemical, mineral and physical characterisation. They have, however, shown that sampling tailings facilities for resource characterisation can be expensive. Much of the characterisation work to date has been conducted with a view to re-mining target minerals (Bellenfant et al., 2013; Maroušek et al., 2023; Nwaila et al., 2021a, 2021b; Žibret et al., 2020).

Suppes and Heuss-Aßbichler (2021) demonstrated their screening tool for assessing the re-mining potential of a tailings resource on a single German tailings facility. They used several criteria, including waste and site-specific aspects, social and environmental criteria, and also completed a stakeholder assessment. They did, however, have the benefit of access to waste characterisation data previously published in academic papers, which is not the case for most land-disposed mine waste. Monardes and Sepúlveda (2023), likewise screened Chilean tailings for re-mining, but used the base metal content and resource size as criteria.

Some researchers have conceptualised tools for assessing the reusability of bulk wastes (Park and Martin, 2007; Pereira, 2006). Pereira (2006), for instance, suggests a process for finding uses: characterising, identifying alternatives, comparing volume of material produced vs demand for application, and calculating whether the application is viable. The researcher characterised the waste in terms of chemical, thermal, physical, mineralogical, and toxicological attributes. The approach, however, only considers potential use as construction materials and removes hazardous waste and re-mining from consideration, limiting its scope. Park and Martin (2007) put forth a rudimentary multi-criteria scoring mechanism for assessing industrial waste reuse options with the collaboration of the producing company. They suggested identifying opportunities, scoring them with the help of experts and taking the best option forward for analysis. While their approach provides a useful conceptual starting point, they do not ground it in rigorous decision support theory nor do they assess data quality, amongst other issues. The outcome of their process is therefore not necessarily valid.

2.1.6 Mine waste valorisation obstacles

Commercial waste valorisation is currently limited to re-mining of wastes for the recovery of precious metals and backfilling of mine cavities (Acordi et al., 2023; Blasenbauer et al., 2020; Haibin and Zhenling, 2010; Riina et al., 2014; Suppes and Heuss-Aßbichler, 2021), with few attempts to re-use waste components for other applications (Segura-Salazar and Franks, 2023). This limitation can be attributed to several intrinsic and extrinsic constraints. One of the first and fundamental problems with implementing mine waste valorisation at scale is that mine waste is heterogeneous within a waste facility and across different mines' facilities (Abdellatif et al., 2019; Acordi et al., 2023; Johnson, 2003; Suppes and Heuss-Aßbichler, 2021; Taha et al., 2022; Žibret et al., 2020). This makes assessing the size and characteristics of the resource, which is necessary for constructing process flow sheets for reusing mine waste, difficult (Bellenfant et al., 2013). It also means that the same process flow sheets cannot always be used for the wastes of different mines (Binnemans et al., 2015), especially if they target minerals specific to a waste body.

Another issue associated with the composition of mine waste is the difficulty associated with purifying different streams (Allard et al., 2022; Bellenfant et al., 2013), which means that it will be difficult to produce pure feed streams for specialty products. Even streams that are not intended for pure mineral use might still contain impurities, such as water or sulfur, that might make producing desirable products difficult or expensive (Binnemans et al., 2015).

Another potential problem is that in re-mining and/or reusing a waste stream it is possible that a larger volume of secondary waste is generated. Bian et al. (2010), for instance, uses the example of burning coal waste for energy production, which creates large volumes of boiler slag, bottom ash and fly ash. Reusing mine wastes may even cause pollution if the process leads to hazardous waste production or requires toxic processing chemicals that may spill (Binnemans et al., 2015; Oliveira et al., 2016). Processing mine waste for reuse may also require more materials and other resources than is justified by the gains. It is therefore imperative to evaluate and select process routes for mine waste reuse that have fewer environmental and social impacts than land disposal.

The regulatory framework governing mine waste may also provide some obstacles to valorisation (Godfrey et al., 2007; Pactwa et al., 2020). Examples of potential problems are the ownership of legacy mine waste storage facilities, poor enforcement of legislation, and legal definitions of wastes and minerals along with permitting requirements (Masson et al., 2013; Pactwa et al., 2020; Van der Schyff, 2016).

Lastly, it is considered likely that many of the environmentally beneficial approaches to mine waste reuse will not be economically profitable and environmental or social benefits may thus be needed to bolster the business case (Bellenfant et al., 2013; Binnemans et al., 2015). This is especially likely since economies of scale can be a challenge to achieve with waste reprocessing, given the size and heterogeneity of resources (Breytenbach, 2016).

2.1.7 Section summary

Mine waste valorisation presents a potential solution to both the problems of negative environmental impacts and squandering of mineral resources. While waste reprocessing and bulk waste reuse show promise as solutions, a better approach is likely to be separating mine wastes into fractions with distinct characteristics and potential for reuse. This approach still faces some challenges, however, such as the shortage of data to develop, assess, and select viable waste valorisation technologies. While progress towards methods for identifying, selecting, and implementing mine waste valorisation technologies was made a decade and a half ago (Park and Martin, 2007; Pereira, 2006), the methods have limitations and no further progress has been made to address these or enhance the tools. The need for improved methods for identifying, designing, and developing mine waste valorisation approaches thus remains.

2.2 Process development and design

To transform mine waste from a nuisance or hazard to a product is likely to be a long and complex process in most cases. There are a variety of process design and technical development perspectives that can be called on to guide that process, but none fit the problem of creating and selecting technology options for waste valorisation neatly. Technology development processes provide step-by-step or phase-by-phase guidance for taking a technology from an idea to a product on the market. They, however, tend to have insufficient focus on the technical aspects that are needed for designing a chemical processing facility. Chemical process design methods involve the use of technical information to create a plan for a chemical processing facility for converting feedstocks to specified products. These tend to assume that much of the technical development work has been done and that interactions between feedstocks and processes are known (Azapagic et al., 2006; Seider et al., 2004a; Sinnott, 2005). Both tend to make commercial assumptions that might not be relevant to mine waste valorisation, as will be discussed later, and may therefore affect implementation. In the next few sections, process design, technology development, and design for sustainability are discussed, and the strengths and shortcomings of each approach for enabling waste valorisation considered.

2.2.1 Process design

There are several conceptualisations of the method to be used in process design. This section briefly considers these and then makes a case for focussing on the early stages of design. Chemical process design has also developed approaches for incorporating sustainability considerations into the design method and these are included in the discussion that follows.

Design methods are commonly conceptualised as the progression from receiving a problem statement to completing the final design (schematics can be seen in Appendix B). Towler and Sinnott (2008), Azapagic et al. (2006) and Dym et al. (2009) consider process design as a series of design steps, moving from general high-level design steps to more detailed, data-intensive design steps (eg. early design, feasibility design, preliminary design, detail design). Cano-Ruiz and McRae (1998) view process design as an iterative process that moves from a problem statement to problem framing followed by iterations on alternative generation, analysis, and evaluation and optimisation. The process culminates in a sensitivity analysis, after which it circles back to the beginning, working at ever greater levels of detail. Figure 2-2 shows a generic design process based on the approaches discussed. Chen and Shonnard (2004) also consider design as a series of progressively more data-intensive steps, but include iteration in the early parts of the design. Lastly, the design process can be conceptualised as a hierarchy of process steps where certain design tasks must be engaged in before others (Douglas, 1988; Stewart et al., 2003). As the design progresses, discrete design alternatives will be progressively eliminated, and the design focus will increasingly be on optimal operating regimes. The design must also be based on better data as the design progresses (Basson and Petrie, 2001; Sinnott, 2005; Stewart et al., 2003).

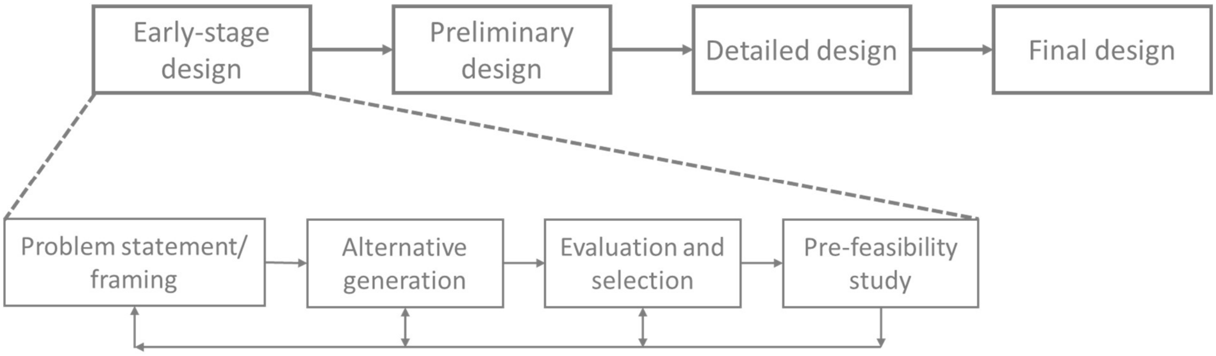

Figure 2-2 A schematic of a common conception of design processes based on the work of Cano-Ruiz and McRae (1998), Azapagic et al. (2006), Towler and Sinnott (2008) and Dym et al. (2009).

It is worth noting that since various conceptualisations of process design exist, the taxonomy for process design is not standardised. For instance, words such as early-stage design, conceptual design and project initiation have been used to describe the same stage and activities in chemical process design and are often used interchangeably (Azapagic et al., 2006; Dym et al., 2009; Park et al., 2020; Ruiz-Femenia et al., 2017). Chen and Shonnard (2004), on the other hand, extend early-stage design to the finalisation of a base case flow sheet. Different conceptualisations of what process steps are appropriate for early-stage design can be seen in Table 2-3 and there is no standard early-stage chemical process design sequence. Starting with a form of initial problem ordering step, variously called *Project initiation*, *Project specification*, *Problem framing*, and *Initial design task* is, however, common. Azapagic et al. (2006) include the identification/generation and evaluation of alternatives in the initiation step, while Cano-Ruiz and McRae (1998) and Chen and Shonnard (2004) have a separate step for that. Towler and Sinnot (2008) does not include an explicit alternative identification/generation step, but they do call for evaluation. This is generally followed by some form of selection, except in Chen and Shonnard’s (2004) conceptualisation. Then follows a series of more detailed development of flow sheets and subsequently, preliminary costing and sustainability analysis, which will be called pre-feasibility analysis. For the remainder of this thesis early-stage design is used to mean the design steps from project structuring to the pre-feasibility study.

The early stages of design is where substantial impacts on the final design can be realised, since it is relatively unconstrained compared with later design stages (Basson and Petrie, 2001; Stewart et al., 2003; Ullman et al., 1988). It is therefore in the early stages that the greatest impact on a design’s future environmental and social footprint can be realised. This study consequently focuses on the early stages of design. The components of early-stage design are identification of stakeholders, design criteria, alternative process routes, and evaluation and selection of the alternatives (Azapagic et al., 2006; Broadhurst et al., 2002; Chen and Shonnard, 2004; Sinnott, 2005; Stewart et al., 2001). The next few sections consider each of these project initiation phases in turn.

Table 2-3 Different conceptualisations of early-stage design tasks.

Azapagic et al. (2006)	Towler and Sinnott (2008)	Cano-Ruiz and McRae (1998)	Chen and Shonnard (2004)
1. Project initiation Initial identification of sustainability design criteria and relevant stakeholders Identification and evaluation of alternatives on sustainability criteria 2. **Preliminary design** Process selection and description Flowsheet preparation Preliminary cost estimates Preliminary assessment of sustainability and further identification of sustainability criteria	Project specification Initial evaluation Process selection Preliminary flow diagrams Material and energy balances Preliminary equipment selection Process flow sheeting Preliminary cost estimation Authorisation of funds	Problem framing* Alternative generation* Analysis* Evaluation and optimization* Sensitivity analysis*	Initial design task Process synthesis and base case flowsheet development 1. Reaction pathway evaluation 2. Solvent selection 3. Technology selection 4. Equipment selection Process simulation Process diagnostic summary tables Improved base case flowsheet

* Each of these steps contain several sub-steps, which were considered too detailed for this table. The steps can be seen in Figure A 4.

2.2.1.1 *Problem statement and framing*

The first step in design is problem framing where design teams decide on objectives, constraints, stopping rules, battery limits, and evaluation criteria (Cano-Ruiz and McRae, 1998; Hanes and Bakshi, 2015). They also scope the analysis and ensure that the problem is clearly defined (Cano-Ruiz and McRae, 1998; Hanes and Bakshi, 2015). In this phase, process design for waste valorisation diverges from classical design. Process design literature tends to frame process design as something that is initiated by a customer brief and ends in final design documentation (Dym et al., 2009; Sinnott, 2005). The underlying assumption is that the customer specifies the product(s) and constraints, while the engineering design team will work with available feed streams and processing routes as variables to create a profitable process design (Chen and Shonnard, 2004; Dym et al., 2009; Palaniappan et al., 2002; Sinnott, 2005; Towler and Sinnott, 2008; Zhang et al., 2018). This is not how the majority of published mine waste valorisation research has thus far been conducted, as shown in Table A 1 in Appendix A. Waste valorisation work has emanated from research institutions mostly without financial assistance or involvement from mines or other commercial partners. This means that a clearly defined product, specifications, and constraints are either absent or driven by the research institution. Additionally, waste valorisation work is by nature driven by resource availability and characteristics rather than industrial commercial opportunities. This affects project framing and represents a departure from traditional design literature.

Design for sustainability literature notes that stakeholders (such as employees, affected communities and potential customers) must be identified and consulted relatively early in the process to ensure that their concerns are integrated in the design (Basson and Petrie, 2007a; Corder, 2015; Goodfellow et al., 2014). Goodfellow et al. (2014) contend that, to be truly ethical, stakeholders need to be included in decision-making from an early stage. Corder (2015) noted how the lack of social license to operate could delay or derail projects, emphasising the importance of getting approval and including communities in the design process. Obtaining stakeholder input into design is therefore arguably both ethical and advantageous.

Goodfellow et al. (2014) attempted to obtain stakeholder input for early-stage nuclear design decisions by surveying a cross-section of the UK population. This approach, however, assumes a high literacy rate amongst respondents and requires careful sampling protocols to ensure that the views of all affected parties are incorporated. This approach also has limited applicability in cases of early-stage technology design and development for mine waste valorisation, since mine waste valorisation is an issue of local importance and no specific locations for constructing and implementing the technology solutions have been identified. Prematurely conducting stakeholder engagement could also unrealistically heighten some stakeholders' expectations (Corder, 2015). Basson and Petrie (2007a) used two approaches for considering stakeholder preferences. In their first case study they conducted decision-making at the early stages of design internally to the company involved. They chose to make final, later-stage decisions with a wider stakeholder group. In their second case study they considered criteria that would be important for a wide range of stakeholders. Since decisions early in the design process have disproportionate impact on a design's outcome, as discussed before, the second case study's approach is considered more consistent with sustainable development principles.

The criteria used for assessing the appropriateness of a design are based on decision-maker values and have traditionally been techno-economic (Seider et al., 2004a; Towler and Sinnott, 2008). Seider et al. (2004a), for instance, used technical, market and economic indicators to guide their evaluations. To move from traditional design to design for sustainability, a consideration of wider socio-environmental factors is required in this phase in addition to the standard techno-economic considerations (Azapagic et al., 2006; Cano-Ruiz and McRae, 1998; Chen and Shonnard, 2004; Serna et al., 2016; Stewart et al., 2003). Earlier process design for sustainability approaches only considered environmental sustainability, which was operationalised by the addition of environmental objectives and evaluation criteria to traditional design processes (Cano-Ruiz and McRae, 1998; Chen and Shonnard, 2004; Ouattara et al., 2012; Park and Martin, 2007; Serna et al., 2016; Stewart et al., 2003). Cano-Ruiz and McRae (1998), for instance, put energy efficiency and emission avoidance alongside profitability and conversion efficiency as criteria for prospective processes. Acknowledgement that chemical process plants' interaction with their social environments were also important meant that social indicators or criteria were later also added to the evaluation process (Azapagic, 2004; Azapagic et al., 2006; Corder, 2015; Corder et al., 2010; Goodfellow et al., 2014; Serna et al., 2016). An example of some of the criteria suggested and used in literature is shown in Table 2-4. More complete lists of criteria can be found in Appendix C, Table A 3 and Table A 4.

Table 2-4 Examples of process criteria and objectives from literature.

Indicator	Literature source	Explanation
Economic		
Capital costs	(Azapagic et al., 2006; Sinnott, 2005; West et al., 2008; Wright et al., 2010)	The cost of constructing the process equipment
Profitability	(Azapagic et al., 2006; Cano-Ruiz and McRae, 1998; Sinnott, 2005; West et al., 2008; Wright et al., 2010)	Normally measured in terms of net present value or internal rate of return.
Social		
Society benefit	IChemE	Community benefit per value added
Employee health and safety	(Azapagic et al., 2006; Chen and Shonnard, 2004; Palaniappan et al., 2002)	
Environmental		
Energy usage	IChemE; IMA; GRI; WAR (Azapagic & Perdan, 2000)	Usage of energy (in its different forms, such as electricity and fuel oil) per year or per unit product. One can make provision for energy sourced from renewables
GHG emissions	(Azapagic et al., 2006; Global Reporting Initiative, 2013; IChemE, 2002; Ouattara et al., 2012; Serna et al., 2016; US Environmental Protection Agency, 2011)	The emissions of greenhouse gasses by operations. Can also be reported in GHG intensity
Mass of waste	GRI; (Azapagic and Perdan, 2000; Cano-Ruiz and McRae, 1998; Palaniappan et al., 2002)	Should be delineated by type and disposal method
Environmental emissions	GRI; IChemE; LCA; WAR (Azapagic et al., 2006; Cano-Ruiz and McRae, 1998; Ouattara et al., 2012)	This category can include water, air and land emissions, specifically the emissions of NOx, SOx, persistent organic pollutants, volatile organic compounds, hazardous air pollutants and particulate matter

2.2.1.2 Alternative generation

To increase the likelihood of producing an optimal design, several technology alternatives are considered in the early stages (Stewart et al., 2003; Towler and Sinnott, 2008). These are then investigated and the number of alternatives reduced through a selection or elimination process (Basson and Petrie, 2007a; Dym et al., 2009; Towler and Sinnott, 2008) so that the most promising alternative(s) can be investigated in subsequent design stages.

Several methods exist for generating design alternatives, as shown in Box 2-1 (Cano-Ruiz and McRae, 1998; Stewart et al., 2003; Towler and Sinnott, 2008). To manage risk, the adaption of existing designs is popular in chemical process design (Duffy et al., 1995; Towler and Sinnott, 2008). Heuristics are also popular in the minerals industry due to, amongst other things, lack of thermodynamic information for minerals processing and variability of ores and wastes (Stewart et al., 2003). Hierarchal procedures specify process design steps to include in different design phases, corresponding to the increased detail, and will be relevant in later design phases, as discussed in Section 2.2.1. Thermodynamic targeting, expert systems and artificial intelligence and mathematical programming are also more relevant at the later stages where more data are available and more detail is required.

Box 2-1 Alternative generation methods

- Adjustment of existing designs
- Combining of existing designs
- Heuristics
- Hierarchal procedures from design literature
- Thermodynamic targeting
- Expert systems and artificial intelligence
- Mathematical programming

As mentioned in Section 2.2.1.1, in classical design the product is fixed at project initiation (Azapagic et al., 2006; Chen and Shonnard, 2004; Sinnott, 2005). When designing for waste valorisation, contrary to traditional design, the design feedstock is set, while the product can be any of a wide variety of products (Acordi et al., 2023; Binnemans et al., 2015; Harrison et al., 2020). This increases the costs associated with data acquisition in the early stages of a project, because product specifications and potentially widely different process routes must be considered for each of the potential products (Azapagic et al., 2006; Sinnott, 2005; Zhang et al., 2018). This is then followed by process synthesis culminating in a base-case flowsheet (Chen and Shonnard, 2004; Seider et al., 2004b; Sinnott, 2005). The base-case flowsheet includes identification of processing routes and aspects such as energy sources and raw materials (Azapagic et al., 2006; Cano-Ruiz and McRae, 1998).

2.2.1.3 *Evaluation and selection*

It has been known for some time that engineering designers tend to satisfice[2] due to bounded rationality[3] (Ball et al., 1998; Ullman et al., 1988). Some design texts suggest heuristics, such as choosing mature technology alternatives, in order to improve the basis from which to satisfice (Sinnott, 2005; Stewart et al., 2003). Alternative decision processes in traditional process design include Pugh matrices, quality functional deployment and decision trees for process evaluation (Bertoni et al., 2017; Infotox, 2012; Leifer and

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[2] To satisfice during process design means to choose satisfactory designs as opposed to optimal designs (Ball et al., 1997).

[3] Bounded rationality refers to the limited processing power, information, and time that people typically have to make decisions (Stewart and Losa, 2003; Ullman et al., 1988).

Steinert, 2011; Park and Martin, 2007). Decision tree methods are satisfactory when alternatives' performance on only a few criteria (technical performance, economics) must be considered. When the numbers of alternatives and/or criteria grow, however, the problem becomes too complex. Pugh matrices and quality function deployment make use of less precise data inputs and the outcomes are therefore more tentative (Ayag and Özdemir, 2009; Bertoni et al., 2017). It has been noted that the success of a design is contingent on selecting a good technology solution in the early stages of design, since the degrees of freedom for effecting substantial change will have reduced drastically by later design stages (Basson and Petrie, 2001; Stewart et al., 2003; Ullman et al., 1988). It is therefore advantageous to make decisions that are as optimal as possible, based on all the criteria of importance, during the early design stages.

When sustainability considerations are included in a design, selection of alternatives becomes a multi-criteria decision analysis (MCDA) problem, considering social and environmental aspects alongside techno-economics (Basson and Petrie, 2007a, 2001; Lizarralde and Ganzarain, 2019; Stewart et al., 2003; Wunderlich et al., 2021). MCDA methods allow for the structured consideration of multiple alternatives based on multiple criteria, improving understanding of the decision-problem and facilitating the exploration of trade-offs (Belton and Stewart, 2002; Lizarralde and Ganzarain, 2019). They are important tools for incorporating sustainability in process design (Lizarralde and Ganzarain, 2019; McLellan et al., 2009; Petrie et al., 2007; Sugiyama et al., 2008; Wunderlich et al., 2021).

MCDA is a general class of decision support methods that include multi-attribute decision analysis (MADA) (for discrete decision problems, such as choosing a preferred processing technology) and multi-objective decision analysis (MODA) (for continuous decision problems, such as choosing an operating regime) (Basson, 2004). Several MADA techniques are commonly used in process selection, as shown in Table 2-5. Value theory has been used in decision support in the context of design for the minerals industry (Basson and Petrie, 2007b; Stewart et al., 2003). It has also been used in a variety of other contexts such as carbon capture and storage process selection (Fozer et al., 2017), assessing ecological management solutions (Langhans and Schallenberg, 2021) and mapping walkability in urban environments (Fancello et al., 2020). The model structure of value theory allows exploration of bias and bounded rationality, which can be useful in interrogating both data and stakeholder values (Estévez et al., 2018; Stewart and Losa, 2003).

Popular decision support methods are AHP and TOPSIS, which are simple and easy to implement (Ayag and Özdemir, 2009; Boran et al., 2009; Darende et al., 2021; Olabanji and Mpofu, 2020; Ouattara et al., 2012), but suffer from theoretical concerns[4], rank reversal[5] and accuracy problems (Bana e Costa and Vansnick, 2008; Çelikbilek and Tüysüz, 2020; García-Cascales and Lamata, 2012). Outranking methods, developed and mostly used in French-speaking contexts, assume that decision-makers' preferences are somewhat unstable and undefined, and therefore offer a process for structuring and exploring the decision problem (Bouyssou, 2001; Stewart and Losa, 2003). Outranking methods, however, are relatively complicated, require non-intuitive inputs, and the relation between inputs and outputs are sometimes difficult to understand or counterintuitive (Belton and Stewart, 2002). Value theory, on the other hand, is simpler to implement and transparent to interpret (Beaudrie et al., 2021; Salo and Hämäläinen, 2010; Stewart et al.,

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[4] Theoretical issues with AHP include: the use of a ratio scale when comparing alternatives using verbal statements which may have no natural zero; the relation of phrases to numbers which may or may not be correlated for a decision-maker; the meaning of weights (Basson, 2004; Belton and Stewart, 2002).

[5] A phenomenon where the addition or removal of an alternative changes the preference order of the remaining alternatives. This is a serious criticism for decision support methods (Salo and Hämäläinen, 2010).

2001; Stewart and Losa, 2003). It requires care in the structuring phase, however, since it carries the requirement that axiomatic foundations be respected in the decision support process to achieve sound results (Belton and Stewart, 2002). Sound results are also predicated on the exploration of decision-makers' preferences and uncertainty through sensitivity analyses.

Value theory has been used in decision support in the context of design for the minerals industry (Basson and Petrie, 2007b; Stewart et al., 2003). It has also been used in a variety of other contexts such as carbon capture and storage process selection (Fozer et al., 2017), assessing ecological management solutions (Langhans and Schallenberg, 2021) and mapping walkability in urban environments (Fancello et al., 2020). The model structure of value theory allows exploration of bias and bounded rationality, which can be useful in interrogating both data and stakeholder values (Estévez et al., 2018; Stewart and Losa, 2003).

Table 2-5 MADA techniques commonly used in process selection

MADA technique	Advantages	Disadvantages	References
Value theory	Simple Transparent Strong axiomatic foundation Ease of exploring bounded rationality	It is possible to implement value theory in a way that disregards axioms. Results are sensitive to value functions that are inappropriately linearised.	(Langhans and Schallenberg, 2021; Salo and Hämäläinen, 2010; Stewart et al., 2001; Stewart and Losa, 2003)
Outranking methods (eg. ELECTRE, PROMETHEE)	Does not force ranking in cases of uncertainty. Able to include alternatives that are not strictly comparable	Complex to implement, requires several non-intuitive inputs and difficult to communicate the method and outcomes to wide audience.	(Bezerra et al., 2021; Bouyssou, 2001; Stewart and Losa, 2003)
Analytical Hierarchy Process (AHP)	Simple to implement	Rank reversal can result, theoretical questions remain.	(Ibáñez-Forés et al., 2014; Olabanji and Mpofu, 2020; Promentilla et al., 2008)
Technique for Order Performance by Similarity to Ideal Solution (TOPSIS)	Simple to implement	Rank reversal can result, can be inaccurate.	(Darende et al., 2021; Ibáñez-Forés et al., 2014; Kamble et al., 2017)

2.2.1.3.1 Data for evaluation and selection

Comparing alternative processing routes based on technical, social, environmental, and economic criteria necessitates having sufficient data to do it meaningfully. Data availability is a problem both for designing for mine waste valorisation and evaluating and selecting between designs (Broadhurst and Petrie, 2010; Stewart et al., 2003). In normal chemical process design, physicochemical properties can be found in various databases (Martin et al., 2022; Serna et al., 2016). As mentioned in Section 2.1.6, however, waste bodies are heterogeneous within- and between mines and feedstock characterisation for an entire resource is therefore difficult. This data are also not routinely collected in practice (Reddick, 2006; Suppes and Heuss-Aßbichler, 2021). Additionally, because of the simultaneous presence of several mineral components in mine waste, data and understanding on process interactions are typically scarce (Stewart et al., 2003). In design, data deficiency is normally solved by doing laboratory or pilot plant experiments (Gear et al., 2018; Seider et al., 2004b). Running lab tests to characterise the waste materials' behaviour in several widely different processing scenarios will, however, be expensive (Zhang et al., 2018). The normal difficulty with data availability at the early stages of design (called the "design paradox") (Chebaeva et al., 2021; Toniolo et al., 2014) is therefore exacerbated in the case of process design for mine waste valorisation. Access to good-quality data is, however, necessary for meaningful decision support (Broadhurst and Petrie, 2010).

For more mature technologies and at later stages of design when the processing route is more fully developed, life cycle analysis (LCA) data are appropriate and available to use (Chebaeva et al., 2021; Chen and Shonnard, 2004; Elginoz et al., 2022; Gear et al., 2018; Hanes and Bakshi, 2015; Kamble et al., 2017; Rodríguez-Vallejo et al., 2019; Stewart et al., 2003). While progress has been made in adapting LCA to early-stage design and development, problems such as data availability, uncertainty and complexity still remain (Cucurachi et al., 2018; Moni et al., 2020; Segura-Salazar et al., 2019; Steubing and de Koning, 2021; Toniolo et al., 2014). LCA also does not answer social questions and so cannot be used in isolation from other methods. Environmental impact assessment (EIA) information has been suggested to fill the gap in social data and supplement environmental data (Stewart et al., 2003). EIAs are, unfortunately, expensive to do and can only be done in later stages of chemical process design, when the location has already been chosen (Middle and Middle, 2010). Corder et al. (2010) have suggested that a proprietary database would be useful and have accumulated data on Australian energy generation and transport impacts. Such databases are, however, expensive to develop and not widely available for mineral wastes.

Contemporary design tools are also of limited help here. The majority of design tools and design for sustainability tools, whether early or later stage, are aimed at facilitating design for pure chemicals and mature technologies, where more information is typically available (Chen and Grossmann, 2017; Diwekar and Shastri, 2011; Li et al., 2022; Martin et al., 2022; Othman et al., 2010; Ouattara et al., 2012; Palaniappan et al., 2002; Rodríguez-Vallejo et al., 2019). These tools typically incorporate software and simulations, and sometimes MCDA methods, all of which require data which they get from either pre-existing data bases or experimentation. Simulation tools specifically for design for mining and minerals processing are steadily improving, but tend to focus on modelling commercial mining unit operations such as flotation and comminution (Segura-Salazar et al., 2019). These, again, need data inputs. Also, simulation capability for the novel application of mine waste in other contexts is unlikely to be realised soon.

Unsurprisingly, due to the data deficiency, existing approaches for valorising mine waste incorporates thorough testing regimes as initial steps (Acordi et al., 2023; Pereira, 2006; Taha et al., 2022). Acordi et al. (2023), however, assume that the waste will be used as feedstock for one of a few construction materials, simplifying the design problem, but potentially missing promising alternative uses. Infotox (2012) implements a quick screening of potential product alternatives at the beginning of the design process and may therefore be biased toward more mature products and technologies. Classical design literature cautions inexperienced engineers to favour technically mature technologies when designing, to avoid the costs and delays associated with designing and developing novel technologies (Douglas, 1988; Sinnott, 2005). Indeed, potential design solutions have been removed from consideration in literature due to a lack of available information and industry preference for mature technologies (Stewart et al., 2003). In a university innovation and design setting, removing alternatives that could turn out to be superior and be further developed in its laboratories is clearly undesirable. Many of the technologies used for mine waste valorisation can also be expected to be novel or at least unproven for the mine waste in question. The preference for mature technologies in process design must be challenged for design and development of effective waste valorisation technologies.

2.2.1.3.2 Expert judgements as data for evaluation and selection

When experimental data are unavailable, Dym et al. (2009) suggests using expert judgement input, but stops short of explaining how this can reliably be done. One approach to doing this, called SUSOP (SUStainable OPerations), has been developed in the context of the mining and minerals industry by adapting the standard HAZOP process (Corder, 2015; Corder et al., 2010). The SUSOP method obtains expert judgement input in a workshop setting (akin to focus groups) to identify and prioritise sustainability opportunities and risks (Corder, 2015). The SUSOP process was developed for use by commercial mining companies, with the aim to integrate into existing project management processes.

Expert input is also commonly used in other applications, such as guiding policy development (Curtright et al., 2008a; Morgan, 2015; Yoon, 2018), forecasting (Bolger and Wright, 2017) and risk assessment (Montibeller and Von Winterfeldt, 2015; Song et al., 2018). It has furthermore been used in the creation of conflict mitigation tools for use in the mining context (Ocampo-melgar et al., 2018). Expert input is increasingly used in different decision support for sustainability scenarios (Darende et al., 2021; Demirkan et al., 2022; Kamble et al., 2017). There is therefore precedent from other contexts for expert judgement elicitation on more technical matters.

Common methods for eliciting expert input include questionnaires/surveys (Demirkan et al., 2022; Sadr et al., 2018), interviews (Curtright et al., 2008a; Kamble et al., 2017), focus groups (Corder, 2015) or a combination of these (Hobballah et al., 2018; Ter Berg et al., 2019). Questionnaires have been used in decision modelling (Bezerra et al., 2021; Estévez et al., 2018; Ezbakhe and Perez-Foguet, 2018; Salo et al., 2021) and a variety of different research contexts (Curtright et al., 2008b; Ganotakis and Love, 2012; Ruokonen, 2020; Shongwe, 2017). These are relatively inexpensive, efficient and simple to administer over large sample sizes and are therefore the method of choice when large quantitative data sets must be obtained (Robson, 2002: 233-234; Seale, 1999). Questionnaires can, however, suffer from problems such as low response rate, social desirability response bias[6], and undetected ambiguities and misunderstandings in responses (Ezbakhe and Perez-Foguet, 2018; Ponto, 2015; Robson, 2002). Data quality must therefore be investigated before accepting results.

Interviews have likewise been used in decision modelling (Kamble et al., 2017; Salo et al., 2021), as input in various aspects of design (Goodfellow et al., 2014; Hobballah et al., 2018) and other engineering applications (Kabiawu et al., 2016; Stewart and Petrie, 2006). Conducting interviews is a relatively efficient method for gaining insight into a person or population's opinions, perspectives and motives (Robson, 2002: 272-273). Expert interviews are a specific class of interviews that aim at obtaining information on technical or quasi-technical matters that cannot be investigated efficiently using conventional literature searches or experimental means (Bogner et al., 2009). They are useful for providing perspective on engineering or engineering-adjacent problems that could not be gained by a more technical research design.

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[6] This bias involves the respondents giving answers that they believe other people would like to hear.

Consequently, to be effective, the experts to be interviewed must be active in the field of enquiry and thus possess the technical and process knowledge of interest to the study (Bogner and Menz, 2009).

Limitations of interviews include experts' imperfect and incomplete knowledge (bounded rationality) and memories as well as unformed opinions, if the subject of the interview is not part of the experts' daily duties (Montibeller and Von Winterfeldt, 2015; Morgan, 2014). Technical or personal biases of either the experts or interviewer or social desirability response bias may also affect the responses given (Robson, 2002). Linguistic variability, where the meaning of words may be slightly different depending on who is asked, also plays a role in producing uncertain data (Darende et al., 2021; Sadr et al., 2018). Lastly, recent events may affect an experts' perception as to the salient aspects of a phenomenon or the likelihood of an event (Montibeller and Von Winterfeldt, 2015; Morgan, 2014). Expert opinions are therefore neither objective nor infallible truth (Bogner and Menz, 2009) and must be used judiciously.

Focus groups can be advantageous in that several experts can be canvassed at once, saving research time, and the experts can jog each other's memories and enhance each other's thinking (Robson, 2002). The interactions between experts during focus group sessions, however, add to the complexity already present with interviews. For instance, groups of people tend to mostly air opinions common to the group and suppress contradictory or dissenting ideas (Robson, 2002). This may mean that important information is not mentioned or that aspects that most of the members of the group are aware of receive heavier weights than they should. Focus groups therefore necessitate excellent group facilitation skills to manage group dynamics. Focus groups also require several experts to be available simultaneously and at the same location, which can prove difficult.

2.2.1.4 Pre-feasibility study

The initial steps in early-stage design are often followed by a pre-feasibility study or some sort of market and profitability study before more detailed design is undertaken, especially for large infrastructure projects (Corder et al., 2010; Douglas, 1988; Infotox, 2012; Sinnott, 2005). This is a decision-point where the commercial assumptions the design is based on are verified and weaknesses identified for correction before the design progresses.

The first commercial assumptions to be considered are the early indications of technical feasibility, such as technological maturity, material properties and location specifics (Corder et al., 2010; Douglas, 1988; Yoon, 2018). Financial analysis is also generally included in the form of capital expenditure assessments, revenue stream assessments and profitability assessments (Douglas, 1988; Smith and Anderson, 2009). Profitability is assessed using net present value (NPV) and internal rate of return (IRR) calculations with specific hurdle rates (Smith and Anderson, 2009). Market, regulations, and risk assessments are also considered important at this stage (McLellan et al., 2009; Smith and Anderson, 2009). It has been noted that the project planning phase represents an opportunity to incorporate sustainability considerations into the design for minerals process (Corder et al., 2010; McLellan et al., 2009). Examples of such considerations are the potential impacts of the process on the environment, society, and the economy (Corder et al., 2010; McLellan et al., 2009).

When designing and developing technologies for waste valorisation, however, the technologies are likely to be either unproven for the feed materials or novel. This means that capital expenditure, profitability, and aspects such as location and community characteristics are more uncertain than with mature technologies. A rudimentary technical and financial feasibility study is therefore more suitable. Douglas (1988: p.5), for instance recommended 'back-of-the-envelope' calculations, for assessing the profitability of a design. Likewise, the market, sustainability and risk assessments are more likely to be appropriate at a rudimentary level.

2.2.2 Technology development and innovation theory

In most cases, waste valorisation technologies require further development before they are ready for implementation, especially when they are not construction related. Insights from technology development literature may therefore provide useful insights into addressing technology development for valorising mine waste. Chemical process development literature focuses on aspects such as unit operations and modelling without spending much time on the process for technology development (Zhang et al., 2018; Zhao, 2017). More generic technology development processes are therefore discussed here. Technology development processes in literature are conceptualised distinct from, but related to, the concepts of technology roadmapping (Caetano and Amaral, 2011; Cho et al., 2016) and product development (Eldred and McGrath, 1997). Technology roadmapping is about developing a rational, executable technology strategy for companies (Caetano and Amaral, 2011; Cho et al., 2016). Product development is about the conversion of ideas and technologies to saleable products (Cooper, 1990; Eldred and McGrath, 1997). These focus on aspects of the technology development infrastructure in corporate entities that are outside the scope of this work, since they do not propose any structure for early-stage technology development. Another related idea is that of innovation management (Hansen and Birkinshaw, 2007; Lercher, 2016), which includes technology innovation along with other business aspects. Since we are considering early-stage design and development of value from waste technologies within a research and academic context, technology development processes and innovation management processes are considered here.

Technology development is popularly conceptualised as a funnel, as shown in Figure 2-3 (Aristodemou et al., 2019; Clark and Wheelwright, 1992). It shows that multiple technologies exist in idea form and the technology development process whittles them down and develops the most promising ones. Technology development processes provide a roadmap for project teams to follow when aiming at fast, cheap, and successful technology development (Lind, 2006; Yapps Cohen et al., 1998).

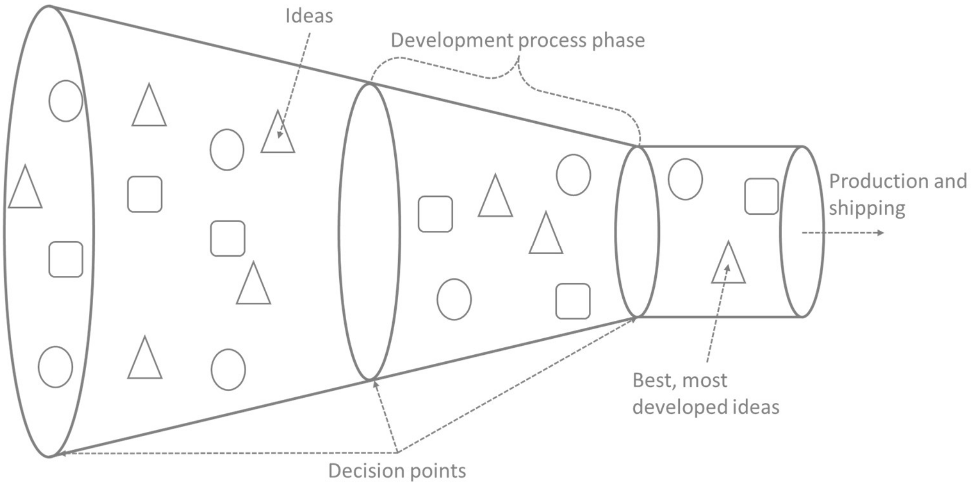

Figure 2-3 Technology development funnel, showing the progression from many, poorly developed ideas to few, fully developed technologies (Clark and Wheelwright, 1992)**.**

These processes commonly show technology development as a series of tasks, with specific deliverables, and decision points throughout the process, of which an illustrative example is shown in Figure 2-4 (Aristodemou et al., 2019; Cooper, 2006; Lercher, 2016; Lind, 2006; Yapps Cohen et al., 1998). Several technology development process steps are available for project teams to choose from.

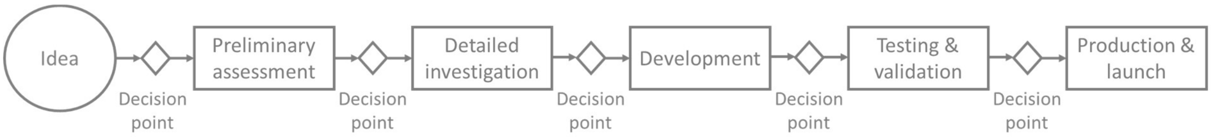

Figure 2-4 Cooper's (1990) **stage-gate process for new product development.**

Technology development processes have historically been either idea or problem focussed (see Section 8B.2 of 8Appendix B). For example, the technology development process put forward by Caetano et al. (2011) moves from *Idea* to *Technology* with regular opportunities to decide whether a technology is to be further developed, but with no indication that multiple technologies are considered in tandem or that a specific problem must be addressed. This approach is also followed by Cooper (2006) and Yapps Cohen et al. (1998). In contrast, Lind (2006), Whitney (2007) and Schulz et al. (2000) frame the starting point in terms of a company's strategy and opportunities. This approach therefore sets out with a specific idea of what the company would like to achieve and is in a sense problem driven. Problem-driven processes assume that multiple different alternative solutions to a problem must be generated and analysed, and that one or more of the alternatives are then selected for further development. Idea-driven technology development processes assume that an innovative technical idea is already selected for further development. As such, these processes do not include a step for considering and selecting between several different options with the aim of focusing on further development of those most likely to solve a problem. They are therefore useful for later stage development and can indeed provide guidance for the 'development' step seen in many problem-driven technology development processes (Figure 2-5 below). They do not, however, provide guidance for approaching the early stages of problem-driven technology development.

The problem-driven methods are similar in their approach, as can be seen in Section 8B.2 8Appendix B. For instance, after having decided strategic directions, they follow up with alternative identification, evaluation and selection, and development steps (Lind, 2006; Schulz et al., 2000; Whitney, 2007). Both Schulz et al. (2000) and Lind (2006) complete their technology development processes with commercialisation steps. There are differences between the processes, however. For example, Lind's (2006) process is circular, emphasising the continual nature of corporate innovation, while the process of Schulz et al. (2000) is linear, emphasising technology development's project-based nature. Whitney's (2007) process is linear but has many feedback loops, emphasising the iterative nature of technology development. Since we are not concerned with corporate innovation, the problem-based technology development process for a project can therefore be simplified to the process steps shown in Figure 2-5.

Figure 2-5 The technology development process simplified from Lind (2006) and Schulz et al (2000).

Interestingly, Figure 2-5 is very similar to the Innovation Value Chain of Hansen and Birkinshaw (2007) and to aspects of the Big Picture Innovation Model of Lercher (2016), both given in Section 8B.3 of 8Appendix B. There are minor differences in that the Innovation Value Chain expands the alternative generation process and the Big Picture Innovation Model uses multiple small evaluation steps (Hansen and Birkinshaw, 2007; Lercher, 2016).

The 'initiation', 'alternatives identification', 'evaluation and selection', 'development' (Figure 2-5) progression is common to the early stages of several relevant technology development processes. While 'initiation' and 'alternatives identification' are important first steps, these are similar to the intital steps of problem framing and alternative generation in process design and will therefore not be considered further in this section. Technology development literature has some different approaches to 'evaluation and selection', discussed next. The initial stages of the development step as well as the contribution of technology transfer are also discussed.

2.2.2.1 Evaluation and selection

Before engaging in serious evaluation, several authors recommend pre-screening the identified alternatives to remove non-starters from evaluation (Lercher, 2016; Martin et al., 2022; Serna et al., 2016; Tugnoli et al., 2008). This reduces the resources needed to evaluate multiple alternatives.

Ideas that pass this first screening are then subjected to further examination and evaluation to determine final alternatives as well as the development trajectory (Lercher, 2016; Schulz et al., 2000; Whitney, 2007). Traditionally, evaluation was based on techno-economic criteria and laboratory studies (eg. Schulz et al., 2000), but a sustainability focus has more recently gained prominence (Kralisch et al., 2016). Following design for sustainability literature, criteria derived from LCA and social-LCA have been suggested in addition to techno-economic criteria (Kralisch et al., 2016; van Haaster et al., 2017). Again, as with design for sustainability, the evaluation process has consequently become more complex and specialised evaluation methods are needed. A variety of methods applicable at the early stages of technology development have also been suggested, including streamlining life cycle costing, economic models, checklists, MCDA (and specifically outranking methods), and collaborative input from experts (Chebaeva et al., 2021; Kralisch et al., 2016; Whitney, 2007). Whitney (2007) also suggests using qualitative methods for evaluation in the early stages of technology development. The problems of lack of data availability and the lack of evidence for the methods' appropriateness remain, however.

2.2.2.2 Development: scoping studies

The 'development' step in problem-focussed technology development and innovation processes do not tend to be described in much detail. As mentioned before, the idea-focussed technology development processes can guide development after the 'idea' has been crystallised by the alternative identification and selection steps. The first step of the more focussed technology development is a scoping assessment to formalise the technology status-quo and map out future development needs (Caetano et al., 2011; Cooper, 2006; Lercher, 2016; Yapps Cohen et al., 1998). Activities such as conducting technical and intellectual property literature reviews, opportunity (market) assessments, and composing plans for development are typically undertaken (Caetano et al., 2011; Cooper, 2006).

In practice similar studies are sometimes required to access research and development funding. For instance, the government of Korea requires a pre-feasibility study, which includes a technology scoping analysis and description of idea selection in addition to business case and policy analyses, before committing funds to large research and development projects (Yoon, 2018). This qualitatively assesses technical issues as well as the projected return on investment.

2.2.2.3 Technology transfer

All successful technology development approaches culminate in the transfer, application or commercialisation of the finalised technologies (Caetano et al., 2011; Cooper, 2006; Lercher, 2016; Lind, 2006; Schulz et al., 2000; Yapps Cohen et al., 1998). As Leifer and Steinert (2011) put it: “While still grounded solidly in engineering principles and construction, we have realized that the Meta level issue of customer adoption should be the defining parameter for measuring the success or failure of a new product or system”. Technology transfer means successful implementation and continual use of the technology (Leifer and Steinert, 2011; Souder et al., 1990). Technology transfer can be characterised as either market pull, where technology is developed with customer needs in mind, or technology push, where technology is developed based on an institution’s technology competence (Caetano and Amaral, 2011). Cases of novel technologies or novel applications are more likely to be technology push, where an invention must be adapted to a market application (Caetano and Amaral, 2011; Leifer and Steinert, 2011).

Technology transfer activities include identification of development partners, marketing, and stakeholder consultation (Atkinson and Bonfield, 2022; Caetano and Amaral, 2011; Lercher, 2016). Most techology development and innovation approaches place much of the transfer activities, other than market analysis, at the end of the process (Caetano et al., 2011; Cooper, 1990; Hansen and Birkinshaw, 2007; Lercher, 2016; Lind, 2006; Schulz et al., 2000). In doing so, these implicitly posit a technology pull commercial environment, where transfer wil not entail more effort than marketing. Mine waste valorisation technologies are likely to be novel technologies aimed for implementation in the setting of a traditionally conservative industry (Stewart et al., 2003). These must therefore assume technology push, which is a much more difficult underaking (Leifer and Steinert, 2011). Furthermore, transfer of sustainability-related technologies may be more difficult because the financial benefits are not always sufficient to drive adoption (Adams et al., 2017; Mishra et al., 2019). Several authors have argued for the importance of starting technology transfer activities early in the technology development process, to improve the likelihood of eventual implementation (Atkinson and Bonfield, 2022; Caetano and Amaral, 2011; Cooper, 2006; Davis et al., 1989; Greiner and Franza, 2003; Lind, 2006; Souder et al., 1990). None of the technology development processes place technology transfer activities at the outset of technology development, however.

2.2.3 Section summary

Designing and developing technologies for mine waste valorisation is not neatly captured in either traditional design, design for sustainability, or generic technology development approaches. There are similarities in that both design theory and technology development theory provide several step-wise methods for arriving at a satisfactory endpoint. Both sets of literature are also structured such that progressively fewer alternatives are considered at ever greater levels of detail. They differ in that for process design theory the endpoint is a suitable process for producing a specified chemical product rather than the product itself, while technology development and innovation theories focus on developing and marketing the product. Technology development theory recognises the importance of planning and executing technology transfer, while technology design theory assumes that it follows naturally. Design and development for waste valorisation differs from both in that the problem involves a specified feedstock with which to produce, via a variety of processing routes, an unspecified commercial product. Nevertheless, process design theory provides a valid approach for some aspects of this problem, whilst technology development and innovation theories provide tools for parts of the problem that are foreign to traditional process design, such as explicit consideration of technology transfer. Current technology development approaches, however, need to be amended to adequately incorporate technology transfer considerations in the early stages of development. Technology development and innovation literature has not been applied in the context of minerals or early-stage process design. Also, a lack of data availability is problematic for both sets of theories. Expert judgement has been suggested as an alternative source of data, but its reliability must still be investigated.

2.3 Developing the hypotheses: A new approach to technology design and development for mine waste valorisation

The review in Section 2.2 has highlighted that a structured approach to the early-stage design and development of waste valorisation technologies is needed to support technology selection and innovation at universities and research institutions. Whilst current process design and technology development frameworks can provide a basis for such an approach, it is necessary to adapt these to render them suitable for waste valorisation, since forcing a problem into an ill-fitting process can lead to frustration and even unjustified failure (Cooper, 2006; Lind, 2006; Seider et al., 2004b).

This section starts by proposing a systematic approach to the design and development of mine waste valorisation technologies (Section 2.3.1). This approach is then used as the basis for developing the research hypotheses and key questions that are addressed in this study (Section2.3.2).

2.3.1 Description of the proposed approach

A proposed generic approach for the early-stage development of waste valorisation process is presented in Figure 2-6. The generalised approach comprises 5 steps, the application of which forms the basis for this study. A brief outline of each step is provided in Sections 2.3.1.1 -2.3.1.5 below. A more detailed description of the methods used for each step, as applied to the case study, can be found in Chapter 3 (Research Methodology). These methods are then expanded on in the papers describing the outcomes of each step (Chapters 4 to 6)

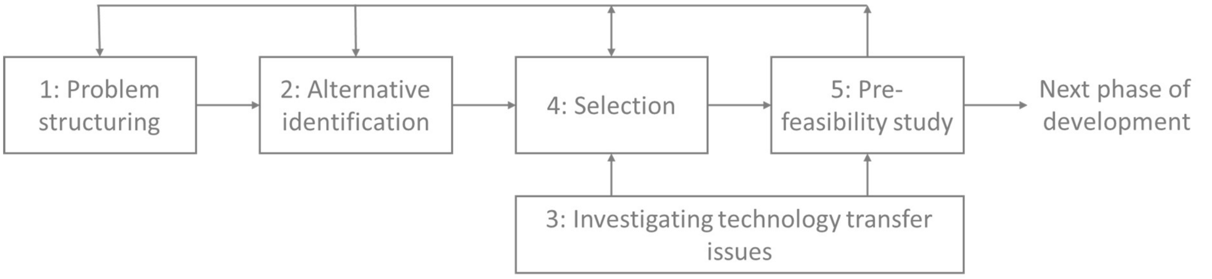

Figure 2-6 The generalised early-stage waste valorisation technology design and development process proposed by this thesis.

2.3.1.1 Step1: Problem structuring

Problem structuring is an important starting point in chemical process design, design for sustainability and technology development and innovation and is therefore the starting point for the generalised approach proposed in this study (Figure 2-6.) Problem structuring objectives include formulation of the design and development goal and identification of the decision-makers and stakeholders, as well as their values. These values can then be operationalised as criteria, as discussed in Section 2.2.1.1.

2.3.1.2 Step 2: Alternative Identification

In line with chemical process design and problem-focussed technology development, the generalised early-stage waste valorisation technology design and development process specifies that multiple technology options must be considered. There are several suggested approaches for identifying alternatives, as shown in Box 2-1 (Section 2.2.1.2). In the case of design for mine waste valorisation, a combination of the adjustment and combination of existing designs and heuristics based on general technical knowledge was considered most relevant.

2.3.1.3 Step 3: Investigation of technology transfer issues

Construction and implementation of designs (i.e., technology transfer) in traditional chemical process design is a natural outcome of a successful design process, given that the commercial opportunity identified at the beginning of the process is still relevant when the design is completed. When solicited by commercial entities, technology transfer is implicitly included in the design process from the very beginning, during the client brief and clarification step, and this continues with client interactions throughout the design process. Technologies developed at universities and research institutions, however, do not have similarly natural or automatic technology transfer trajectories, due to the absence in many cases of a committed commercial partner (see Table A 1 in 8Appendix AA-1).

A review of the literature has shown that existing process design frameworks do not explicitly consider technology transfer, whilst technology development processes normally only specify technology transfer as the last stage in the process. The approach presented in Figure 2-6 departs from conventional process design and technology development frameworks in that consideration of technology transfer drivers and barriers, as well potential commercialisation partners, is integrated across the early stages of the design and development process. This is done with a view to developing a better understanding of the industry into which the selected technology is likely to be implemented and to ultimately improve the likelihood of such implementation. It is further proposed that interviews with industry representatives and experts will provide a suitable method for gaining relevant information. This is because interviews provide rich data and can be implemented when concepts (such as mine waste valorisation) are known, but not widely implemented.

2.3.1.4 Step 4: Technology evaluation and selection

Both chemical process design literature and problem-driven technology development and innovation literature recognise the importance of alternative evaluation and selection of preferred technology alternatives. This focusses resources on designing and developing the most promising technologies. In the generalised early-stage technology design and development process, evaluation and selection involves a pre-screening step followed by MCDA methods for decision support. The pre-screening step removes obviously unsuitable alternatives and is in line with technology development literature. MCDA decision support provides a structured approach for taking into consideration decision-makers' values as identified in the problem structuring step and is recommended by both design for sustainability and some technology development literature. Knowledge gained from the consideration of technology transfer issues is also used to ensure that the understanding of stakeholder values is as complete as possible. The MCDA method proposed in this approach is value theory, which has been found to be appropriate to the minerals design context (Stewart et al., 2003). Data availability, already a problem in design for minerals processing, is likely to present a serious difficulty for designing and developing technologies for mine waste valorisation, especially at the evaluation stage. Expert judgement input is therefore proposed as a data source for evaluation and selection of mine waste valorisation technologies. Several authors have suggested using expert input to overcome the lack data for process evaluation (Darende et al., 2021; Demirkan et al., 2022; Whitney, 2007) and this approach is also used in practice (Corder, 2015; Dym et al., 2009; Song et al., 2018; Von Winterfeldt and Fasolo, 2009; Yoon, 2018). The suitability and robustness of this approach for technology selection has nevertheless not been demonstrated. Common expert judgement data acquisition methods include surveys/questionnaires and interviews (Curtright et al., 2008a; Demirkan et al., 2022; Kamble et al., 2017; Sadr et al., 2018)

2.3.1.5 Step 5: Pre-feasibility study

The last step in the proposed approach (Figure 2-6) is a pre-feasibility study, which considers the practicalities of implementation, including the available market and technology development business case, with the aim of assessing technology viability and creating a plan for technology development. This is in line with both process design and technology development literature. Process design approaches recognise the importance of checking market information, such as choice of feedstocks, energy sources, process routes and product prices, in the early stages (Cooper, 1990; Seider et al., 2004b). This ensures that the design is economically feasible and the market is favourable (Infotox, 2012; Seider et al., 2004b; Sinnott, 2005). These requirements, however, assume a level of technology maturity and data availability that is unlikely to be true of early-stage, unproven or novel mine waste valorisation technologies. Technology development approaches, which consider less mature technologies, require scoping analyses to assesses technology characteristics and the business opportunity with the aim of creating a technology development roadmap. More detailed economic and market analyses then follow later, when the business case is considered (Cooper, 2006; Lercher, 2016). Scoping studies and pre-feasibility studies are therefore similar and are considered appropriate at the early stages of mine valorisation technology design and development. The step in the process is called pre-feasibility study to align with mining design terminology. To increase the likelihood of technology commercialisation, the technology transfer considerations that were identified during the technology transfer stage are included at the pre-feasibility stage.

2.3.2 Hypotheses and research questions:

Section 2.3.1 outlined the proposed generic approach. This section formulates the hypotheses and research questions pertaining to the application of this approach. The hypotheses were developed based on chemical process design and technology development theories and Figure 2-7 illustrates the relationship between the hypotheses and generalised early-stage technology development approach. Hypothesis 1 (Section 2.3.2.1) concerns the application of expert input in the selection and technology transfer issues steps. The investigation of technology transfer issues and application to process selection and pre-feasibility studies is considered in hypothesis 2 (Section 2.3.2.2). Hypothesis 3 (Section 2.3.2.3) concerns the application of pre-feasibility study methods to early-stage technology design and development.

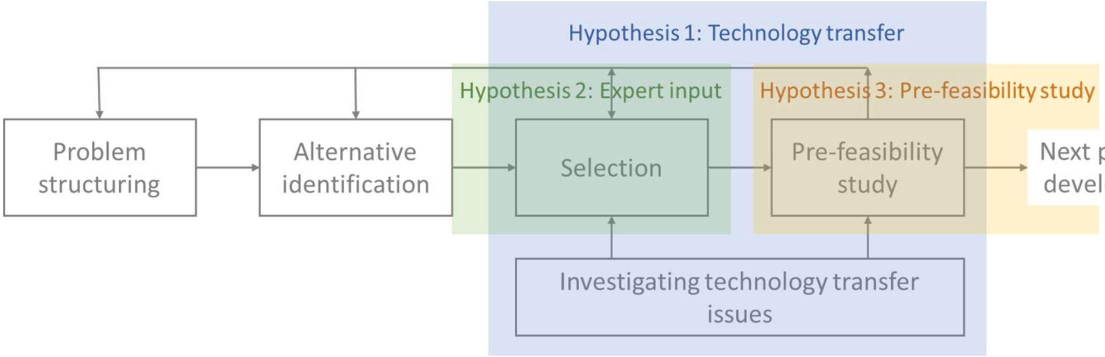

Figure 2-7 The relationship between the generalised early-stage technology development approach and the thesis hypotheses.

2.3.2.1 *Hypothesis 1:*

Literature has shown that considering technology transfer from the early stages of technology design and development is important for increasing the likelihood that developed technologies are implemented. This is especially important to consider when universities or research institutions design and develop technologies for mine waste valorisation, since a natural implementation partner is absent and waste valorisation technologies are likely to face other implementation barriers. With foreknowledge, these barriers can potentially be overcome. *Within this context it is therefore hypothesised that technology transfer considerations identified through interviews with industry stakeholders can play a key role in guiding the early stages of design and development of technologies for waste reuse.*

Key questions:

1. What are the potential key enablers and barriers to technology transfer for mine waste valorisation technologies?
2. What key partnerships must be developed to expedite technology design, development and transfer?
3. How can knowledge of potential technology transfer issues inform the early stages of mine waste valorisation technology design and development?

2.3.2.2 *Hypothesis 2:*

Given the lack of data on which to base mine waste valorisation process selection, an alternative source of credible data are needed. Expert judgement elicited though surveys/questionnaires and/or interviews has been used to support decision-making in different sustainable development applications and has also been proposed as means to obtaining the data needed for process evaluation and selection. *For this reason, it is hypothesised that expert interviews and questionnaires can support technology selection and contribute positively to early-stage technology development of mine waste valorisation technologies in line with sustainable development principles.*

Key questions:

1. Does conducting surveys with technical experts using questionnaires lead to the acquisition of data of adequate quality to enable defensible technology selection?
2. Does the supplementation of technical expert judgement surveys with interviews improve data quality?
3. How can data derived from interviews with technical experts add additional value to the early-stage technology design and development process?

2.3.2.3 Hypothesis 3:

In accordance with conventional process design and technology innovation theory, pre-feasibility or scoping studies are typically conducted to validate process or technology viability and to identify further developmental requirements prior to detailed design. However, in integrating such studies into early-stage design, it is equally important that data requirements for such studies remain manageable. This is particularly important in the case of mine waste valorisation, due to the significant data deficits typically encountered. In this context, *it is thus hypothesised that pre-feasibility studies which apply publicly available data and first-order calculations can play a key role in supporting the establishment of a sound business case and programme for the systematic development and implementation of mine waste valorisation technologies*.

Key questions:

1. Based on requirements identified in the technology transfer work, what data and information are required for a pre-feasibility study to assess the technology viability at the early stages of technology development for mine waste reuse?
2. What input data and methods are suitable to derive this information?
3. How can the information derived from a pre-feasibility study guide design and development?

Chapter three – Research methodology

This chapter describes the methodological approach and methods that are used in this thesis and is divided into 3 sections. Section 3.1. describes the methodological approach taken to answer the research questions presented at the end of Chapter 2. Section 3.2. details the case study of sulfide-enriched fine coal mine waste and the technology alternatives that were identified for the study. Section 3.3. contains the published book chapter included in this chapter, which describes the details of conducting interviews, since it is a common method used in two chapters.

3.1 Generalised early-stage technology design and development: Methodological approach

The aim of this study was to increase the rate and success of mine waste valorisation technology design and development conducted at universities and research institutions. To this end, the study developed a structured approach for designing and developing waste valorisation technologies in a way that overcomes data deficiency and encourages technology transfer. This was done with input from process design, and technology development and innovation literature. The outcome of this process was the generalised early-stage mine waste valorisation technology design and development approach described in Section 2.3. The generalised approach was then applied to the case study detailed in Section 3.1.1. Sections 3.1.2 through 3.1.5 discuss the methods used in each step and how these relate to answering the key questions posed in Chapter 2. Application of each step in the generalised approach, except problem structuring and alternative identification, is considered in a dedicated chapter, as indicated in Figure 3-1. Most of the details of the methods used in the study are consequently reserved for the papers in which they are published.

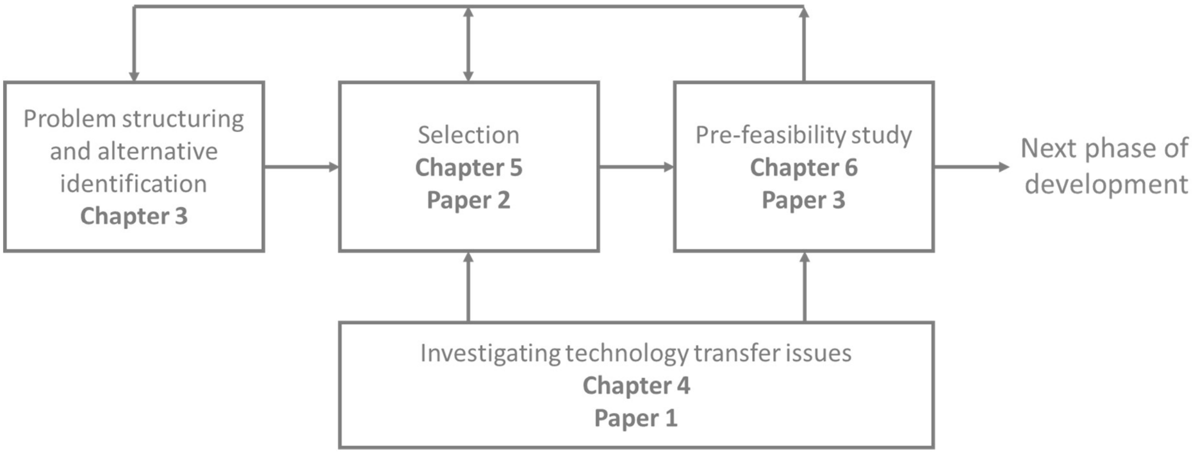

Figure 3-1 The generalised early-stage technology design and development process with thesis chapters indicated.

3.1.1 Case study selection

To investigate implementation, the generalised approach was applied to the case of South African sulfide-enriched fine coal waste. This waste was chosen because it suffers from all of the problems noted in the background: it presents a physical risk in the form of dust dispersion and potential tailings facility failures, and chemical risks in the form of acid rock drainage generation and spontaneous combustion. For these reasons, coal waste has been the focus of programmatic study at the Department of Chemical Engineering, with separation of coal waste having been investigated since the early 2010's (Iroala, 2014; Kazadi Mbamba et al., 2013, 2012). Since this work forms part of the programmatic study of coal waste, the academics leading group investigations were recognised as the decision-makers for the selection step. They were interested in gaining insight into developing and transferring technologies as well as which technologies were the best candidates for further development.

Due to the prior separation the material has undergone, it contains particularly high concentrations of the acid-forming sulfide mineral, pyrite. It is therefore representative of a particularly hazardous mine waste, which means that it is useful as a type of worst-case scenario. Furthermore, the nature of the waste forces the study to look further than the construction-related applications that are traditionally put forward for mine waste valorisation. To this end, when identifying mine waste valorisation alternatives for this material, the hazardous component (pyrite) was used as the target component for identifying uses.

3.1.2 Problem structuring and alternative identification

Certain aspects of the problem were considered at the outset, as shown in Box 3-1. During problem structuring it was established who the decision-makers are, who the stakeholders are likely to be, as well as what these groups' values are likely to be. The decision-makers in this case were the academics who supervised the study as well as a select few colleagues. Stakeholders were identified in collaboration with the decision-makers to be mining companies, regulators, local municipalities, workers, and local communities. Since this study is on early-stage design and development, the exact location and therefore communities, municipalities and workers were unknown.

Box 3-1: Typical questions to be addressed during problem structuring (Acordi et al., 2023; Cano-Ruiz and McRae, 1998; Hanes and Bakshi, 2015; Von Winterfeldt and Fasolo, 2009).

- Identify decision-makers
- Identify stakeholders
- Identify decision-makers' values
- Identify stakeholders' values
- Design and development objectives
- Stopping rules
- Material composition
- Material hazards
- Material advantages
- Scope
- Battery limits

The decision-makers invested time and effort into participating in the generalised early-stage design and development process because they want to improve mines' environmental footprints with sustainable development and the circular economy in mind. This forms the basis of the design and development objectives: improve mines' environmental footprints through design and development of mine waste valorisation alternatives. As a consequence of the identities of stakeholders still being uncertain, stakeholder values were unknown. These were, however, assumed to be in line with sustainability literature and can be found in 8Appendix C. The completeness of the criteria set was checked by comparing it with the values of the coal industry participants interviewed, as seen in Chapter 4. More detailed values were elicited for decision support in the form of criteria and their weights (relevant to the selection step) and can be found in Stander et al. (2022a)[7] in both the *Collection 1* and *Collection 2* Excel workbooks.

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[7] Link found in Appendix D

Material-related aspects were identified and can be found in the discussion on the case study in Section 3.2.1.

The fact that the generalised approach considers the early stages of design and development for mine waste valorisation in a research environment sets the problem scope, stopping rules and battery limits. The level of detail to which the alternatives were developed, analysed, and evaluated was in accordance with early-stage design and development and were consequently relatively rudimentary with the aim of preventing excessive use of resources. This included the development of proposed flowsheets for the processes as well as the expected mass balances. To simplify the problem, the characteristics of specific technology alternatives were considered in isolation from their implied value chains.

Alternative identification can be done for one component in the waste stream or for several alternatives individually or in combination with each other. This study did not include methods for further upgrading the sulfide-rich stream but considered potential use-cases for it as well as the processing requirements for realising these uses. Since the most important sulfidic mineral in South African coal tailings is pyrite, alternative identification focuses on the uses and corresponding processing requirements for pyrite. To consider only the relevant technology alternatives in the selection step, the larger list of alternatives was screened using the following criteria:

- Is it technically conceivable that the technology alternative could be implemented with a 20% pyrite (i.e. relatively impure) feed stream?
- Is there scope for implementing the technology within the South African context?

This screening was conducted during a meeting with the decision-makers.

3.1.3 Investigating technology transfer issues

In the cases of the technology transfer and selection steps, data for the case of South African sulfide-enriched fine coal waste was obtained in the form of expert input. In the case for technology transfer, much of the available information inheres in the understanding, attitudes, and perceptions of industry participants. This information can be obtained by interactions with industry participants, whether by conducting ethnographic research, document analysis, focus groups, written surveys, or interviews. No immediately relevant and generalisable mining-technology implementation project was available for either ethnographic research or document analysis. Written surveys tend to obtain superficial and not nuanced data (Ruokonen, 2020). Semi-structured interviews, by contrast, are an efficient way of learning about subjects that specific people have deep knowledge on, but that is not available in document or other form (Bogner et al., 2009; Robson, 2002).

In this study technology transfer was investigated using interviews capturing the nuance and complexity of the opinions, motivations, and constraints of the coal mining industry, as conceptualised by interview participants. To investigate the potential barriers and enablers of technology transfer of mine waste valorisation technologies, industry participants were therefore interviewed. It is important to note that the real barriers and enablers to transferring a specific technology in a specific context cannot be known until transfer is attempted. The interviews attempted to identify the probable barriers and enablers to enable planning for them from an early stage. More detail on the method of expert interviews can be found in the book chapter related in Section 3.3 and details on participant selection can be found in the paper in Chapter 4.

Conducting interviews with industry participants addressed Hypothesis 1, which considers whether and how technology transfer considerations can guide the design and development of mine waste valorisation technologies. Specifically, the interviews were designed to address key question 1, which asks what the specific barriers and enablers to transfer of sulfide-enriched coal mine waste technologies are likely to be, as well as question 2 around who the key partners in design, development and transfer are likely to be. Interview data also provided the foundation for starting to address key questions 3, which consider how knowledge of technology transfer issues can inform technology selection and pre-feasibility studies with an aim to improve technology design and development success.

3.1.4 Selection

The evaluation and selection of technology alternatives for South African sulfide-enriched coal mine waste valorisation requires input on technical matters. This study tested the validity of using expert input to inform technical decision-making for early-stage design and development. Expert input for technology evaluation can be obtained through questionnaires, focus groups, or interviews. Questionnaires and interviews are simpler and less human-resource-intensive to administer and were therefore tested in this study.

The questionnaires were constructed in line with value theory and interpreted using its theoretical lens, as discussed in Chapter 2. The questionnaires were constructed using criteria that reflect the decision-makers and coal industry participant values that were identified in Chapter 3 and presented in 8Appendix C. To conduct the questionnaires, experts were contacted by email and sent an introduction pack. When they responded favourably, they were sent a report with available details of the alternatives as well as the rating sheets with constructed scales (see Stander et al. (2023a), link provided in Appendix D). The questionnaire itself contained a descriptive (linguistic) rating scale for each criterion, which contained five possible numerical ratings that the expert could choose from, based on their descriptions. Later, interviews were conducted with a smaller sub-group of the most qualified of the respondents. The same questionnaires were used, but the question set was reduced by focussing only on cases of extreme divergence. More details on the specifics of the method used can be found in Chapter 5.

The expert judgement input to value function methods were numerical. This allowed for the quantitative investigation of the suitability of expert input for use in decision support using value theory. This investigation was done using distinguishability analysis, as developed by Basson (2004), which provides a measure of whether alternatives are distinguishable from each other. If they are not distinguishable, based on the available data, then it is impossible to select the best performing alternatives with any degree of certainty. The degree to which superior alternatives can be identified and selected using expert judgement input into value function analysis was therefore used as an indication of the appropriateness of expert judgement input as data source for technical evaluation.

Chapter 5 addressed Hypothesis 2's key questions number 1, 2 and 3, which consider whether written questionnaires completed by - and interviews conducted with - technical experts provide data that can be used to support technology selection. The hypothesis and key questions also consider approaches that can be taken to improve data quality and other uses that the data might potentially have within the technology design and development process. The ease and extent to which priorities identified during the technology transfer investigation can be incorporated in the weighting of criteria for selection, also contributes to answering the third question of Hypothesis 1.

3.1.5 Pre-feasibility study

After the evaluation stage, technology-specific development requirements for the preferred sulfide-enriched mine waste valorisation technologies are investigated in the rudimentary pre-feasibility study. The pre-feasibility study provides an opportunity to conduct a more detailed literature-based technical feasibility assessment and also investigate specific issues identified during the technology transfer study. In so doing, another opportunity for selection is presented and a technology development plan can be developed.

The technical feasibility of the selected technology alternative was first considered by conducting an extended literature survey and investigating the details around implementation. This included a consideration of potential implementation partners as well as social and environmental risks associated with the technology. A preliminary costing analysis showed what the economics of the selected alternatives are likely to be, followed by a size-of-market analysis. Lastly, a sensitivity analysis was done to quantify the influence of different variables on the analysis outcomes.

This chapter aimed to answer Hypothesis 3, key questions 1 through 3 as well as Hypothesis 1, key question 3. Hypothesis 3 considers what aspects must be included in a pre-feasibility study and what data sources are available to conduct such studies. It also considers whether pre-feasibility studies can provide sufficient context to inform technology development and how it can address selection uncertainties. Hypothesis 1, question 3 considers how information derived from technology transfer can inform pre-feasibility studies.

3.2 The case of sulfide-enriched coal waste: Problem structuring and alternatives

In this section, the case study is discussed followed by the mine waste valorisation alternatives that were identified for the stream in line with the problem structuring section.

3.2.1 The case of South African sulfide-enriched fine coal waste

As discussed in Section 3.1.1, South African coal waste is associated with several negative environmental and social consequences and is therefore the focus of programmatic study at UCT's Department of Chemical Engineering. The next section provides background and information pertinent to the waste valorisation design and development problem.

3.2.1.1 Background: the South African coal industry

Coal mining is important to the South African economy for more than 75% of its electricity production, around 30% of its liquid fuel production, export revenue and as a reductant in metallurgical processes (Chamber of Mines of South Africa, 2014; Hancox and Götz, 2014; Minerals Council of South Africa, 2022a). In the last decade and a half, around 250 Mt per annum of saleable coal was produced (Chamber of Mines of South Africa, 2013; Minerals Council of South Africa, 2022b). This number has remained relatively stable, with the most divergent numbers still within 10% of the mean, as seen in Figure 3-2. The production of slurry into the future is, however, likely to change as ESKOM decommissions coal fired power plants and industry actors start to rely more on exports for revenue production (Minerals Council of South Africa, 2023). The South African coal mining industry is concentrated in the province of Mpumalanga, specifically in the Emalahleni-Middelburg-Ermelo region, with mines also located in Limpopo, Kwazulu Natal, and the Freestate (Eberhard, 2011; Hancox and Götz, 2014).

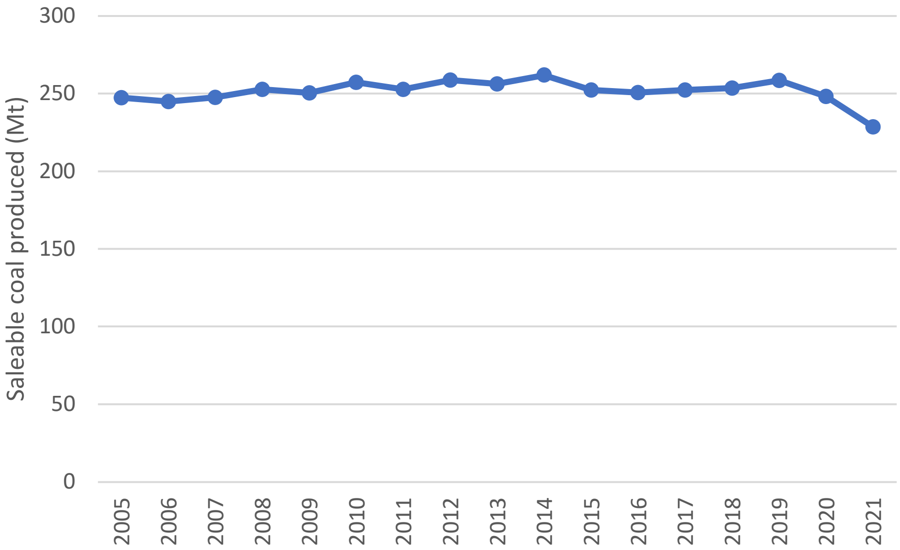

Figure 3-2 South African saleable coal production (Chamber of Mines of South Africa, 2013; Minerals Council of South Africa, 2022).

3.2.1.2 *Coal Beneficiation and Waste*

South Africa's coal reserves have a relatively high ash content of between 25% and 35%, with some seams having an ash content of up to 65% in the Waterberg region (Eberhard, 2011; Lloyd, 2000). To reduce the ash content of coals, and thereby its quality, coal can be washed (Hancox and Götz, 2014; Horsfall, 1980; Van Dyk and Keyser, 2005). Many mines produce two product streams when washing coal: high quality export coal and a lower quality 'middlings' coal, which are sold to South African power stations (ESKOM) or exported (Prévost, 2011; SACRSC, 2013; Thungela, 2021). The washing process creates low calorific value coarse waste with a high ash content as well as fine and ultrafine waste material with a calorific value similar to run of mine (ROM) coal [8](Horsfall, 1980; Reddick et al., 2007). This waste is associated with environmental problems such as dust formation, spontaneous combustion and acid mine drainage (Lloyd, 2000; McCarthy and Pretorius, 2009). The coal waste production rate seems to have remained relatively consistent between 1990 and 2006, with a waste production rate of 20% of ROM production in 1990, compared with the 22% of ROM waste production rate of 2006 (Lloyd, 2000; Chamber of Mines, 2007).

The coarse (100mm – 12mm) and intermediate or smalls (12mm – 0.5mm) fraction of coal waste is referred to as discards, while the fine and ultra-fine (<0.5mm) fractions are often discarded in the form of a slurry and referred to as tailings (DME, 2001). From the survey done by the Department of Minerals and Energy in 2001, it was calculated that around 21% of the total mine waste was disposed of in the form of slurry. If this ratio has remained constant and one assumes that the original figure included 79.5% water [9] (Reddick,

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[8] Run of mine coal is the coal mined but not yet beneficiated through separation processes such as screening or other separation methods. As such run of mine coal typically still contains a significant gangue and low-grade coal component.

[9] Reddick (2006) found several mines whose waste had a slurry solids load of 15% and, with the technology available at the time, a solids load of 26% was considered easily achievable. The average, 20,5% solids load was therefore used.

2006), South Africa produced around 2.9Mt of dry slurry in 2006[10]. Given the relative stability of coal production (Figure 3-2) it can be assumed that the mass of slurry produced annually is relatively constant.

3.2.1.3 Two stage separation process

In order to valorise the fine coal waste stream, previous researchers at the University of Cape Town developed a two-stage separation process using froth flotation to separate fine and ultra-fine (75% <150µm) coal slurry waste into different fractions (Howlett and Marsden, 2013; Iroala, 2014; Kazadi Mbamba et al., 2013, 2012). These include a coal ultra-fines stream, a sulfide-rich tailings stream and a sulfide-lean tailings stream, as shown in Figure 3-3. Despite results of separation of coal slurry wastes from different regions varying regarding the relative deportment of coal, ash and sulfur, the three streams' properties remain distinct from each other (Broadhurst and Harrison, 2015). The coal product's quality is improved as compared with the feed slurry and can be sold, while the desulfurisation tailings carries negligible AMD generation risk and can be used in various construction and mine rehabilitation applications, as discussed in Section 2.1.3 (Amaral Filho et al., 2020; Broadhurst and Harrison, 2015; Iroala, 2014; Kazadi Mbamba et al., 2013, 2012). The sulfide-rich concentrate is of interest to this work.

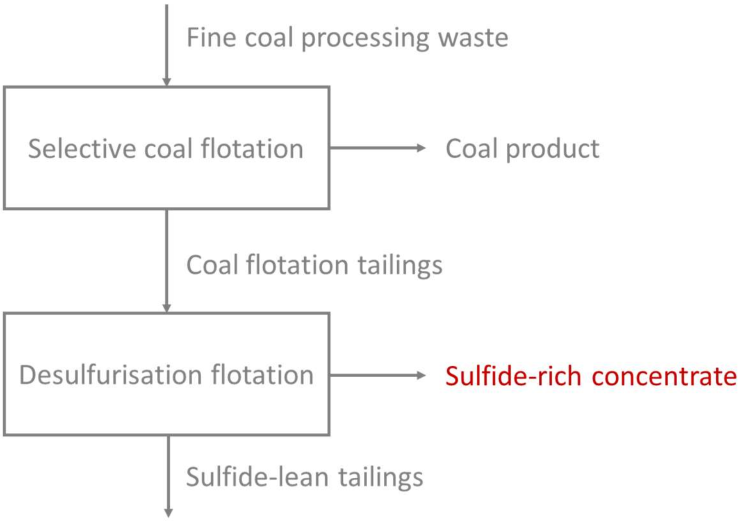

Figure 3-3 The two-stage froth flotation process, developed at the University of Cape Town. This process separates coal waste into a useful coal product, a sulfide-rich stream and a sulfide-lean stream.

3.2.1.4 Sulfide-enriched stream characteristics

In all cases, the sulfide-rich fraction is potentially acid-generating (Broadhurst and Harrison, 2015; Iroala, 2014; Kazadi Mbamba et al., 2013, 2012). Table 3-1 shows the typical compositions of the sulfide-rich fraction derived from the laboratory-scale test work conducted to date[11]. Based on sulfur speciation test work at UCT and literature, the pyrite content of the sulfide-enriched coal waste stream is between 2% and 16%[12] (Fundikwa, 2015: 44; Iroala, 2014 49; Moyo, 2018; Pinetown et al., 2007).

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[10] $Waste\ produced \times slurry\ percentage \times solids\ in\ slurry = 67{,}7Mt \times 0{,}21 \times 0{,}205$ (Chamber of Mines of South Africa, 2007; Department of Minerals and Energy, 2002; Reddick, 2006)

[11] for more detail see Stander et al. (2022b) (link in Appendix D) in the Excel workbook called Data for characterisation of s-rich, in the Flotation test results tab.

[12] Calculations shown at Stander et al. (2022b) (link in Appendix D).in the Excel workbook called Data for characterisation of s-rich in the Flotation test results tab in the Calculation of min & max pyrite expected in s-enriched material box

Table 3-1: Typical sulfur and coal content of the sulfide-enriched material (Howlett and Marsden, 2013; Iroala, 2014; Kazadi Mbamba et al., 2012; Magabane and Naidoo, 2011; Moyo, 2018)[13].

	Sulfur	Coal	Ash
Maximum	19%	68%	60%
Minimum	3%	26%	27%

Table 3-1 shows that coal and gangue components are still significant components in the fine sulfide-enriched coal waste. The particle size distributions of sulfidic minerals will be in the range acceptable for flotation ($D_{80} < 150\mu m$), due to oversized slurry waste being resized for flotation (Jera, 2013).

As far as minor and trace metals are concerned, available data shows that only thorium (Th) and uranium (U) are significantly enriched in coal wastes[14] and that these are present in relatively inert forms (Moyo, 2018). Due to the variability of waste composition between mines and even within the same mine, however, it is difficult to make generalisations about the compositions of the separated fractions (Moyo, 2018). Knowing the likely composition and characteristics of the waste allows one to consider the applications for which it may be suitable. This will be done in the next section.

3.2.2 Sulfide-enriched coal mine waste valorisation alternatives

The purpose of this subsection is to present the list of waste valorisation technology alternatives for the sulfide-enriched coal waste fraction, specifically the pyrite component, and to outline the screened list. Alternative identification was conducted by undertaking a literature search and included papers, patents and technical reports. A variety of processing options are available for realising value from pyrite of various levels of purity, as shown in Table 3-2. These were screened for applicability to a 20% pyrite feed stream and appropriateness to the South African context, as mentioned in Section 3.2.1. The design superstructure for the screened alternatives is shown in Figure 3-4. The superstructure was constructed in line with early-stage project feasibility requirements and is therefore qualitative in nature. Analyses in Stander et al. (2023a)[15] also include mass balances based on data found in literature sources.

Table 3-2 Mine waste valorisation alternatives for pyrite.

Full list of mine waste valorisation technology alternatives	Screened list of mine waste valorisation technology alternatives
Production of sulfuric acid Production of sulfuric acid and paint pigments Use as glass pigments Production of ferric sulfate coagulant Production of ferric sulfate heptahydrate Use in hard/secondary lead refining Use in copper smelting Use as chromium(VI) reductant Use as soil ameliorant Use in cemented paste backfill Use for facilitating heap leaching Production of photovoltaics Production of nano and micro linear actuators	Production of sulfuric acid Production of sulfuric acid and paint pigments Production of ferric sulfate coagulant Production of ferric sulfate heptahydrate Use as chromium(VI) reductant Use as soil ameliorant Use in cemented paste backfill

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[13] These results are based on six samples: Emalahleni region: 3, Middelburg region: 2, and Waterberg region: 1

[14] Relative to the average crustal abundance.

[15] Link in Appendix D.

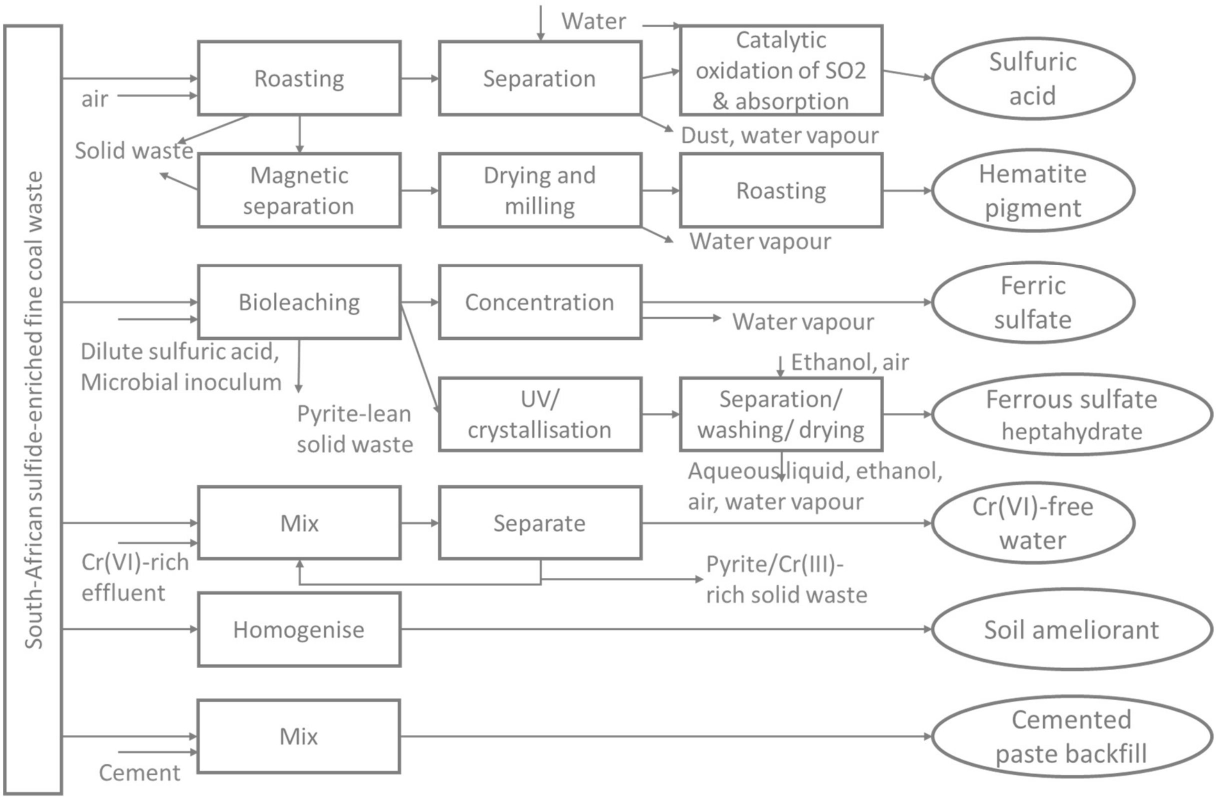

Figure 3-4 The design superstructure of the mine waste valorisation options that passed the pre-screening stage.

The first option in Figure 3-4 is the production of sulfuric acid by roasting pyrite (Runkel and Sturm, 2009). The sulfur dioxide produced in the roasting step is then cleaned and catalytically oxidised to sulfur trioxide before being absorbed in water to form sulfuric acid (Runkel and Sturm, 2009). The pyrite roasting step produces an iron-rich solid waste, which could potentially be purified using magnetic separation to isolate the magnetite (Shoumkova, 2003). The magnetite could then be milled and roasted to produce hematite pigment (Shoumkova, 2003).

The next set of options shown in Figure 3-4 starts with bioleaching as the first step. The resulting ferric sulfate solution can then be concentrated to produce coagulant for water treatment (Colling et al., 2011) or further reduced to produce ferrous sulfate heptahydrate (Vigânico et al., 2011). Ferrous sulfate heptahydrate can be used as fertiliser, coagulant or in medicine, depending on the purity.

Pyrite can also be used to reduce chromium(VI), which is a by-product of chromite refining, stainless steel production and pigment production (Kim et al., 2002). Chromium(VI) is class A human carcinogen and highly mobile, but can be reduced to chromium(III) by using pyrite as reductant (Kim et al., 2002; Lin and Huang, 2008).

Pyrite can be used as a soil ameliorant to improve the fertility of calcareous, otherwise alkaline and/or nutrient-deficient soils (Castelo-Branco et al., 1999; Shamim et al., 2010). It does this by contributing to the soil the acidity generated when it oxidises as well as the inherent iron and sulfur components (Castelo-Branco et al., 1999; Shamim et al., 2010).

Cemented paste backfill is a use of pyrite-rich material that has been considered in various locations (Benzaazoua et al., 2008). The material is mixed with cement and pumped into underground mine workings to support mine stopes (Benzaazoua et al., 2008). This is also a form of disposal.

3.3 Research methods: Interviews

A common method used in the thesis is expert interviews. This chapter therefore includes the book chapter on expert interview method, which is used in interrogating the technology transfer landscape in South Africa as well as in data acquisition for multiple-criteria decision support in the selection phase. The chapter is included in the peer reviewed book *Sustainable Development in Africa: Concepts and Methodological Approaches*, which was published in 2019.

Book chapter: Reflections on method of expert interviews for research on sustainable development of mineral resources in Africa

3.3.1 Abstract:

Sustainable development in the minerals industry requires improved understanding of technical and quasi-technical factors from those directing it, and this can be facilitated by insightful expert interviews. To conduct these interviews well requires skill and thoughtful study design. This will, in turn, make the important and difficult process of analysis easier and more meaningful.

This paper provides an overview of expert interviews as a form of qualitative research, combining the practical experience of post-graduate students engaged in inter-disciplinary research within the Minerals to Metals Initiative at the University of Cape Town with the theories presented in literature. It considers the method of expert interviews, including interview technique, question formulation, respondent identification, and conducting interviews. It also contemplates transcribing and analysis of the data collected, as well as reporting of the findings and ethics in this kind of research. This paper is a primer, intended to be an introduction into the methods for conducting expert interviews with the hope of starting students off on the right track.

Citation: Stander, H.-M. and Broadhurst, J. L. (2019) ‘Reflection on method of expert interviews for research on sustainable minerals development in Africa’, in Nagao, M. et al. (eds) Sustainable Development in Africa: Concepts and Methodological Approaches. Denver: Spears Media Press, pp. 137–155.

Author contributions: The chapter was written upon invitation from the Education for Sustainable Development in Africa (ESDA) initiative. H Stander and JL Broadhurst conceptualised the paper and H Stander researched and wrote the paper. JL Broadhurst provided critical input and editing.

3.3.2 Introduction

Qualitative research methods are valuable additions to the sustainability professional’s toolbox, since they allow deeper insight into perceptions, expectations, contributing factors, and stakeholder priorities and practices around the complex challenges involved.

There are numerous qualitative research methods available, including document analysis, ethnographic research, and case studies. One of the popular qualitative research methods is conducting interviews. Conducting interviews is a good approach to understanding a certain population’s perspectives, opinions, motives, behaviour, history, and habits. Since these things are personal to individuals and cannot always be directly observed, asking people about them is often the best way of eliciting and understanding them (Robson, 2002). Interviews can also be a relatively efficient way of collecting primary data (Bogner et al., 2009), particularly in cases where time frames are relatively short, or where interviews are used as part of a mixed-method approach. Expert interviews differ from traditional interviews in that they involve a conversation with an expert about issues in their field, and often have a subject-specific or quasi-technical subject matter. As Bogner and Menz (2009) put it "The methodological specificity of this kind of interview, though, does not lie in “the expert” as an object of research, but rather in the researcher’s interest in a specific configuration of knowledge".

Expert interviews are applied fairly extensively as part of a mixed method research approach by post-graduate Master’s and Doctoral students housed within the Minerals to Metals Research Initiative (MtM), located at the University of Cape Town in Cape Town, South Africa. This initiative was established in 2007 to address global sustainable challenges facing the mineral sector in an integrated and holistic manner (Broadhurst et al., 2016). In order to promote inter- and trans-disciplinary research, post-graduate students have two or more supervisors from diverse disciplines, often drawing from skills in disciplines as diverse as economics, law, physics, sociology and chemical engineering. This is particularly the case for students enrolled in the Master of Philosophy programme specialising in Sustainable Mineral Resource Development (MPhil), which was specifically developed to generate graduates with both disciplinary depth and a broad understanding of, and sensitivity to, the critical sustainability challenges the minerals sector is facing (Broadhurst et al., 2016). The students enrolled for this programme come from a variety of disciplinary and career backgrounds, and many of them have had little training and experience in qualitative research methods, such as interviews.

This paper provides a reflection on the method of expert interview, drawing from the published literature as well as the experiences of the authors and MPhil graduates, as part of the research conducted at MtM, in the field of sustainable mineral resource development. It attempts to answer the following questions: When and why are expert interviews carried out? What expertise should the interviewer have? How are experts defined and selected? How can expert interviews be structured? How many interviews is enough? How is interview data analysed and reported? In answering these questions, this paper sets out to provide an introduction into the use and application of expert interviews as a research method for post-graduate students and researchers who have limited experience and training in qualitative methods of research.

3.3.3 Expert interviews as a qualitative research tool

According to Bogner and Menz (2009) “An expert has technical, process and interpretative knowledge that refers to a specific field of action, by virtue of the fact that the expert acts in a relevant way (for example, in a particular organizational field or the expert’s own professional area)”. In this conception the expert interview therefore exploits the expert’s subject or organisational knowledge and experience (Morgan, 2014), rather than their lived experience of some phenomena.

Expert interviews can give useful insight into a field that cannot be gained through conducting a document survey or literature review or by attending a taught course or conference. For expert interviews to be the best research method, the question must be about a phenomenon that is not well-documented in literature or elsewhere, or that cannot be answered through a more technical research design (Morgan, 2014). For example, expert interviews and other qualitative research techniques can be used to gain perspective on engineering questions in ways that are unlike the perspectives gained from the quantitative research that engineers and scientists tend to be comfortable with. They thus have the potential to enhance the quality and perceived success of engineering innovations, as well as to improve the understanding and scoping of complex sustainability challenges involved.

According to Bogner and Menz (2009) expert interviews can be classified as either exploratory, systematizing or theory generating. Exploratory expert interviews are used to understand a field of knowledge before embarking on more detailed research, whereas systematizing interviews access expert knowledge “which has been derived from practice, is reflexively accessible, and can be spontaneously communicated” (Bogner and Menz, 2009). Systematizing interviews are therefore used to access facts. Theory generating expert interviews, on the other hand focus on understanding expert knowledge as a category, including the way that experts make decisions and go about their business (Bogner and Menz, 2009).

Expert interviews conducted to date by post-graduate students affiliated with the Minerals to Metals Initiative at the University of Cape Town have been either exploratory or systematizing (Table 3-3), and have all formed part of a mixed methods research approach.

Table 3-3 Interview topics and the experts interviewed as part of research conducted at Minerals to Metals (Chitaka 2015; Munyongani 2016; Kato 2017; Shongwe 2017).

MtM researchers	Experts	Interview topic
Broadhurst et al. (2018)	Coal industry professionals, including executives and consultants	Barriers and enablers to technology transfer from universities to the South African coal industry
Broadhurst et al. (2018)	Technology commercialisation offices at academic institutions	Common challenges in commercialising university technologies
Munyongani (2016); Munyongani et al. (2016)	Engineering process design professionals	Assessing whether introducing life-cycle based eco-efficiency indicators into strategic and design decision making could add any environmental value to the processing of PGMs.
Chitaka (2015); Chitaka et al. (2018)	Scrap metal industry actors	To gain an understanding of the industry status quo and any existing challenges, threats and opportunities.
Kato (2016)	Business executives in Richard’s Bay	The contribution of the minerals industry to human and social capital development though the formation of industrial clusters.
Broadhurst et al. (2018); Shongwe (2017)	Environmental consultants	Understanding the inter-relationship between coal mining and processing, environmental degradation and community impacts.

When deciding upon interviews as a research method, it is also important to consider the weaknesses of the approach. Since interviews elicit accounts from people, imperfect memory and imperfect knowledge is to be expected. Also, people are unlikely to have perfectly tailored opinions about phenomena of interest to one’s research unless it is something that they have thought about extensively themselves and, even then, the turn of phrase used in the interview may spark new thoughts on a subject (Morgan, 2014). This means that the act of interviewing a person can change a person’s opinion on matters and subsequent researchers may therefore get different answers when asking the same person the same question later. Interviewer bias may also subtly skew the responses given (Robson, 2002). Another reason that different researchers may get different results is that people’s opinions are tailored based on who the interviewer is, who they represent, and the nature of the interaction between interviewer and interviewee (Silverman, 2005). For example, an executive of a company is unlikely to disclose the full extent of their company's environmental neglect to a researcher that they perceive to have a strong environmental bias. Lastly, events in the day or week preceding the interview may bring certain aspects of a phenomenon to mind quicker than others, skewing the interview data in favour of recent events (Montibeller and Von Winterfeldt, 2015; Morgan, 2014). The information elicited in this way must therefore never be treated as infallible truth, or as a source of purely objective information (Bogner and Menz, 2009).

In short, researchers can answer research questions in a uniquely powerful way using interviews as data collection method. This can, however, only be done sensibly when the weaknesses of the approach are borne in mind and mitigated in the study design. Interviews must therefore only be embarked on when it is clearly the best approach to answering research questions given the method's limitations. The following sections provide insights into the methodology of expert interviews, including interview techniques, data analysis and reporting, and ethical considerations.

3.3.4 Expert interview methodology

This section briefly explores the methods involved in conducting expert interviews, covering pre-interview preparation, question formulation, identification and selection of the experts, and interviewing technique.

3.3.4.1 Preparation

With qualitative research, as with any research, it is important to keep the objectives of the research in mind, and the research questions that one is looking for answers to. Knowing what phenomenon needs to be understood more fully will guide the development of key questions (Silverman, 2005). Having a set of well-considered key questions, in turn, will guide the researcher in choosing the best approach to conducting their research.

Littig (2009) and Pfadenhauer (2009) stress the need for the interviewer to prepare well before undertaking interviews. In particular, an understanding of the field is considered to be important not only for proper interview question formulation, but also to facilitate conversation during the interview and to convince the expert that the interviewer has indeed approached the research thoughtfully (Morgan, 2014). A number of authors (Bogner and Menz, 2009; Littig, 2009; Meuser and Nagel, 2009; Pfadenhauer, 2009; Trinczek, 2009; Wroblewski and Leitner, 2009) suggest that it is important for an expert to see the researcher conducting the interview as an expert or quasi-expert, in order to be sufficiently impressed and comfortable speaking with the researcher. When experts do not consider the interviewer to have in-depth knowledge of the subject matter, they may reduce the complexity and depth of information to suit the interviewer's perceived depth of knowledge (Bogner and Menz, 2009). The interviewer may even ignore follow-up questions, avoid 'difficult specialist issues' and shorten the interview intentionally, thereby reducing the quality of the information (Bogner and Menz, 2009). In the experience of the MtM post-graduate students this was found to be partially true. For instance, Munyongani (2016) (shown in Table 3-3) needed some insight into process design and life cycle analysis to ask appropriate questions and facilitate the discussion well (see Table 3-3). However, the students found that experts often had no illusions as to the level of expertise of inexperienced post-graduate students, and naïve questions were tolerated. What experts did need to know was that the study has been thoughtfully conceptualised, and that enough pre-knowledge existed for the student to understand and analyse the information well. The student therefore does need to become a quasi-expert in order to have sufficient subject-specific understanding of the field to construct meaningful questions and to convince the interviewer that the research, and their participation, will generate useful information. The fact that the experts wanted to ensure that the information is useful is further illustrated in that many experts asked the student researchers probing questions before the interview to determine whether they, the experts, indeed had the knowledge and experience to answer the questions well.

It is also important that an interviewer practices interviewing before embarking on interviews for research purposes (Silverman, 2005). This is particularly important for novice interviewers, such as post-graduate students. Two to three mock interviews with supervisors and other individuals will alert the interviewer of any questions that are not clearly formulated as well as create the opportunity to hone questioning and conversation-directing skills. The lead author, for instance, changed question order and improved her introduction of the project after conducting some practice interviews.

3.3.4.2 Question formulation

The first task that comes to mind when thinking about interviews is often question formulation. The purpose of the research should dictate the interview style. Interviews may be structured, which means that there is a strong question-answer-question-answer structure to the interview (Robson, 2002). This will most likely not be used in an expert interview, however, since asking the expert to fill in a questionnaire will probably be more efficient. An interview can also be unstructured, which means that few questions are asked and the respondent answers each question at length (Robson, 2002). This design is more likely to be appropriate for pure social science interviews, or theory generating expert interviews where people's experiences and feelings are the substance of the research.

A semi-structured interview is most likely to be appropriate for exploratory or systematizing expert interviews, since it offers the interviewee opportunity to respond at length when necessary, but it also allows the interviewer to impose some structure to get insight on all the facets of the research question (Robson, 2002). All the expert interviews conducted by post-graduate MtM students to date have been semi-structured, and have been guided by a questionnaire comprising a set of simple but comprehensive open-ended questions, specifically formulated according to the expertise or functions of the respondents.

There are several standard best-practices for formulating interview questions, as outlined by Robson (2002). Questions should be short, clear, straightforward and easy to understand, and one question should be asked at a time. Questions requiring simple "yes" or "no" answers, or that lead an interviewee to give a specific answer should be avoided. Lastly, it is worth mentioning that the question set may change. If the researcher realises that some aspects of the research question are not answered sufficiently when the original set of questions is asked, the question set may be amended. Also, additional or fewer questions may be asked during the interview, as the conversation flows (Silverman, 2005).

3.3.4.3 Identification and selection of experts.

Choice of experts is dictated by the research question such that the relevant stakeholder groupings are represented. In the case of expert interviews, appropriateness and information-richness of the interviewees, rather than statistical representativeness, is key, since a few information-rich cases will give more insight than a large statistically-representative sample (Morgan, 2014; Patton, 1990). Also, statistical representativeness will, in many cases, require a sample size that would be too big to analyse effectively. The aim is not to create a study that is replicable when implemented in other settings, but to create an accurate characterisation of the grouping of interest (Lincoln and Guba 1985, referenced in Case and Light 2011). Readers can then determine whether the results are transferrable to their own contexts.

There are a number of methods for identifying interviewees, including extreme case sampling or intensity sampling (Patton, 1990). However, because expert interviews usually draw from a pool of respondents that is relatively small, and because responses are not always guaranteed, access is likely to be an important driver in sampling. Cold calling, especially of experts, typically yields low response rates (Lavrakas, 2008) and, if possible, is to be avoided. Access to experts is therefore primarily through the supervisor, project sponsor and student's professional networks (Littig, 2009), and is consequently a significant determinant of the respondent list. This does not mean that specific important cases and people should not be identified and pursued, indeed they should, but it is useful to start contacting experts that are already known to researchers or supervisors. Experts can also be asked to suggest other experts and, if possible, send an introductory email on behalf of the researcher to increase the likelihood of receiving a response from the potential interviewee. In his studies, MPhil student Kato (2017) (shown in Table 3-3) gained considerable access to experts through his project sponsor. Another MPhil student, Chitaka (2015) (shown in Table 3-3), was able to gain access to many experts in the metal recycling industry due to their interest in her subject.

One of the most frequent questions that arises from research students is 'how many interviews is enough?". As indicated in the National Centre for Research Methods review paper (Baker and Edwards, 2012) there is no definitive answer to this question, with the number of interviews depending on the nature of the research study and the data that needs to be generated to answer the research questions. For any given research methodology and set of research questions, the number of interviews required will depend on the number of new ideas introduced in each interview. When more interviews start to yield few or no new ideas relevant to the topic, theoretical saturation has been achieved and more interviews are not necessary (Patton, 1990). When this point will be achieved depends on the internal heterogeneity of the stakeholder group that is being sampled, as well as the number of stakeholder groups included in the study. Post-graduate students engaged in the MPhil programme at the University of Cape Town have typically conducted between 10 and 20 expert interviews, but more or less can be appropriate or possible (Patton, 1990; Silverman, 2005). As indicated previously, the expert interviews in these studies are employed in conjunction with other methods of data generation, and have a limited time frame, the research component of the programme requiring to be reflective of 1200 nominal hours.

3.3.4.4 The interview process

Interviews can be conducted in person, telephonically or via skype, and on an individual or group basis. Phone calls and Skype calls facilitate access, but may be difficult to conduct well, since the interviewer is generally unsure of the level of concentration or interruptions of the expert as well as lacking the non-verbal cues to meaning (Christmann, 2009). Christmann (2009) has also found that respondents find it easier to cancel or move interview appointments, since the cost to the researcher is perceived by the expert to be low and therefore acceptable. Although post-graduate students have conducted interviews both in person and via skype, both students and interviewees have indicated that they prefer face-to-face interaction where possible. Experts are normally dispersed, unless gathered at a conference, and a different location will most likely be needed for each person on an individual basis. In most cases, Kato (2017) (shown in Table 3-3) for instance, organised interviews at his respondent's workplaces.

Face-to-face, as well as skype, interviews can be conducted individually or with a focus group. Focus groups allow a researcher to access the understanding of several people at a single event and, because people act as memory jogs and checks for each other, may lead to insights that might not have been expressed in one-on-one interviews (Robson, 2002). Here the researcher must also be aware of the limitations, though. Since interviewees tailor their expressed opinions given who they are talking to and focus groups consist of more people, focus group members are less likely to express extreme opinions (Robson, 2002). Also, the members' personality types and power relations determine who speaks (Robson, 2002). For example, more introverted people's opinions are less likely to be expressed, especially if strong extroverts are in the group (Robson, 2002). In such cases the researcher needs to have strong group management skills to still get a variety of opinions (Robson, 2002). Lastly, it is often prohibitively difficult to get many experts in one location given the group members' other commitments, unless it is run in conjunction with other events that they may be attending, or there is strong incentive for them to attend the focus group. For this reason, most of the expert interviews conducted by MtM post-graduate students at the University of Cape Town to date have taken the form of one-on-one interviews.

In the case of expert interviews, professional dress and conduct on the part of the interviewer is of paramount importance. This includes proper introduction of the material to be covered ahead of time, in the introductory emails, as well as setting aside time in the interview to discuss the subject of the study. Before conducting interviews, MtM post-graduate students have typically made a copy of the project abstract, consent form and the questionnaire available to the respondents, in order to make sure they understand the objectives of the study and to give them the opportunity to ask questions relating to the project and their participation. Professional conduct also means that the interviewer stays within the agreed-upon time limits (Robson, 2002). MtM post-graduate students have typically conducted interviews over the course of 45 minutes to an hour. Lastly, the interviewer must be well prepared and relatively well-rehearsed when starting the interview (see discussions in Section 3.3.4.1).

During the interview the interviewer should listen more than speak and take notes of any concepts that seem important (Robson, 2002). This is the first step to becoming familiar with the data and will help guide the interview as well. However, the bulk of the data-collection should, where possible, be done by recording the interview (Robson, 2002; Silverman, 2005). This reduces the effect of interviewer-bias and memory on the data collection process and allows the interviewer more freedom to guide the conversation well. All MtM post-graduate students, who have conducted expert interviews thus far, have recorded them. When conducting an interview with any person it is important to make them feel comfortable enough to share their information. Schostak (2006) goes as far as suggesting that the interviewer shares certain identities with, and mirrors, the respondents in a variety of different ways, in order to build rapport.

A last point on managing interviews: it is good to relax during the interview and have fun (Robson, 2002). Enjoying the company and conversation of your interviewee will put both of you at ease and make the process more rewarding. The quality of the data will also be better if there is not a stiff tension in the room.

3.3.5 Analysing and reporting interview data

Qualitative approaches are extremely diverse and complex, and qualitative analysis cannot be subjected to the same type of criteria and rules as quantitative analysis. While it is impossible to remove bias from qualitative research methods, it is still possible to do it in a way that is responsible and defensible and these should be the goals of conducting and analysing expert interviews (Robson, 2002; Seale, 1999). Therefore, in order for the research outcomes to be considered valid and of merit, the qualitative researcher must demonstrate that data recording and analysis has been conducted and reported in an explicit and methodologically sound manner (Robson, 2002; Seale, 1999). Whilst the discussions in the following sub-sections are concerned specifically with the analysis and reporting of data from expert interviews, the approaches and methods described here are also applicable to qualitative data generated through other methods.

3.3.5.1 *Transcripts*

The first step to analysing interview data is converting the spoken word to written format. This is called transcription. Although it may at first sound like a simple process, there are several interpretive decisions that must be made when transcribing, as shown in Table 3-4.

Table 3-4 Excerpts from interviews to illustrate analytical decision to be made during transcription. Red indicates punctuation decisions, green indicates grammar that could be corrected, grey indicates emphasis that can be added, and blue indicates words that could be omitted.

"we [are] currently looking at"
"Converting the material ~~to product,~~ to saleable product."
"So I think you [have] ~~got~~ to look at it in the context of time, in terms of what can and may or may not have value. And the approach, depending ~~in terms of~~... understanding ~~in terms of~~ what is in the waste material and understanding the shift of technology. I mean one of the things that have been looked at ~~in terms of~~ now is fluidised beds, ~~in terms of~~ burning, ~~in terms of~~ coals. And I think that's a game changer and there are a number of potential IPP's that have talked about it ~~in terms of~~ the last couple of years inside the Witbank area."
"They are in operation in a couple of places. In fact I see the one place they are working in [is] Goedehoop" VS. "They are in operation in a couple of places, in fact. I see the one place they are working in [is] Goedehoop"
"Nothing is ever easy in the coal industry, because they have to be convinced that something will work. Not on the next-door mine, but on their own mine, on their own coal. But on the other hand it is not THAT difficult, if you can prove a process is viable, then people will be willing to consider it."

Punctuation, for example, can change the meaning of a sentence even though the words are in the same order. One also needs to decide whether grammatical errors and stop words will be reproduced in the transcript. These decisions need to be made based on the data analysis method that will be used. To be sure that these decisions are made wisely, and to facilitate deep engagement with the data, it is preferable for researchers to transcribe interviews themselves. Another reason that the researcher may prefer, or indeed be required, to do the transcripts is that oftentimes interviewee's accents are difficult to understand by those who have not attended the interview and become accustomed to it. Transcripts done by others or computer programs may then have large sections labelled "unintelligible". Whether the researcher does the transcribing or not, however, the transcripts need to be thoroughly checked to ensure that they are true to the interview.

MtM post-graduate students have stressed the need to start transcribing as soon as possible after the interview. Doing this helps the researcher reflect on their data and interview techniques, so that any necessary adjustments can be made prior to further interviews.

3.3.5.2 Thematic analysis

There are several methods for qualitative analysis, the most common being interpretative phenomenological analysis, discourse analysis, narrative analysis and thematic analysis. This section of the paper focuses on thematic analysis because this method is most likely to be used for expert interviews, as the phenomena of interest are not as latent (hidden) as in other types of research, for example education research. Furthermore, thematic analysis can be used by researchers with limited experience in qualitative research (such as natural scientists and engineers), as it does not require a thorough knowledge of more complex qualitative analysis methods such as discourse analysis and narrative analysis. Nevertheless, it is still important that the researcher recognises that thematic analysis needs to be done in a rigorous, methodologically sound and systematic manner (Robson, 2002; Seale, 1999) and that it is a time-consuming process, particularly for the novice qualitative researcher. Braun and Clarke (2006) provide an excellent and concise set of guidelines for conducting thematic analysis and, unless otherwise cited, this section draws from that paper.

Theoretical considerations

Thematic analysis can take many forms, depending on the nature of the research and the research question(s), and a number of decisions (summarised in Box 3.2) need to be made regarding the analytical approach and method before analysis can start.

Box 3.2: Theoretical decisions to be made before analysing data (Braun and Clarke, 2006)

Rich description vs detailed account of one aspect
Inductive vs theoretical
Semantic vs latent themes
Essentialist/realist vs constructionist epistemology

Firstly the researcher needs to decide whether the data will be analysed as a rich description of all the themes arising from the entire interview dataset, or as a detailed account of a particular theme, or group of themes, within the data relating to a specific research question (or set thereof). Also, the researcher needs to consider whether to analyse the data in an inductive or deductive (theoretical) way. In inductive analysis, the themes are developed from the data in a bottom-up manner, i.e. without reference to any pre-existing theory. In contrast, in deductive analysis the themes are driven by the researcher's theoretical interest (top-down approach) and the data are coded for quite specific research questions. Another decision is whether to analyse the data based on the surface-level meanings in the data (semantic), or whether to analyse underlying (latent) themes that shape the semantic data. Lastly, the researcher needs to decide whether to analyse 'meaning' (epistemology) in the data as realist or constructionist. This means that the researcher needs to decide whether to understand the words of the interviewees as directly reflecting their meanings and experience or whether to see them as actively constructed (Silverman, 2005). Although there are no hard and fast rules, analytical approaches which are inductive and constructionist consider specific and latent themes, and those which are theory-based (deductive) and realist consider meaning across the whole dataset (rich description) and semantic themes. Expert interviews will tend to be analysed in an essentialist way, since they do not intend to understand structural conditions or sociocultural contexts that shape the tone of an expert's response and are thus typically associated with theoretical approaches. Expert interviews rather tend to develop semantic themes which are developed from a rich description of the datasets.

Guidelines for thematic analysis

In accordance with Braun and Clarke (2006), thematic analysis is essentially "a method for identifying, analysing, and reporting patterns (themes) within data". The process starts during the interviews when the interviewer starts to notice patterns of meaning and statements of key importance to the research questions, and ends with the analysis of the meaning of patterns (or themes) in the data. Thematic analysis of data, as with other qualitative data analysis methods, entails a number of different stages, with continuous moving backwards and forwards between the different stages. However the process can essentially be broken down into four main stages, as shown in Box 3.3.

Box 3.3: Process of thematic analysis (Braun and Clark 2006).

Step 1: Familiarisation with the data (take notes)
Step 2: Coding
Step 3: Establishment of themes
Step 4: Report generation

The first stage entails *familiarisation with the data*. This requires that the researcher becomes immersed in the data by actively and repeatedly reading the transcripts, searching for patterns and relevant statements whilst doing so. It is useful to take notes of important thoughts in the data, since this will aid the researcher in generating initial codes as well as to form an opinion on what the structure of the data might be.

The second stage in data analysis is *coding*. Coding is essentially the process of organising and sorting the data (written transcripts of interviews) into codes, where codes are words or short phrases that represent recurrent features or elements of the data that are relevant to the research topic or question(s). An example of codes from a study by the lead author is shown in Table 3-5.

The process of creating codes, can be pre-set or developed based on the data, depending on whether the analysis is being conducted in a theoretical or inductive manner. A hybrid of these two approaches may also be used. In such an approach a "pre-set" or "a priori" codes may be established based on the theory, prior readings and the research questions. These codes can then be supplemented by codes which are developed during the in-depth reading and analysis of the interview transcripts. Once the initial list of codes has been set up, the time-consuming task of coding the data can be started. Each piece of text can be given a single code or multiple codes or no code, depending on where it fits in with the research and what is applicable. The initial codes list will guide what codes are created, but new codes will almost certainly be added when the text is scrutinised line-by-line. Codes can also be changed, split or combined as the researcher's understanding of the data improves. The rule of thumb is to make the codes fit the data, rather than trying to fit the data to specific codes. This is particularly important when using pre-set codes.

Table 3-5 Examples of codes from the lead author's study.

Code	Lines from transcript
Water liability	Do we actually decrease our water liability? We've spoken about closure liability, water liability in the mining industry is a big concern. The thing with mine water... polluted mine water post-closure, the time frames are very long indeed
Low prices or margins	Ok, ja, look, one thing that you should keep in mind is that the coal industry at the moment are not in a very good position. They are really bleeding at the moment with the low export prices. And what's keeping a lot of the small mining groups in business at the moment really is ESKOM, so I think the one thing is also that the coal industry at best is fairly marginal. The value of the product they sell, for example to ESKOM; they only get just over R200/ton. Nowadays the mining costs are probably very close to that, you know depending on the actual coal deposit, so there is not a huge margin involved.
Coal industry needs defending	He said that those mines were exploiting Eskom and that because of those mines Eskom was in trouble, which was exactly the opposite of reality is that those mines were supporting Eskom and when the mines will go and they will go,

When the text is coded, the data can start to be structured and the codes *sorted into themes and sub-themes* (stage 3), based on an analysis of the relationship between codes, between themes and between different levels of themes. Themes are groups of code that support overarching ideas that describe the bulk of the data. For example, the codes “coal industry needs defending”, “depleting resources”, “funding is becoming more expensive”, “legal requirements onerous”, “low prices or margins”, “mines need to lower sulfur in product” and “water liability” were all grouped in the theme “coal industry under pressure” in a study by the lead author. Themes thus provide a further level of categorising, and form a basis of structuring the final report. The identification of themes normally involves a number of iterations in which themes are derived, reviewed, and refined or collapsed into larger themes. When this iterative process has been completed to the satisfaction of the researcher, the themes are defined and named and a report can be produced. The final number of themes will be dependent on the size and nature of the dataset and analysis. The master’s dissertation have typically contained between 3 and 6 themes or sub-themes. However, it should be noted that more themes are not necessarily desirable, with fewer themes often being the result of deeper analysis and synthesis.

There are a number of ways of actually doing thematic analysis. If using manual methods, data can be coded by writing notes on the text, by using coloured pens to indicate patterns, by cutting printed transcripts, or by using post-it notes. When using computer-assisted qualitative data analysis software coding is done by using tags and keywords. Qualitative analysis software, such as NVivo, makes transcribing and analysis of data simpler and more efficient, especially when many codes are created, and many interviews are analysed (Joffe and Yardley, 2004). These software programmes also have functionality that helps one find relationships in the data. The choice of whether to analyse data manually or electronically depends on the size of the dataset and the preferences of the individual researcher. NVivo has been used extensively, but not exclusively, by MtM post-graduate students in the thematic analysis of expert interview data. Even where data analysis software is used, analysis can be complemented by the use of manual visualisation techniques. For example in a study conducted by the lead author, the codes were visualised on post-it notes stuck to a blank wall, in order to be able to form a better understanding of the structure of the data.

3.3.6 Reporting

After gathering and analysing data, reporting is the next step. This must be done with the aim of communicating results in a way that communicates the study's validity in a concise, coherent and logical way (Braun and Clarke, 2006). Clear communication of the data themes is the primary way of doing this. For each individual theme, a detailed analysis needs to be conducted and reported on in the context of the research question(s) and objectives. Communication is supported by quoting from the data and giving an indication of the percentage of respondents that touched on the theme (Braun and Clarke, 2006). Quoting has the added benefit of giving readers a feel of what was said and what can be found in the data. It is also vital that any contradicting reports be mentioned and, if possible, accounted for in the text, so that readers can be sure that challenging evidence was not ignored and that the themes related are not a result of cherry-picking data (Joffe and Yardley, 2004; Silverman, 2005).

3.3.7 Ethical considerations

Any research that uses human subjects as a source of data is especially sensitive from an ethical perspective (Silverman, 2005). The Faculty of Engineering and Built Environment (EBE) at the University of Cape Town, for instance, has a rigorous process for assessing the ethics impacts and mitigating requirements of a study. This includes an assessment of the impacts of the study on respondents as well as the appropriateness of the intended line of questioning to be employed (University of Cape Town Faculty of Engineering and Built Environment, 2018).

The first issue of importance is consent (Silverman, 2005). It implies that the respondent has been duly informed of the research, its purpose and the method of data collection, and freely consents to participate. Signing of a consent form is normally used to formalise the process, and is an ethics requirement at the University of Cape Town. MtM post-graduate students commenced interviews by notifying respondents of the procedures with regard to confidentiality, and of the subsequent audio-recording of interviews. This enabled the respondents to voluntarily take part with an informed decision. As a failsafe one can start recording the interview at the point where the interviewer explains the process and that a recording is being taken. This ensures that two records of the explicit consent of the interviewee is available. It is pivotal that interviewees are aware that they are free not to participate in the research if they choose not to. With expert interviews this is less likely to be a problem, though, since experts tend to understand that they are doing the interviewer a favour by participating.

Protecting the expert participant is a second issue of importance (Silverman, 2005). The benefits and risks of the research to the participants need to be evaluated and the risks minimised (Silverman, 2005). This is normally done by keeping them unidentifiable during the course of the research (Schostak, 2006). Participants may strongly prefer not have their or their company's details made known in the course of the research. This is especially likely if they are sharing information of a sensitive nature. Other experts may wish to be mentioned explicitly in the research. It is wise to ask each person how they would like their case to be handled and to honour that. Participants can be provided with choices regarding the level of disclosure as part of the consent form, as shown in Box 3.4.

It is advisable to send the research to the participants for them to check whether they are comfortable with what is being written and to receive any other relevant feedback. In the case of the lead author very few responses to the written-up results were received, but those participants that did respond were positive about the outcomes of the research. This could be due to negative perceptions of the research, with respondents taking a 'if you can't say something nice, rather say nothing at all' approach or it could be due to the busy schedules of the respondents, not allowing time for reading and responding to such requests. The difficulty experienced with setting up interviews in the first place suggest the latter explanation.

Box 3.4: Options for disclosure of identity.

Option 1: Yes, I consent to help you under the terms of this document, but would prefer not to have my personal details mentioned in any of the documents resulting from this work.

Option 2: Yes, I consent to help you under the terms of this document, and would like to be referenced or specifically mentioned in the text of the documents resulting from this work

Option 3: Yes, I consent to help you under the terms of this document, but would prefer not to have my personal details mentioned in any of the documents resulting from this work, except for the 'acknowledgment' sections.

3.3.8 Conclusions

Interviews can be a useful qualitative research method to find out about people's perspectives, motives, experiences and knowledge, amongst other things. Expert interviews in particular are useful for illuminating aspects such as finding industry consensus on a topic, insight into know-how that isn't published, opinions on the best direction for future specialised research, estimates on a little-explored area of a field, insights into the process that was followed to get technical results, and opinions on phenomena that influence an industry. Such interviews have been found to be a particularly useful tool by MPhil and PhD students engaged in research on sustainable development of mineral resources within the Minerals to Metals Research Initiative (MtM) at the University of Cape Town, particularly when applied as part of a mixed method research approach. To realise these benefits, however, expert interviews need to be conducted well, with due consideration to methodological rigour. Whilst qualitative research methods cannot be subjected to the same type of criteria and rules as quantitative research, the meaningful application of expert interviews as a research technique requires skill, and it is important that interviews are conducted, and the collected data analysed and reported, in a methodologically rigorous manner. Aspects that need careful consideration include the interview technique and structure, formulation of interview questions, identification of suitable experts, method of data analysis and reporting, as well as ethics.

Whilst this paper provides an overview of expert interviews as a form of qualitative research, combining the practical experience of post-graduate students engaged in inter-disciplinary research within the Minerals to Metals Initiative at the University of Cape Town with the perceptions and theories presented in literature, it is not intended to be a "catch-all" for expert interview and data analysis methodology. Other more extensive sources should be consulted when interviews have been chosen as a research design.

Finally, the importance of choosing the right method for the research cannot be over-emphasised. As Stake (1995, referenced in Case and Light 2011) cautions: "Good research is not about good methods as much as it is about good thinking."

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3.3.10 References

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Chapter four – Technology transfer

A key premise of the approach proposed in this study is that early consideration of technology transfer issues improves the likelihood of successful technology development and transfer at the end of the technology design and development process. This chapter considers the work done to address the first hypothesis and related key questions.

Hypothesis 1:
Technology transfer considerations identified through interviews with industry stakeholders can play a key role in guiding the early stages of design and development of technologies for waste reuse.

1. What are the potential key enablers and barriers to technology transfer for mine waste valorisation technologies?
2. What key partnerships must be developed to expedite technology design, development and transfer?
3. How can knowledge of potential technology transfer issues be used to inform the early stages of mine waste valorisation technology design and development?

The first two research questions were addressed by interviewing stakeholders from various organisations in the South African coal industry to incorporate their understanding of technology selection and transfer in the South African coal mining industry into the process for designing and developing mine waste valorisation technologies. This study is presented in the form of a published paper titled *Understanding the Opportunities, Barriers, and Enablers for the Commercialization and Transfer of Technologies for Mine Waste Valorization: A Case Study of Coal Processing Wastes in South Africa*. The third key question considers the impact that a consideration of technology transfer might have on other steps in the generalised early-stage mine waste valorisation technology development approach and is therefore addressed in Chapter 5 Process selection and Chapter 6 Pre-feasibility study.

Paper 1: Understanding the Opportunities, Barriers, and Enablers for the Commercialization and Transfer of Technologies for Mine Waste Valorization: A Case Study of Coal Processing Wastes in South Africa

4.1 Abstract

The mining and minerals beneficiation industries produce large volumes of waste, the land disposal of which can lead to harmful environmental emissions and a loss of valuable resources. Globally, researchers are developing technologies for recovering valuable minerals and converting mine waste into a resource with market value. However, university-developed technological innovations to long-term environmental problems can be difficult to transfer to the mining industry. This paper focuses on the barriers and enablers to technology transfer in the South African mining industry using the valorization of coal processing waste as a case study. Data and information derived from interviews with relevant experts and published literature were used to gain a better understanding of the landscape of waste valorization technology implementation. Results indicated that financial considerations and demonstration of technical feasibility will be vital in determining the success of technology transfer, as will a changing perception of waste and its value within the sector. Original equipment manufacturers (OEMs) and boutique waste processors were identified as potential commercial partners for further development and commercial implementation of university-developed waste valorization technologies within the mining sector.

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4.2 Introduction

Technology transfer (or diffusion) is a complex process that encompasses the transfer of the technological objects, codified knowledge and tacit knowledge from one organisation to another as well as the acceptance and implementation of the technology in the receiving organisation (Bozeman, 2000; Hipkin and Bennett, 2003; Kostova and Roth, 2002; Teece, 1977; Zander and Kogut, 1995). Teece (1977) defines the process of technology transfer as what happens between the first encounter between technology originator and the adopter and the final implementation of the technology, with Souder et al. (1990) defining a technology as adopted when an adopter has a "strong emotional and financial commitments to [a technology's] routine use". When universities and other research organisations develop technologies, it is often with a view to eventual transfer and commercial adoption.

Understanding technology transfer from research organisations, specifically universities, to industry is crucial when the intentions of the technologies are to improve the environmental and/or social characteristics of industry, and is important for maximising the return of investment to both funders and society at large (Good et al., 2019; Harmon et al., 1997; Lai, 2011; Lowe and Gonzalez-Brambila, 2007; Wright et al., 2004). Social/environmental technologies, such as technologies for improving resource efficiency and establishing a circular economy, can have additional barriers to implementation, since they often address issues that are currently externalised and benefits are not always sufficient to drive adoption (Adams et al., 2017; Guerin, 1999; Trencher et al., 2014). One such externalised issue is mining waste.

Mining and primary ore processing operations produce large volumes of waste. These are normally disposed of in surface waste deposits such as tailings dams and heaps, or backfilled into disused workings (Behum et al., 2018; Chen et al., 2021; Hamberg et al., 2018; Owen et al., 2020; Van Zyl et al., 2002; Villain et al., 2013; Zhang et al., 2019b). Of particular concern in the case of wastes generated from sulfide-bearing hard rock ores and coal, is the formation of acid rock drainage on exposure to air and water (Broadhurst and Harrison, 2015; Leathen et al., 1953a, 1953b). Acid rock drainage (ARD) causes water pollution and soil sterilisation (McCarthy, 2011; McCarthy and Pretorius, 2009). Many South African coals have a significant sulfide mineral content, which reports to both the discards and slurry waste during processing, rendering them potentially ARD generating (Eberhard, 2011; McCarthy and Pretorius, 2009). (Coal processing produces waste of different size fractions. The coarse material (>1 mm) is called discards, while the fine material presents as slurry and is traditionally disposed of as tailings.). While current disposal practices, such as co-disposal and waste compaction, aim to minimise ARD generation by limiting air and water ingress (Behum et al., 2018; Park et al., 2019; Van Zyl et al., 2002), and advances in cementing technology are being made (Barati et al., 2020; Liu et al., 2020), they have yet to be proven effective in eliminating generation of polluting discharges in the long-term and continual monitoring will thus be required (Akcil and Koldas, 2006; Lloyd, 2000). Furthermore, future disturbances, by artisanal miners or land developers for instance, could expose sulfidic minerals and thus increase the risk of ARD generation.

Avoiding land disposal through repurposing and reprocessing mine waste for other uses has the potential to remove these long-term ARD pollution risks. The approach, called valorization, views waste as a secondary resource rather than as an unwanted material, consistent with the circular economy- and resource efficiency principles (Bocken et al., 2016; Kirchherr et al., 2017; Nzihou and Lifset, 2010). For waste to be turned into an asset and these benefits to be realized, innovative technologies and innovative application of existing technologies are needed. Large-scale waste valorization efforts are currently impeded by a lack of industry-wide information on waste characteristics, and therefore potential uses of mine wastes, although European efforts are focused on improving the situation (Blasenbauer et al., 2020; Suppes and Heuss-Aßbichler, 2021; Žibret et al., 2020). The need for updated legal frameworks and societal acceptance has also been noted (Brady, 2016; Suppes and Heuss-Aßbichler, 2021; Tayebi-Khorami et al., 2019). To help overcome some of these barriers, research funding initiatives such as Horizon 2020, EIT Jumpstarter, and WasteAid's Circular Economy network (EIT Raw Materials, 2021; European Raw Materials Alliance, 2021; European Union, 2021; Wilson, 2020) provide opportunities for accessing funding and support. Commercialization and implementation are imperative if waste valorization technologies are to make a difference in mining landscapes and beyond. Technology transfer is necessary for implementation to take place.

Technology transfer of sustainability technologies to the mining industry is a subject that has received little explicit attention, and Suppes and Heuss-Aßbichler (2021) have noted the need for mapping barriers to the development of waste valorization technologies. There also appears to be limited research on the factors influencing university technology commercialization and transfer in South Africa, particularly in the context of coal waste management. This is an important gap in the literature since the mining industry is likely to be more careful with technology implementation due to the high capital cost associated with mining technologies, the long lead time of implementation as well as the highly cyclical nature of the industry itself (Botas et al., 2018; Johnston, 2012). In addition, waste valorization is a sustainability-related technology and, therefore, likely to face additional barriers that are not always immediately apparent.

The objective of this study was, therefore, to develop an enhanced understanding of the factors influencing the commercialization and transfer of university-originated waste valorization technologies to the South African coal industry, as well as the potential roles of different stakeholders. This was achieved through a qualitative analysis of the perspectives and experiences of experts in, or associated with, the South African coal industry. It is envisaged that this understanding will support the development of a defensible business case as well as a technology commercialization and transfer approach for application to waste valorization technologies. Identification of potential implementation partners was also considered a priority since the early involvement of a commercial partner in technology development improves the likelihood of successful development and transfer (Davis et al., 1989; Greiner and Franza, 2003; Souder et al., 1990).

4.3 Method

4.3.1 Interviews as a Method

Investigations of technology transfer for sustainability found in the literature have made use of a variety of methods, such as structured surveys/questionnaires, focus groups, and interviews (Adams et al., 2017; Greiner and Franza, 2003; Lai, 2011; Mishra et al., 2019; Trencher et al., 2014). This list indicates that qualitative research methods are common in investigating technology transfer in sustainability environments. For this study, insights into the perspectives and opinions of experts on the opportunities, barriers, and enablers for the transfer of coal waste valorization technologies in the South African context were gained through the thematic analysis of transcripts derived from semi-structured interviews. In accordance with Bogner et al. (2009) and Robson (2002), semi-structured interviews are an efficient way of learning about issues that certain groups of people have intimate knowledge of, such as their motives and opinions. This type of interview also allows interviewees to explain their reasoning and support their observations with data, which in turn allows for richer interpretations than most surveys.

Expert interviews are a special class of interviews that can be used to gain organizational or subject-specific knowledge from a group of individuals who are active in a field (Bogner and Menz, 2009; Littig, 2009; Stander and Broadhurst, 2019). These interviews are particularly useful when they engage experts on quasi-technical and organizational matters, i.e., expert knowledge gained through practical experience that cannot be answered by a more technical research design or document analysis (Morgan, 2014; Stander and Broadhurst, 2019). These subject-specific and quasi-technical issues include aspects such as common methods employed by, or corporate opinions of, an organization or discipline (Bogner et al., 2009). This provides insights that would have been difficult to glean by other methods.

In this study, coal industry executives and consultants were interviewed along with individuals who were intimately involved with environmental and waste-related technology implementation in the coal industry, as well as people active in applied coal research. These individuals ostensibly had the most knowledge of the functioning of the coal industry and how it relates to environmental technologies. Further details on the selection of respondents and the interview process are provided in Sections 4.3.2 and 4.3.3, respectively. Data analysis (Section 4.3.4) was conducted using thematic analysis, and the results compared with information from published literature to identify synergies and/or anomalies peculiar to the case study under investigation.

4.3.2 Respondent Selection

In accordance with literature guidelines (Morgan, 2014; Patton, 1990), respondents were selected based on stakeholder representation and access, and a variety of sub-groupings active in the coal industry were represented. These included corporate executives from both coal majors and junior miners, individuals who have been part of technology implementation in the coal industry, researchers active in the coal industry, as well as consultants to the South African coal industry. A total of 29 experts were contacted, resulting in 16 interviews. Consistent with the recommendations of Lincoln and Guba (1985), cited in Patton (1990), interviews were conducted until theoretical saturation was reached. Theoretical saturation represents the point where more interviews do not add new perspectives or opinions. It is therefore not necessary to conduct additional interviews after having reached that point (Patton, 1990). The fact that theoretical saturation was reached relatively quickly may be reflective of how closely-knit the South African coal industry is. The method of respondent identification and the number of declined interviews mean that sampling was not completely random. Individuals uninterested in environmental technologies may have been overrepresented in the population that declined interviews, for instance. Some sampling effects may therefore be present.

Also, the nature of interviews and the respondents selected means that in many cases, the information elicited from stakeholders are only their opinion on what may transpire, based on their knowledge of their organizations and the industry as a whole, rather than the lived experience of someone who has successfully implemented. The testimonies of the technology implementers are therefore especially important for deriving useful information. That said, all stakeholders provided their own rich perspectives of the coal industry and its relationship with waste and new technologies. They contributed their own understandings to piece together the bigger picture.

A breakdown of the respondents that were interviewed is shown in Table 4-1. To protect individuals' identities, no personal identifiers are made known unless specifically requested. The two technology implementers were a developer and provider of waste management technologies that have been implemented on multiple mines; and an academic who has successfully commercialized and licensed a waste valorization technology and was in the process of commercializing another at the time of interviewing. The related commodity executive implemented waste valorization technology successfully on the mine where they worked. The coal major executives interviewed were from four of South Africa's five coal major firms: Anglo American, South 32, Exxaro, and Sasol. They mainly headed or were involved in technical departments of these companies, but one was involved with project development. The respondents from junior mining companies headed their engineering- and environmental departments, respectively. Of the consultants interviewed, one had a technical focus, one contributed an industry perspective, one was from an environmental consultancy, and one had a project focus. The researchers interviewed were from industrial research organizations in South Africa. Respondents who declined interviews included a consultant, a technology implementer, two researchers, four major coal executives, and five junior coal executives. This indicates that it was particularly hard to secure interviews with coal juniors and the testimonies of the two coal junior executives are therefore particularly important.

Table 4-1 Stakeholders interviewed.

Technology implementers	2
Coal major executives	5
Related commodity executive/implementer	1
Coal junior executives	2
Consultants to the coal mining industry	4
Researchers active in coal-related research	2

4.3.3 Interview Method

Interviews were conducted over Skype, using telephone calls in the case of technical difficulty with Skype, and in person. In two cases, respondents invited colleagues along to the interview, resulting in impromptu focus groups being conducted. In all cases, the interviews were recorded. Questions ranged from specific organizational processes to respondents' opinions on industry matters, as shown in Box 4.1.

Box 4.1 Question list.

- How do you make the decision to pilot a new technology? (Criteria? People involved)
- How do you make the decision to implement a new technology?
- What if someone from outside the company wants to implement?
- Is there some sort of standardisation in the process of bringing a technology to implementation in the coal industry, or does everybody follow their own process?
- How do you fund your projects? (Bank loan? Company balance sheet?)
- Which players (organisations) would be the most likely to implement value-from-waste technologies? [Mines? Boutique waste processors? Community-based business? Etc? Why? Examples? Experience?]
- Do you think the process of implementation of value-from-waste technologies will be easy or difficult? Why?
- What are the most important barriers to implementation? / What will be the difficulties of implementation?
- Which are the most important drivers of implementation?
- What is your opinion on the legal side of implementing value-from-waste projects?
- How would the barriers and drivers be different for different implementers?
- What do you think needs to happen for implementation to become more likely or easy? Overcome barriers?
- Are there any stakeholders whose buy-in are especially important? What group of stakeholders do you need buy-in from?
- Have you implemented something similar and what were the issues?
- Would you consider developing processes with research bodies, such as universities? What are the issues?

- Do you think that reprocessing coal tailings for other purposes is a good idea?
- Do you have anything to add that we have not discussed?

4.3.4 Analysis

The interviews were analyzed using thematic analysis (Braun and Clarke, 2006). The thematic analysis was conducted semantically, therefore focusing on surface meanings and from a realist perspective, which means that the words of participants are viewed as reflecting the participants' meanings (Braun and Clarke, 2006). The data were also analyzed to give an overall picture of the themes present in the data and inductively, which means that the themes considered were not derived from theory but from ideas encountered in the data set (Braun and Clarke, 2006). This means that less interactional detail was required than for conversation analysis, for instance, and the transcriptions did not account for tone of voice or other non-verbal communication. In addition, some simplifications of the data were considered acceptable to improve readability. Examples include the correction of minor grammar errors (such as is/are mistakes), removal of oft-repeated stop phrases such as "actually" in cases where the word choice did not make sense, and the removal of repeated words. Transcription and analysis were conducted using NVivo software.

4.4 Results and Discussion

The results are discussed under two main headings, each reflecting the research objectives: barriers and enablers to transfer (Section 4.4.1); the roles important stakeholders can be expected to play in transfer (Section 4.4.2). Themes under each heading are then discussed and supported by published literature.

4.4.1 Barriers and Enablers

The results of the study have shown that there are several factors, both technical and non-technical, which constrain or facilitate the commercialization and transfer of potentially feasible technologies for the valorization of coal processing wastes. The main influencing factors can be broadly grouped into the following sub-themes, discussed in Sections 4.4.1.1–4.4.1.4: the technical aspects of technology development; the business case for implementation; the legislative and regulatory climate; and corporate culture and values.

4.4.1.1 Technology Development and Demonstration

Technology must be proven to be effective before it can be implemented in practice since success at a laboratory scale does not guarantee success at a pilot or demonstration scale. This is according to 11 of the 16 respondents. Nine respondents then described piloting and demonstration plants as the way to prove a technology. This process is, however, long and expensive according to all the coal major executives, a consultant, and a researcher, so the availability of funding and partners with experience in scaling-up was discussed as important considerations.

Assuming that the technology is proven, industry awareness of the technology and its efficacy was believed to be an important driver of implementation by two-thirds of the respondents. This was considered especially important when some in the industry have pre-conceived ideas around the efficacy of a technology, such as the case of the froth flotation of coal. As a technology implementer remarked: "We spend a lot of time to show people what we've achieved, how it works and where it's implemented. You know, that whole concept of seeing is believing. That helps tremendously." Allowing industry stakeholders access to demonstration or industrial-scale plants to experience it working is, therefore, an important part of a technology awareness strategy. Other ways of creating awareness in the industry were also proposed by the respondents: presentations at industry assemblies such as the Fossil Fuel Foundation (https://www.fossilfuel.co.za/ (accessed 12 April 2021)) conferences and Coaltech (https://coaltech.co.za/ (accessed 12 April 2021)) meetings; and publicizing lab testing results of different coals. These observations by the respondents agree with the literature, which states that technology risk is easier to assess in technologies that are easy to understand and in cases where representatives of a company have opportunities to interact with the technology (Souder et al., 1990; Teece, 1977).

Half of the respondents mentioned that proven technologies must be tested for efficacy in their own setting, with their own materials and infrastructure. This means that even when a technology is proven in principle, mines would like to be convinced that it will work on their own material and in the context of their own plant. This aspect is especially important when working with waste. Six respondents mentioned that robustness is needed due to waste's inherent variability and uncontrolled nature. The related commodity executive commented that the technology needs to produce a consistent product from material with a wide compositional range since the composition of waste can vary significantly between different areas of a waste dump. They put it as follows: "I mean it is like standing there in the dark and not knowing what you are going to get. That's what dealing with waste is like." Waste compositions for different mines are also likely to vary fairly significantly (see, for example, Moyo et al. (2019)).

These observations by the respondents are consistent with findings reported in the literature. As highlighted by Souder et al. (1990), a prospective technology implementer has to assess the technology based on whether it is appropriate for their application, as well as whether they can assume the level of technological risk inherent in the technology at its stage of development. Consequently, a technology's stage of development is of utmost importance in technology transfer, as the first implementation is the riskiest and most expensive (Greiner and Franza, 2003; Johnston, 2012; Teece, 1977). As noted by Grano et al. (2009) and Teece (1977), the scale-up process is uncertain and mature technologies are more likely to be successfully transferred since the difficulties with implementation have been ironed out in different contexts, and the technology is well-understood. As one of the coal major executives put it: "It's rare that you see a total new technology in a total new greenfields." Technology reliability and maintenance requirements are also easier to estimate when technologies are mature (Souder et al., 1990). Implementing new technologies opens a company up to technology risk.

A potential barrier to technology transfer efforts specific to the coal mining industry, identified by almost half of respondents, is the lack of appropriate technical expertise within mining companies due to their focus on core business and business strategy. Six respondents noted that mines prefer to focus on their core business, which is producing and selling commodities, to the exclusion of other business models. This has meant that they do not develop technologies to sell to other mines and therefore do not staff adequate research and development (R&D) departments to engage in specialized technology development, according to three coal major executives and a technology implementer. As one of the coal major executives noted, "We're not into developing the technology to sell it to other mining companies. They're our competition." Four of the respondents suggested that buying well-supported robust technologies off-the-shelf is a preferable approach for most mines, as opposed to funding development or developing new technologies in-house.

Given the lack of technical skills at mining companies, management may find it difficult to appreciate the potential of technologies or the technical risk that will have to be managed. This increases the transfer risk since literature reports that an important contributor to success is an adopting organization that has the skills to understand the technology, implement it, and operate it (Grano et al., 2009; Hilson, 2000; Kimberly and Evanisko, 1981; Kostova and Roth, 2002; Lee and Win, 2004; Teece, 1977; Zander and Kogut, 1995). It is unlikely that those in the adopting organization will support the technology and its implementation if the advantages of the technology are unclear, unvalued, or intangible, all of which are more likely if the management team has little technical background and it is likely to be dismissed or end in failure (Greiner and Franza, 2003; Hilson, 2000; Kostova and Roth, 2002; Nikolaou and Evangelinos, 2010).

4.4.1.2 Business Case

Regardless of in-house technical expertise, all 16 of the respondents agreed about the necessity of having a convincing business case and considered techno-economic viability as the biggest determinant of successful technology transfer. Two respondents even started the interview with an exposition of the importance of a business case before the first question could be asked. The published literature corroborates this sentiment (see for example Ankrah et al., 2013; Greiner and Franza, 2003; Lamprecht, 2012; Sizhen et al., 2005; Souder et al., 1990; Teece, 1977).

Respondents mentioned that a sound business case would either reflect a reduction in a company's costs and liabilities, or an increase in income, with two-thirds of the respondents mentioning the reduction of disposal costs and liabilities as an appropriate focus for a business case for waste valorization. Inherent in the concept of a convincing business case is an economic market for the product that the producer can access, as stated by six respondents. A major coal executive related an instance where his team had a product, but where the customer was not convinced about the appropriateness of it for their application, and the product consequently failed. As one consultant put it: "The hurdles are going to be project-specific, but the fundamental hurdle is that there's got to be an economic market for the product." Having a market can therefore be considered important to be able to sell the product and recoup the costs incurred in development and implementation.

As discussed in Section 4.4.1.1, technology development can be expensive. Almost all the respondents mentioned that the cost associated with technology development and implementation, including financing and transfer costs, can be a significant barrier, especially when financial resources are constrained, such as for mining juniors. This finding is consistent with literature (Hilson, 2000; Johnston, 2012; Kostova and Roth, 2002; Lee and Win, 2004; Nikolaou and Evangelinos, 2010; Rochon et al., 2010; Teece, 1977). In addition to the financial costs of technology development, the cost in terms of time and effort of developing and piloting a technology was also seen as a significant barrier to implementation by 12 respondents. In South Africa specifically, the dearth of funding for scale-up and scarcity of other resources such as skilled personnel is a significant barrier (Gericke, 2014). Most timelines that were mentioned were between eight and 15 years. Three respondents also noted that long timelines open companies to the risk that the market might not be available anymore by the time the technology is mature enough to implement. This then presents a significant financial risk due to the high cost of technology development mentioned earlier.

A common indicator of the viability of a project is the internal rate of return (IRR) that it achieves (Johnston, 2012), despite the fact that a focus on the IRR of a project does not recognize less tangible benefits associated with waste valorization, such as a reduction in occupied land for waste storage (Godfrey et al., 2007). One researcher mentioned that an IRR of around 17.5% could be considered the hurdle rate for technologies in the South African mining industry. Research by Johnston (2012) places the hurdle rate for implementation of technologies in the mining industry higher, at an IRR of 23%, even when a technology has other environmental benefits as well. Lamprecht (2012) places the hurdle IRR for innovative technologies even higher, at 30%, to offset the associated risk and costs. While the researcher's figure is somewhat lower than the figures mentioned in the literature, it is still significant. High IRR's to the exclusion of other benefits could be required in environments where there is difficulty in accessing debt financing (Sizhen et al., 2005) or because of the tangible financial repercussions of failure (Lee and Win, 2004).

Three respondents mentioned that a possible barrier to achieving high IRR's in the case of mine waste valorization is the need to achieve economies of scale. Tailings impoundments, while large and capable of generating significant ARD burden, might not be big enough to achieve the economies of scale that a mining company would require for investment. Eight respondents mentioned that the large distances between coal waste heaps, the fact that not all coal mines produce fines, which reduced the number of potential sources, as well as ownership issues with waste may present commercial barriers to combining waste heaps to achieve economies of scale.

4.4.1.3 Regulatory Environment

Consistent with literature reports (Greiner and Franza, 2003; Perkmann et al., 2013), two-thirds of respondents considered South African legislation to be a potential driver for mines to implement value-from-waste technologies. This is largely because stringent waste management legislation can significantly increase the cost of traditional waste disposal methods, thereby improving the business case for implementing waste valorization technology. An example from the South African National Environmental Management: Waste Act 59 of 2008 that was mentioned by five respondents includes regulations that require lining of tailings dams for disposing of mine waste containing hazardous components. As one consultant noted: “you don′ t see many people with slimes dams, for example, because it is just too complicated to actually try and get permission for a slimes dam. So now all of a sudden, even though filter presses are expensive, people realize slimes dams are expensive.” Five respondents also mentioned that involvement in developing environmental technologies should create goodwill toward the mining company at certain government departments, making interest from mining companies and consequently implementation more likely.

Eleven respondents, however, mentioned that some aspects of legislation also act as barriers to the implementation of waste valorization efforts. One such aspect, mentioned by half of the respondents, is the requirement to get licenses and permission for activities from various government entities when changing or adding activities. One example of licensing and permissions that was mentioned by four respondents is legislation that requires permission from the National Energy Regulator of South Africa or the minister for setting up waste-burning power plants bigger than 1 MW for their own use. This makes adopting an obvious value-from-waste option difficult and onerous. Another aspect that was mentioned by four of the respondents was that they thought that South African legislation, in general, puts unreasonable expectations on mines. For instance, one technology implementer mentioned that the requirement for water discharge purity was higher than the purity of the river into which it is discharged. Other legal issues that were mentioned were issues with liability for, and ownership of, waste which can stifle collaboration between mines; expenses associated with legislation that hurt mines' profitability; and social and labor plan-related requirements, which also adds costs. A review of South African law on waste valorization indicates that it has only recently been explicitly legislated (Department of Environmental Affairs, 2018), despite having been espoused in the National Waste Management Strategy for many years (Department of Environmental Affairs, 2011). The respondents did not question the objectives of the laws but commented on the fact that they were too ambitious, too rigid, restricted the mines' options, and used compliance exclusively instead of complementing with incentives.

4.4.1.4 Corporate Values and Culture

According to half of the respondents, business culture-related barriers to waste valorization within the coal sector include corporate inertia, bureaucracy, and pre-conceived ideas, all of which need to be challenged and changed if a novel waste-related technology that reprocesses or repurposes bulk waste material is to be implemented. In general, it appears that waste is not seen as imminently valuable in the coal industry for anything other than the residual coal it contains. Ideas of waste being hazardous, being gotten rid of, and as a liability were voiced by half of the respondents. When asked about value-from-waste technologies, the dominant conceptions were of extracting the residual coal or mineral value from the waste or burning coal waste to recover residual energy value as opposed to considering the bulk material as a resource. One notable exception was the case mentioned by a coal major executive of an entire waste heap being worked away by being repurposed, but this was not the norm. Interestingly, while most of the respondents were open to new technologies unlocking interesting value propositions, they did not think that any currently existed.

The interview data also indicated that, in order to understand the culture within the South African coal industry, it is important to understand that it views itself as under-valued by outsiders and under pressure. Half of the respondents mentioned challenges such as depleting coal resources, increasingly onerous legal requirements, volatile commodity prices and looming social and environmental liabilities. For some in the industry, this pressure has made them defensive, as shown by two respondents who, unprovoked, defended the industry and explained its importance in detail. According to the arguments presented by Sizhen et al. (2005), these pressures may have the effect of making a business case based on financial returns exceedingly important for the implementation of new technology since mines feel that their livelihoods are at risk.

Nevertheless, these pressures can also be a force of positive change. As a technology implementer put it: "because of the legislation, and of the pressure that environmental bodies put on mining houses, they're forced to do something, because the public does not like acid water, they do not like pollution. If it's screened on Carte Blanche [a South African investigative journalism television program], people see it and then there's a lot of pressure to reduce this pollution and footprints." These views are consistent with literature reports which show that implementation of technology is influenced by the interests and experience of the managers of organizations and by the social background, knowledge, and acceptance of the implementing staff, among other factors (Davis et al., 1989; Greiner and Franza, 2003; Kimberly and Evanisko, 1981; Kostova and Roth, 2002; Lang, 2004; Zander and Kogut, 1995). Company values are influenced by that of the surrounding communities and society at large, so societal values and corporate reputation may be drawn on to support technology implementation (Brønn and Vidaver-Cohen, 2008; Kostova and Roth, 2002).

4.4.2 Stakeholder Roles

Technology transfer is a complex process involving several stages and stakeholders. Figure 4-1 shows stages and role players that are commonly involved in technology transfer (Souder et al., 1990). These stages are: prospecting, which involves finding or disseminating technology; developing, which involves adapting technology for implementation; trialling, the process of testing it onsite; and adoption, the final stage of implementation. These stages are iterative, and some aspects can run in parallel (Souder et al., 1990). Common role players in the process are: sponsor, developer, adopter, disseminator, and implementer (Souder et al., 1990; Spann et al., 1995) but the same organization or person can play multiple roles, and different organizations can co-operate to play the same role.

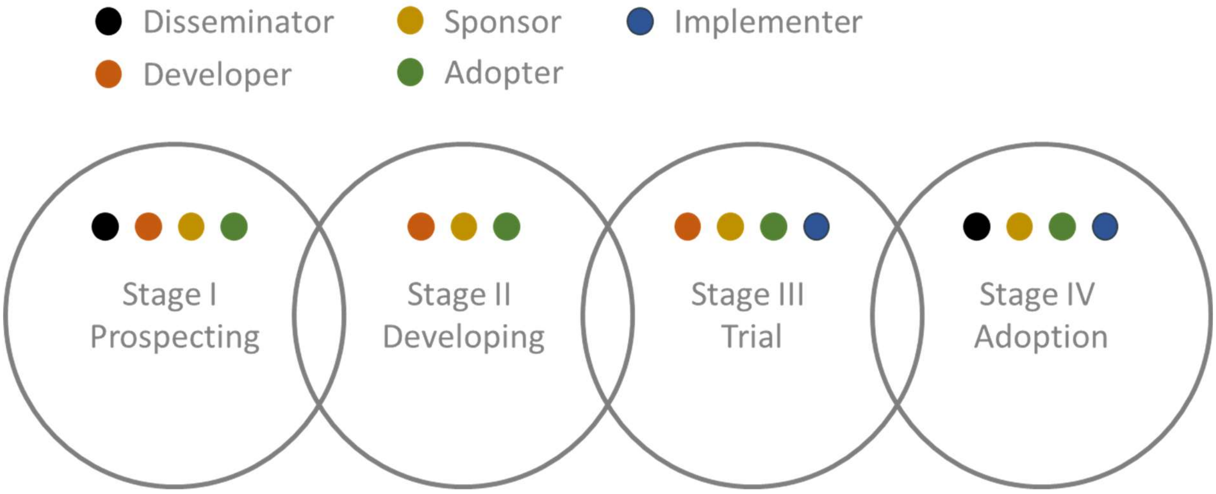

Figure 4-1 The process of technology transfer loosely based on a diagram by Souder et al. (1990).

In the transfer of university-developed technologies for the valorization of waste generated by coal mines, these same stages and stakeholders are expected to be key. Universities and their technology transfer offices can play the roles of disseminator and developer. University technology transfer offices in particular can be important bodies in the technology transfer landscape and provide essential services to the process (Good et al., 2019). Mining operations or organizations are also key stakeholders who can play the roles of the adopter, sponsor, and historically developer and implementer. Additional direct role players identified in this research are original equipment manufacturers, who can play the roles of developer, implementer, and perhaps even adopter; commercial research institutions to co-play the role of the developer; and communities to play the role of the adopter, if the technology is sufficiently robust. The roles of these external stakeholders are discussed in more detail in Sections 4.4.2.1–4.4.2.3.

4.4.2.1 Role of Mines

In the past, universities have worked with mines and big mining companies to commercialize technologies (Broadhurst et al., 2009). The mining companies took on the roles of co-developer, adopter, sponsor, and implementer. However, findings from this study indicate that this approach may not be appropriate anymore. According to respondents, the mining business model is not technology development but raw materials production (see discussions in Section 4.4.1.1), which means that mining houses have systematically moved resources away from technical departments and have outsourced technical functions. Mines have focused on their capacity to produce ores and minerals and, according to two consultants and a coal major executive, reduced their research and development and specialized technical functions.

As the business model of mines has led them to disinvest in specialized technical functions, it has also meant that mines are not developing alternative business strategies. A third of respondents suggested that the business strategies of mines are important in the implementation decision. As a coal major executive noted, the business strategy of a mine is not manufacturing or electricity production which means that they do not have intimate knowledge of those businesses and markets. The executive also noted that mining companies will therefore also not have their corporate structures set up in a way that will support the marketing and sales of other (non-core) products. These perspectives suggest that the lack of corporate structures to support ventures outside the narrow mining business model increases the risk and effort associated with waste valorization ventures. This means that management may rightly be reluctant to enter such businesses.

Another potential barrier to mine implementing is the tendency of waste valorization to produce a small profit stream compared with the mine's core business. A technology implementer, researcher, and consultant all emphasized that the small profit stream is one of the key reasons that waste reprocessing has historically been poorly managed at mines. According to these respondents, the results of neglect have then sometimes been mistaken for technology failure.

Mines can therefore be technology sponsors but will most likely transfer the implementer, and perhaps even the technology adopter role, to another organization. Two major coal executives mentioned that they are aware of companies that push much of the technical research that they require on to trusted original equipment manufacturers (OEMs), also known as technology providers, who they then hire to test and implement any technologies that they may need. The OEMs thereby become technical mediators for the mines. Likewise, one technology implementer's company became the technology adopter on behalf of the mines they work with. Nevertheless, a third of the respondents mentioned that mines, or holders of the waste to be processed, should be intimately involved with the process of implementation because they will derive value and are best placed to understand the composition of their waste.

4.4.2.2 Role of OEMs and Commercial Waste Processors

As indicated above, half of the respondents considered OEMs to be in a better position to implement, operate and maintain the equipment for waste reprocessing than the mine. In line with this, one technology implementer and four major coal executives thought that a well-respected OEM or technology provider would be a better partner for technology commercialization than the mines themselves. Examples by respondents suggest that this is indeed the case. In almost all the cases mentioned where a value-from-waste technology was implemented on a mine and with the help of the mine, the OEM or waste processor was the party that implemented the technology, runs it, and maintains it. Respondents indicated that OEMs already have the business strategy (they service multiple mines), experience, technical skills, contacts, and credibility with the industry to be able to commercialize technologies successfully and can thereby avoid the risk of mining companies failing to operate waste valorization operations effectively (see Section 4.4.2.1). One coal major executive also believed that it would be appropriate for an OEM to fund part of the technology development since they would draw advantage from its success. The appetite of OEMs for acting as commercial partners of universities and other research organizations would have to be tested;

however, since they fall outside of the sample that was interviewed, and issues such as the ownership of intellectual property (IP) are likely to be important considerations in such partnerships.

One coal industry researcher suggested that commercial waste processors may also be a good option as partners for commercializing value-from-waste technologies. In the case mentioned by a coal major executive where an entire waste heap was worked away, this was also done by an external party who took ownership of the waste stream as well as the profits arising from the processing. Sylvania, a commercial waste processor which runs scavenger plants between chrome production facilities and their waste disposal heaps (Sylvania Platinum Limited, 2015), was cited as an example of a similar business model. The arguments advanced for having a commercial waste processor take over the waste stream were similar to that of enlisting OEMs.

4.4.2.3 Role of Third Parties

In the discussion thus far, mines and OEMs or commercial waste processors have been identified as the primary partners of the university. Nevertheless, according to the literature, these are unlikely to be the only entities of interest in technology commercialization and transfer process. Both respondents and literature indicated that other entities, such as transfer offices and other commercial research institutions, are also likely to play a role in successful commercialization and transfer (Ankrah et al., 2013; McAdam et al., 2012; Trencher et al., 2014). For instance, a quarter of respondents suggested that national science councils, such as the Council for Scientific and Industrial Research (CSIR) in South Africa, have more experience in applied research than university researchers and could be helpful research partners when early commercialization research needs to be done. Given the emphasis placed on technology scale-up, discussed in Section 4.4.1.1, this is likely to be a critical partnership.

Lastly, seven respondents mentioned that if the technology can be proven to be sufficiently simple to operate and robust, the opportunity to have communities take ownership of the technology would be welcomed as something to include in a mine's social and labor plan. However, four respondents mentioned that, even in such cases, the mine would have to ensure that the community service provider is able to handle the technology from a technical point of view and may need to help the organization to obtain certain permissions and approvals. An external technical oversight body may, therefore, still be needed. Two respondents noted that mines would still want to provide oversight to the community service provider because of the long-term liability associated with mining waste.

4.5 Conclusions

Mining waste is produced in large volumes and can be hazardous to the environment and surrounding communities. Valorizing mining waste will reduce the land footprint taken up by mining waste as well as the risks associated with it. Despite these advantages, the commercial implementation of such technologies is limited. This study set out to understand the drivers and barriers to waste valorization technology implementation, with a specific focus on the South African coal mining industry, and to understand the roles of different stakeholders in the industry as well as their potential roles in technology implementation.

The results of this research have shown that there are a variety of factors constraining and/or driving the adoption of waste valorization technologies within the South African coal sector. These factors, furthermore, tend to be highly interlinked, making for a complex landscape for implementation. For instance, the complexity of the technology impacts the development timelines as well as the cost of development, thus influencing the appetite that a potential implementer is likely to have for implementing the technology. This aspect, therefore, has technical, economic, and business implications. Results show that traditional techno-economics is likely to dominate the considerations in the transfer and implementation of waste valorization technologies in the South African coal mining industry. This, coupled with the narrow perspective on waste and valorization, is likely to make advocating for a technology based on environmental grounds alone unsuccessful. Robust business cases and demonstrations of technical feasibility and suitability are thus important factors for waste valorization technology implementation success in the sub-sector. Furthermore, while increasingly stringent regulations should, in theory, provide an incentive for the implementation of waste valorization technologies, the onerous and restrictive nature of the current regulatory landscape in South Africa serves to make the impact uncertain in practice. South Africa's regulatory environment, therefore, simultaneously enables and hinders the implementation of waste valorization technologies.

The study has also indicated that mining companies are unlikely to be implementers of environmental technologies since technology development is not part of their business model, and their technical support bases have eroded. Original equipment manufacturers (OEMs) and boutique waste processors are potentially better placed to be commercial partners in technology transfer from universities since they are the technical mediators for mining companies. They also service multiple mining companies and therefore have a bigger market for the technology than a single mining company. In addition, applied research organizations such as the CSIR may be helpful in technology development.

While the findings of this study are directly applicable to the South African coal mining industry, they could be extended to other mining sectors and geographic regions. The barriers and drivers and their relative significance will, however, vary to a lesser or greater extent, according to the specific risks associated with different commodities, ore bodies, and geopolitical contexts.

4.6 References

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Chapter five – Evaluation and selection

The evaluation and selection of technologies is an important step in the generalised mine waste valorisation technology design and development approach, as discussed in Chapter 2. In the proposed approach the Value Function method is used to evaluate the identified technology alternatives, leading to a decision recommendation after extensive decision-maker consultation and sensitivity analysis. Data for process evaluation is, however, scarce and the use of expert judgements as data inputs have been suggested. The reliability of this approach, however, remains unknown.

This chapter addresses Hypothesis 2 and its associated research questions, as shown below. Technical experts were asked to assess technologies based on the criteria and value functions discussed in 8Appendix C and these results were then analysed using distinguishability analysis and thematic analysis. This study was presented in the form of a paper titled *Validity of using expert judgements to inform multiple criteria decision analysis: Selecting technologies for sulfide-enriched fine coal waste reuse*. The paper then draws conclusions on the validity of using expert judgements as data for technical decision support and what information of use may be gathered in this manner.

Further details on the contribution of information derived from technology transfer interviews to the compilation of the set of criteria used in this study (Hypothesis 1, key question 3) is provided in 8Appendix C. As discussed in Chapter 4, this question was concerned with the role of an initial consideration of technology transfer issues in informing early-stage design and development.

Hypothesis 2:
Expert interviews and questionnaires can support technology selection and contribute positively to early-stage technology development/design for reusing mine waste in line with sustainable development principles.

1. Does conducting surveys with technical experts using questionnaires lead to the acquisition of data of adequate quality to enable defensible technology selection?
2. Does the supplementation of technical expert judgement surveys with interviews improve data quality?
3. How can data derived from interviews with technical experts add additional value to the early-stage technology design and development process?

Paper 2: Validity of using expert judgements to inform multiple criteria decision analysis: Selecting technologies for sulfide-enriched fine coal waste reuse

5.1 Abstract

Mine wastes are produced in large volumes and carry environmental and social risks. Reuse of these wastes can reduce or remove the associated risks. Mine waste reuse technologies are, however, largely undeveloped. Even where such technologies exist, the heterogeneity of mining and mineral waste materials as well as the associated lack of data must be overcome when selecting the most appropriate technology alternatives for reusing such waste. Expert judgement is an emerging technique for soliciting data to support decision-making, but the reliability of this technique has not been rigorously studied. The objective of this study was to assess the suitability of expert judgement input as data for decision support for selection of mine waste valorisation technologies, using sulfide-enriched coal processing waste as a case study. In this study multiple criteria decision analysis, specifically the value function method, was used and 17 criteria grouped into technical, social, economic, and environmental categories were considered. Experts provided questionnaire-type input to a decision rubric supported by linguistic constructed scales. The data for the overall group of experts were then compared with questionnaire and interview data from a subset of minerals design experts. The suitability of using the elicited expert judgement input to inform selection of preferred mine waste reuse technology options was investigated using distinguishability analysis. Approaches to improving the distinguishability of the expert judgement input included improving participant selection and conducting interviews. This study has indicated that the application of expert judgement to inform MCDA does not provide sufficient certainty for reliable decision-making. Improving the selection of experts as well as conducting interviews improved the distinguishability of the technology alternatives, but the goal of being able to support credible technology alternative selection was not reached. Interview data showed that uncertainty and disagreement among experts were crucial concerns in cases where high variability was found. This indicates that expert judgement input must be used with care in cases of decision making under high uncertainty. Expert interviews did, however, lead to technical insights and provided direction for future technology development. This paper demonstrates that distinguishability analysis is a rigorous method for interrogating uncertainty when soliciting expert judgements for decision-support.

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5.2 Introduction

The mining industry provides the minerals and metals that support global economic vitality (Valero et al., 2018; Walton and Anderson, 2021; Watari et al., 2019). The process of mining, however, creates large volumes of waste which can be hazardous to local environments and people, through water contamination, soil contamination, air pollution and physical instability (Behum et al., 2018; Chen et al., 2021; Martin et al., 2002; McCarthy and Pretorius, 2009; Van Zyl et al., 2002). A potential long-term solution to the problems associated with mine waste is beneficially reusing it. This will allow for maximum possible utilisation of all the materials that are mined, as well as the energy and natural resources that were spent in mining. Reusing waste reframes the waste as a secondary resource and is in line with circular economy and resource efficiency principles whilst feeding into broader sustainability objectives (Bocken et al., 2016; Brady, 2016; Kirchherr et al., 2017; Suppes and Heuss-Aßbichler, 2021).

Few commercial technologies for reusing large-volume mine wastes (including tailings, overburden/waste rock and coal discards) currently exist, but several technologies are being developed (Amaral Filho et al., 2020; Barati et al., 2020; Benahsina et al., 2022b; Binnemans et al., 2015; Kotsiopoulos and Harrison, 2018; Veiga Simão et al., 2022; Zhang et al., 2019b). Many of these technology applications are focussed on the construction sector (Barati et al., 2020; Benahsina et al., 2022b; Veiga Simão et al., 2022), but some mine rehabilitation, agricultural and industrial technology applications are also being developed (Amaral Filho et al., 2020; Kotsiopoulos and Harrison, 2018; Zhang et al., 2019b). A wider variety of technologies are, however, needed to address the problem of mine waste on a global scale, due to the variety and variability of mine wastes. Developing technologies for reuse of mining waste is, however, notoriously difficult due to their heterogeneity (Broadhurst and Harrison, 2015; Hudson-Edwards et al., 2011; Kazadi Mbamba et al., 2012; Žibret et al., 2020) and the lack of relevant information such as on the thermodynamics and material interactions in the materials and processes (Petrie et al., 2007). This makes technology selection difficult since there is little information available on which to base process selection.

Several authors have explored overcoming data deficiencies by substituting modelling and analytically derived data with expert judgement input in decision-support contexts (Darende et al., 2021; Demirkan et al., 2022; Egilmez et al., 2015; Kamble et al., 2017). No rigorous way of interrogating the appropriateness of expert judgement input for decision support has been put forward, however. Distinguishability analysis, originally developed to assess uncertainty in environmental data for industrial process selection (Basson, 2004), provides an approach for assessing the validity of expert judgement data. Neither expert judgement nor distinguishability have, however, been applied to decision-making in the context of mine waste reuse.

This paper explores the feasibility of overcoming data deficiencies in selecting technology alternatives for reuse of mine wastes by using expert judgement inputs as a data source, using sulfide-enriched coal waste as a case study. It proposes a multiple criteria decision analysis (MCDA)-based approach for eliciting expert judgement inputs and uses distinguishability analysis for assessing the data validity. In doing so, it demonstrates an important check for expert judgement data input into decision support processes. This approach to data collection and validity testing is illustrated and tested by using technology selection for the reuse of South African sulfide-enriched fine coal mine waste as a case study. The approach should, however, be applicable to a wide range of technology selection decisions where information is scarce.

5.3 Expert judgement in decision support

5.3.1 Early-stage decision support: a need for data

Complex decisions such as technology selection in the early stages of design or technology development are often approached in a non-systematic or even satisficing way by practitioners (Ball et al., 1998, 1997; Eriksson and Kadefors, 2017; Kabiawu et al., 2016), which may lead to sub-optimal technology selection decisions being made. The normative way prescribed for making such decisions is identifying a number of alternatives, describing them to a similar level of detail and then making a decision based on a form of MCDA (Azapagic et al., 2006; Beaudrie et al., 2021; Lizarralde and Ganzarain, 2019; Petrie et al., 2007; Wunderlich et al., 2021). MCDA provides a framework for analysing complex decision problems with relatively large numbers of alternatives by formalising important criteria and allowing exploration of trade-offs in any given solution (Belton and Stewart, 2002; Lizarralde and Ganzarain, 2019). Descriptive literature has illustrated that it is feasible and desirable to do this (Darende et al., 2021; Kamble et al., 2017; Olabanji and Mpofu, 2020). MCDA is more expensive in terms of time, effort, and data charges than satisficing or other less rigorous approaches but is appropriate when the cost associated with development and the potential payoffs are both high.

A variety of MCDA tools have been used in technology selection, the most common being value function methods (Langhans and Schallenberg, 2021; Salo and Hämäläinen, 2010), the analytical hierarchy process (AHP) (Ibáñez-Forés et al., 2014; Olabanji and Mpofu, 2020; Promentilla et al., 2008) and distance-to-target methods, such as Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) (Darende et al., 2021; Ibáñez-Forés et al., 2014; Kamble et al., 2017). Bana e Costa and Vansnick (2008), however, made the point that the eigenvalue method used in AHP leads to problematic outcomes such as rank reversal[16]. Distance-to-target methods, such as TOPSIS, have also been found to give rise to rank reversal under certain conditions (García-Cascales and Lamata, 2012) and also suffer from accuracy problems (Çelikbilek and Tüysüz, 2020). Value function methods (or value theory) are advantageous because of their transparency and simplicity of use (Beaudrie et al., 2021; Cartwright et al., 2012; Langhans and Schallenberg, 2021; Salo and Hämäläinen, 2010; Stewart and Losa, 2003). Another advantage of value function methods for the context of this paper is the relative ease with which bias and bounded rationality is exposed and explored (Stewart et al. 2001; Stewart and Losa 2003). Multi-criteria value function methods are considered appropriate for discrete decision problems, as early-stage technology selection invariably is, in the minerals industry (Stewart et al. 2001). Regardless of the decision support method used, however, a defensible analysis must be based on data.

Data for technology design and development in the minerals industry is notoriously sparse due to the heterogeneity and variety of the minerals in a single ore and across ores as well as their interactions with process environments and each other (Broadhurst and Harrison, 2015; Petrie et al., 2007; Segura-Salazar et al., 2019; Žibret et al., 2020). This makes obtaining data from databases for chemical process modelling particularly difficult. Stewart, Basson and Petrie (2003) suggested obtaining data for minerals process design from environmental impact assessments (EIAs) and Life Cycle Impact Assessments. EIAs, however,

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[16] Rank reversal is a phenomenon in MCDA whereby the order of preference for alternatives (eg. A3>A1>A4>A2) is reversed when an alternative is either added or removed from the analysis (eg. A4>A1>A3). This violates the invariance principle (Utility Theory) (García-Cascales and Lamata, 2012). Bana e Costa and Vansnick (2008) calls this *Condition of Order Preservation*.

are expensive, apply to a fixed location, and can set expectations from communities due to the public participation requirements (Middle and Middle, 2010). They are therefore inappropriate to inform early project stages. In other technology selection examples, life cycle assessment (LCA) has been used to inform technology design and selection (Elginoz et al., 2022; Kamble et al., 2017; Rodríguez-Vallejo et al., 2019). One does, however, need feedstock- and process-specific data to inform the LCA model. While progress has been made in adapting LCA for use in the early stages of technology design and development, problems such as data availability, uncertainty and complexity still remain (Cucurachi et al., 2018; Moni et al., 2020; Steubing and de Koning, 2021). Implementation of these LCA methods is also likely to be time and effort intensive (Moni et al., 2020), especially in the context of multiple sustainability dimensions. A different potential source of information on process performance, that is often tapped in practice but less so in descriptive literature, is the experience and opinions of experts active in the field of mineral processing.

5.3.2 Expert judgement as data source

Expert judgement has been used as an input to guide policy development (Curtright et al., 2008a; Morgan, 2015), in risk assessment (Montibeller and Von Winterfeldt, 2015; Song et al., 2018), and in forecasting (Bolger and Wright, 2017). Stewart and Petrie (2006) used expert input to verify the process models that they applied to inform their decision making. Soliciting expert judgements to inform MCDA is also becoming more common, often to supply weights for criteria or to support criteria selection (Egilmez et al., 2015; Ibáñez-Forés et al., 2014; Lizarralde and Ganzarain, 2019). More recently, researchers have started using expert input as a data source on which to base decision analysis. Examples include the case of renewable energy technology selection for Turkey (Darende et al., 2021), selection of appropriate waste water treatment technologies (Kamble et al., 2017; Sadr et al., 2018) and supplier selection (Deng and Chan, 2011). Although the authors claimed that expert judgement input successfully aided decision support, they did not rigorously analyse the data's variance.

AHP and fuzzy techniques are commonly considered appropriate approaches for including expert judgement in decision problems because of their mechanisms for dealing with imprecision in human language (Demirkan et al., 2022; Egilmez et al., 2015; Janssen et al., 2010; Kamble et al., 2017; Promentilla et al., 2008; Saaty, 1990). Imprecision in human language is, however, only one of the sources of uncertainty introduced by expert judgement inputs. People are prone to various biases, of which the ones which are relevant to early stages of technology design and development are noted in Table 5-1. Some biases are errors of thinking, while others are errors due to experts' motivation (Montibeller and Von Winterfeldt, 2015). People may also have an imperfect understanding of a problem, make imprecise statements, struggle to concentrate, or simply disagree with each other (Bolger and Wright, 2017; Promentilla et al., 2008; Woudenberg, 1991). All these factors introduce variability and uncertainty into a decision problem, which may affect the appropriateness of the data for decision support. The authors, however, did not report making provision for the uncertainty caused by these factors (Darende et al., 2021; Deng and Chan, 2011; Kamble et al., 2017; Sadr et al., 2018).

Table 5-1 Examples of biases that may affect experts when their judgements are used as a data source for decision support (Montibeller and Von Winterfeldt, 2015; Nikander et al., 2014).

Bias	Type of bias	Mitigation
availability bias, where an event is considered more likely if it is easy for the expert to recall, which is linked to their personal and professional experience	Thought bias	Providing additional statistics and counterexamples may widen an expert's perspective
proxy bias, where proxy attributes are treated differently from fundamental objectives, often assigned more importance	Thought bias	It is better to not use proxy attributes, but if one must, it is advised to model the relationship between the fundamental and proxy, and then focus decision support activities on the fundamental objectives
desirability of options, which leads an expert to over-estimate or under-estimate values in a way that advantages their preferred alternatives	Motivational bias	Ways of encouraging accountability and structuring incentives for accurate results must be explored. Also, obtaining input from multiple experts should reduce the impact of an individual's personal motivational biases on the decision outcome.

5.3.3 Assessing the usefulness of aggregated expert judgements

Asking for the input of multiple experts is a way to reduce the impact of individual misjudgements and motivational biases (Montibeller and Von Winterfeldt, 2015). The resulting proliferation of data, however, presents a new problem: how to aggregate the expert judgements in a way that improves accuracy and makes the data useful. There are traditionally two ways of aggregating: behavioural or mathematical (Bolger and Wright, 2017).

Two popular methods for behavioural aggregation are the committee decision and Delphi methods (Bolger and Wright, 2017; Kamble et al., 2017; Woudenberg, 1991). A weaknesses of committee aggregation is that the results are subject to strong personalities and the airing of knowledge common to the group as opposed to specialist knowledge. Delphi methods suffer from strong pressure to artificial conformity through the structured feedback methods (Bolger and Wright, 2017; Woudenberg, 1991). It is therefore uncertain whether the results from these aggregation methods are superior to any given expert's individual judgements.

Mathematical aggregation on the other hand, commonly involves simple arithmetic operations such as calculating the averages or weighted averages of experts' judgements (Bolger and Wright, 2017; Darende et al., 2021; Keeny and Raiffa, 1976). Mathematical aggregation, however, assumes independence between experts, which might not be the case, since experts may have similar backgrounds and biases (Wilson, 2017). This must be addressed through careful expert selection. The method also assumes that multiple expert judgements will average to a more accurate judgement than any individual expert judgement. Keeny and Raiffa (1976) suggested improving the likelihood of getting accurate results by weighting expert judgements according to the perceived expertise of an expert. Bolger and Wright (2017) and Morgan (2014), however, caution that one needs to have good reason for weighting expert opinions when aggregating, since equal weighting has been shown to be superior in most circumstances. Assessing the accuracy of expert judgements is sometimes done by attributing weights to experts based on their performance on 'seed questions', the answers of which are known, (Bolger and Wright, 2017; Morgan, 2014). This method's effectiveness and accuracy are still open to debate, however, given that seed questions are fundamentally about something that is knowable in the present, but experts are often asked to forecast or estimate unknown, complex scientific quantities (Morgan, 2014). A possibly less obvious problem with mathematical aggregation is that the averaging out of diverging data may mask important differences in experts' judgements (Morgan, 2015). When experts do not agree on the properties of an alternative, the resulting data may be too uncertain or variable to support clear decision making.

Distinguishability analysis, developed by Basson (2004), provides a way to quantify the level of uncertainty in the data and help determine whether the data are appropriate to inform decision support. It adapts aspects of more advanced methods in the outranking decision school that account for uncertainty to produce a single indicator that measures whether the data are sufficient for distinguishing alternatives (Basson, 2004). This was originally done in the context of early-stage industrial decision support using LCA or similar data (Basson, 2004). The method uses the concept of dispersion thresholds, which define the range within which a data point is likely to fall, and pairwise comparison of alternatives. It can therefore also be used to assess whether mathematically aggregated data allows for credible decision support by pairwise comparing the alternatives' average and standard deviation data on each criterion. A distinguishability score can then be calculated based on the number of instances of distinguishability. The score indicates in what proportion of cases an alternative is distinguishable from other alternatives. Although no immutable rules exist for what constitutes an adequate distinguishability score, Basson (2004) suggests that a score of above 0.5 is needed to conduct a ranking exercise. In other words, an alternative must be distinguishable from other alternatives more than half of the time to be used in decision support. It is important to note that this does not necessarily indicate whether the data are accurate, but it does indicate to what degree alternatives are distinguishable from each other based on the expert assessments. A description of how distinguishability analysis works can be found in section 5.5.3.1 of this paper.

5.4 Case Study: Finding uses for sulfide-enriched fine coal waste

In this study, the elicitation of expert judgement input as a source of data as well as the approach of using distinguishability analysis to test the data's validity has been applied to the case of reusing South African sulfide-enriched fine coal waste. In South Africa, around 60% of run-of-mine coals are washed to produce higher quality coals (SACRSC 2011). This process also produces relatively large quantities of coal waste (20% of run-of-mine coal) comprising of both low-calorific value 'discard' waste and fine waste slurry (Reddick et al. 2007; SACRSC 2011). Despite having a coal content and calorific value similar to that of run-of-mine coal (Reddick et al., 2007), the fines are typically disposed of to land (SACRSC 2011). Apart from representing a loss of valuable coal, the fines also contain pyrite and thus pose a risk in terms of acid rock drainage generation and spontaneous combustion (Bian et al., 2010). Deposits of fine coal waste also generate dust and pose a risk of geophysical failure (Bian et al., 2010).

In order to remove the risks associated with the land disposal of this fine coal waste stream, researchers at the University of Cape Town have developed a process for separating fine coal waste into three streams by means of froth flotation (see Figure 5-1) (Iroala, 2014; Kazadi Mbamba et al., 2012). The use case for the recovered coal component is energy generation, while the sulfide-lean gangue can be used for a number of applications, such as fabricated soils and as neutralising barriers for co-disposal with coarser acid-generating material such as waste rock (Amaral Filho et al., 2020; Kotsiopoulos and Harrison, 2017). Due to its relatively high sulfide content (estimated sulfur concentrations are expected to range between 3% and 19%[17]), the sulfide-enriched stream will be required to be disposed of in a hazardous facility if it is not reused. Its hazardous nature also requires that a wider suite of potential uses than the typical construction materials must be considered. This paper's case study thus focuses on the reuse of the sulfide-enriched fine coal waste component. The decision-makers are the academics who have conceptualised and developed the multi-stage separation process for fine coal waste. They wanted to know what waste reuse technology options would be the best to further develop, to provide a complete suite of technologies for applying fine coal waste.

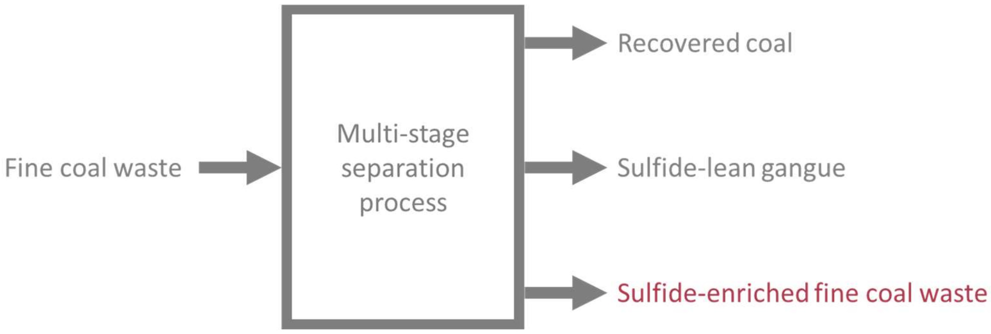

Figure 5-1 The multi-stage separation process that produces the sulfide-enriched fine coal waste stream on which the case study is based *(Iroala, 2014; Kazadi Mbamba et al., 2012)*.

Between 20 kt and 600 kt of the material could be produced annually in South Africa, given current industry practices. As the majority of the sulfur in the sulfide-enriched coal waste can be assumed to be in the form of pyrite (Moyo, 2018; Pinetown et al., 2007), technology alternatives for applying pyrite-enriched fine coal waste were initially identified by conducting a literature search on applications for pyrite. Peer-reviewed literature, industry sources, and patents were included in the results. The fourteen alternatives (Harrison et al., 2020) were then screened to include only the solutions that could potentially still be feasible for a low-grade (20%) pyrite content feed material, since this is a waste stream, and be useful in South Africa, which is where the waste is located. The seven solutions shown in Box 5-1 were subsequently taken forward for further analysis and screening in this case study.

Box 5-1 Technology alternatives for processing pyrite.[18]

Sulfuric acid production
Sulfuric acid and pigment production
Ferric sulfate production
Ferrous sulfate production
Chromium (VI) reduction
Soil amelioration
Cemented paste backfill

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[17] Further data are available in the supporting data file at Stander et al. (2022b). Link in Appendix D.

[18] More information on the technology alternatives can be found in the supporting data file Stander et al. (2023a). Link in Appendix D.

5.5 Method

The description of the study method is divided into three sections, as shown in Figure 5-2 below. The first section (*Problem structuring and initial analysis*) concerns the background work that was needed to structure the decision analysis approach and create a framework that can be used to elicit expert judgements. The second section (*Data set creation*) concerns the creation of the data sets that are used to investigate the use of expert judgements as a data source in decision support. Data set creation is discussed under questionnaires, expert selection, and interview question selection. The third section (*Analysis methods*) concerns the methods used to analyse and compare the data sets.

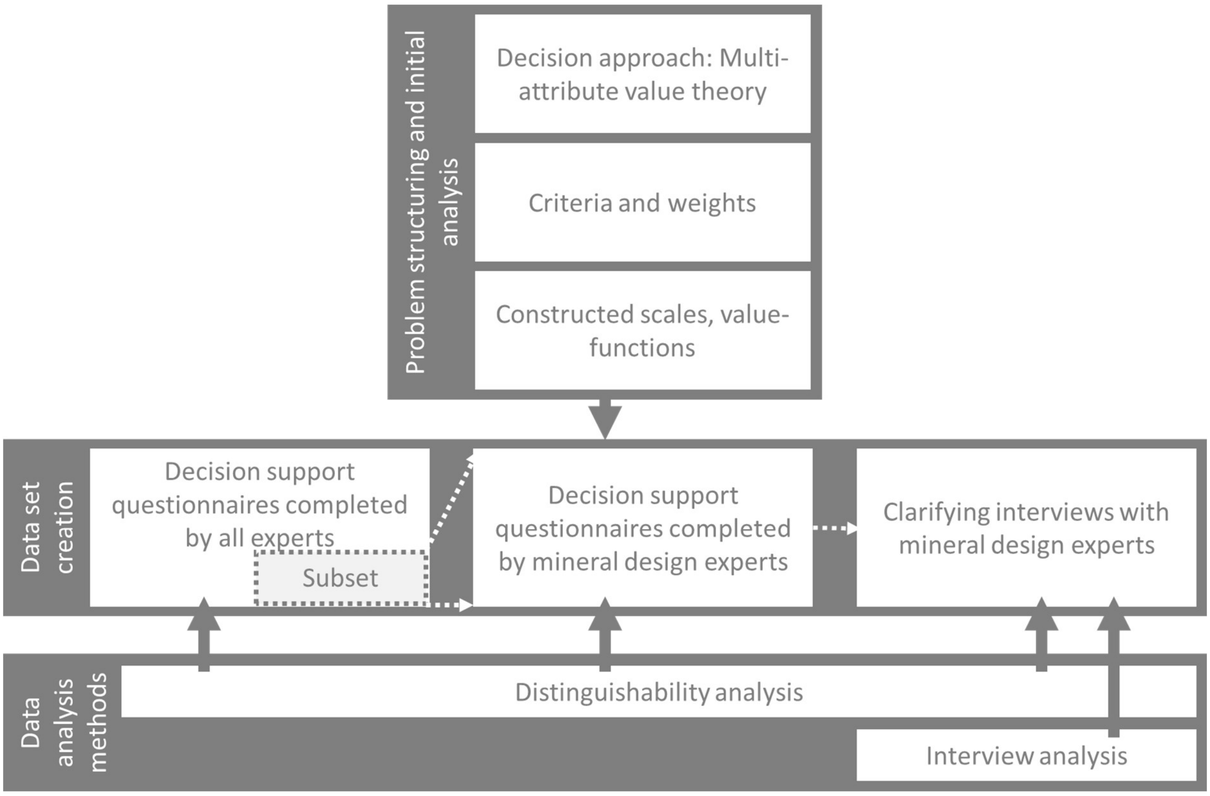


Figure 5-2 A schematic of the study method.

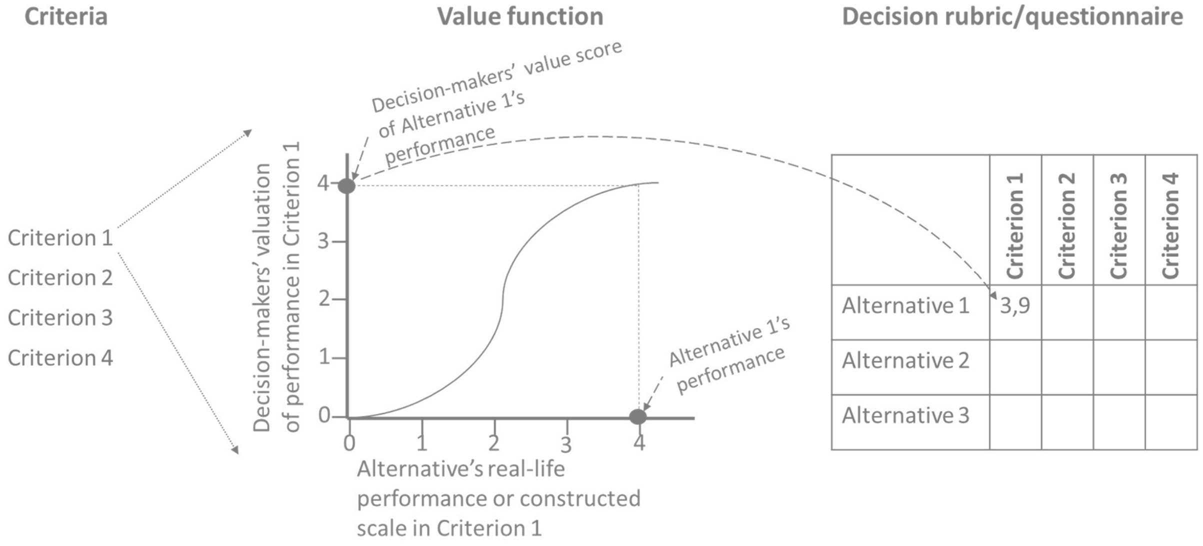
5.5.1 Problem structuring and initial analysis

The initial problem structuring elements, such as problem description and identification of uncertainties, have already been discussed in the introduction and case study section above. What follows are some of the important aspects that are needed to understand the decision-making approach, criteria selection and operationalisation, as well as what alternatives were evaluated.

5.5.1.1 Decision approach: Multi-attribute value theory

Multi-attribute value theory (a.k.a. value function methods) was used as the decision support framework. This approach involves the identification of the values of decision-makers and stakeholders and then converting those to an appropriate set of criteria, which is described and operationalised by value functions (Belton and Stewart, 2002). Value functions attempt to capture the value that a decision-maker attaches to the performance of an alternative on a criterion, as illustrated in Figure 5-3. A value function is developed for each criterion and the performance of each alternative is then evaluated and placed on the value function, so as to obtain a value score for that criterion (Belton and Stewart, 2002). In this way, the performance of an alternative is linked to decision-maker values and transformed into numerical data, which can be used to compare the performance of alternatives.

To be able to compare alternatives across and between criteria, it is necessary to know how decision-makers value the criteria relative to each other within the value ranges relevant to the decision problem. To achieve this, the criteria are weighted using formal methods that reduce bias and improve consistency. Aggregation of value scores and weights can be done using several methods, but the weighted sum method for aggregation is common (Belton and Stewart, 2002) and was used in this instance. It is shown in Equation 1 below.



	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Alternative 1	3,9			
Alternative 2				
Alternative 3				

Figure 5-3 A schematic of translating performance scores in individual criteria into value scores using a value function.

$$OS_A = \sum_{C=1}^{n} VS_{AC} W_C \tag{1}$$

OS = Overall Score
VS = Value Score of an alternative on a criterion
W = Weight of a criterion
A =Alternative A
C = Criterion C

5.5.1.2 Criteria and weights

In any decision scenario, criteria should be developed based on the values of both the decision-makers and stakeholders. At the early stages of technology development and design, however, a well-defined group of stakeholders cannot yet be identified, since these depend on the location and the type of solution contemplated. For example: communities and local governmental authorities are important stakeholders for the implementation of any processing technology, but these will change depending on the location. Interviews aimed at understanding the barriers and enablers to waste reuse technology transfer in the South African coal industry were conducted by Stander and Broadhurst (2021). These indicated that techno-economic factors are still of paramount importance to the industry and should therefore be included in this study.

Since too little is known about exact stakeholders at the early stages, the criteria used in this case study were identified using the techno-triple bottom line as foundation. This ensured that the criteria characterise the sustainability performance of the technology alternatives as extensively as possible. Several pre-existing indicator sets (Azapagic et al., 2006; Bare, 2012; Global Reporting Initiative, 2016; IMA, 2001) were used as a starting point for crafting this case study's criteria. Care was taken to create a set of criteria that would be both as comprehensive and as simple as possible, as shown in Table 5-2.

Table 5-2 Criteria used to assess the technology alternatives and their normalised weights[19].

Technical	Simplicity of chemistry and process control	0.07
	System complexity	0.03
	Technical maturity	0.07
Social	Job creation	0.03
	Operating health and safety	0.07
	Community health and safety	0.1
	Skills development	0.03
Economic	Entrepreneurship	0.05
	Expected profitability	0.07
	Existing market	0.06
	South African deficit	0.1
	Scale of use	0.01
Environmental	Waste generation	0.11
	Mineral recovery	0.01
	Energy consumption	0.09
	Water consumption	0.09

Both the criteria and constructed scales (next section) were tested and refined with input from decision-makers, visiting academics and a decision-support expert. The decision-makers at the time were three senior academics associated with the Minerals to Metals Research Initiative within the University of Cape Town with backgrounds in minerals processing, bioprocess engineering, and chemical engineering. The visiting academics were one senior international bioprocess academic and a professor emeritus of mining. The decision-support expert was a senior academic at the Department of Statistics at the University of Cape Town. They were shown the decision-structure at different stages of its development and suggested improvements and changes.

Weighting of the criteria was conducted after the constructed scales and value functions were completed. In this case, the SWING weighting method, as described in Belton and Stewart (2002) was used during a weighting workshop held with the available decision-makers. It was chosen for its ease of use and considered appropriate, given that the results of different weighting methods have been shown to provide similar results (Pöyhönen and Hämäläinen, 2001).

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[19] The data can be found in both *Collection 1* and *Collection 2* Excel workbooks in Stander et al. (2022a). Link in Appendix D

5.5.1.3 Constructed scales and value functions

Five-point linguistic constructed scales where then developed for each criterion, both to encourage consistency of meaning across experts as well as to provide a starting point for value function creation. The constructed scale for the criterion *simplicity of chemistry and process control* is shown as an illustrative example in Box 5-2 below. These were developed such that the linguistic intervals would be wide enough to capture a technology's performance comfortably, while still being small enough that the technology alternatives' scores do not all fall in the same interval. These were subsequently provided to the experts as guidance for filling in the decision rubrics[20]. The constructed scales were an attempt to directly measure the attributes of interest rather than use proxy values thereby reducing proxy bias in the experts' assessments.

Box 5-2 The constructed scale for *simplicity of chemistry and process control*, shown as an illustrative example.

0	1	2	3	4
The process will be difficult to control and be sensitive to fluctuations in the operating environment and feed compositions, but relatively low-level staff will be able to make adjustments under supervision/ guidance from experts.	The process will be relatively difficult to control and be sensitive to fluctuations in the operating environment and feed compositions, but relatively low-level staff will be able to make adjustments with guidance of experts available **from time to time.**	The process will require adjustments to be made to account for differing operating conditions or inputs, but relatively low-level staff will be able to make the adjustments.	The process will require some adjustments to be made periodically, but not constantly, and low-level staff will be able to make the process adjustments.	Process control will be simple and the process will be relatively unaffected by changes in operating conditions or feed compositions.

Value functions were then created based on the linguistic constructed scales during a session with decision-makers. The constructed scales were created with the purpose of producing linear value functions for simplicity but in some cases these needed correcting and became non-linear. The value functions were corrected in a separate session with decision-makers, who were asked whether the level of improvement between two points were valued equally to the level of improvement between two other points. For example, a question posed to the decision-makers would have been: "is the level of improvement between 0 and 1 the same, bigger or smaller than the level of improvement between 3 and 4?" If the answer was that it differed, the question would be followed up with 'how much'? These were then checked between different points, such as 0 and 2 and 1 and 3, etc. to ensure consistency and that the value function is accurate throughout. All value functions were created such that a score of '4' is preferable to a score of '0'. An illustrative example of a corrected value function is shown in Figure 5-4 below.

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[20] The constructed scales can be seen in the supporting information (Stander et al. 2022a).

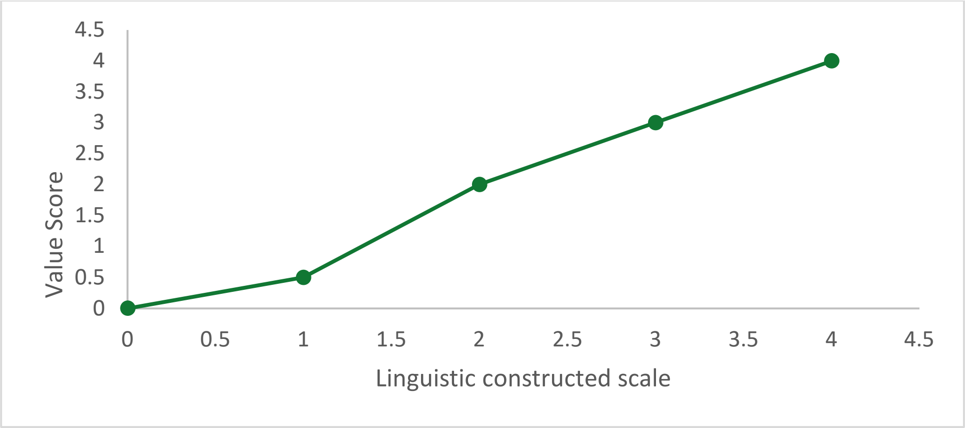

Figure 5-4 The value function of simplicity of chemistry and process control**. It is shown here as an illustrative example.**

5.5.2 Data set creation

As indicated in Figure 5-2, this study compares the distinguishability of three data sets of expert input: that of the larger expert group, the mineral design experts sub-group, and the post-interview data of the mineral design experts sub-group. For each of these a distinguishability analysis is done. The interview data presented an opportunity to identify some of the sources of variability in the data.

5.5.2.1 *Expert selection*

For data acquisition, 48 experts were canvassed of which 17 completed the decision questionnaires. In Table 5-3, the experts are classified according to their occupation at the time of completing the questionnaire. Of the 17 experts who completed the questionnaires, most had more than 20 years of experience. From that group four minerals design experts were identified of which two were academics and two were industry professionals who have worked at the interface of research and industry for many years. All four had more than 30 years of experience in the industry and were highly regarded by the decision-makers. Although the minerals design experts appear to be from similar backgrounds, their professional experience is quite diverse. One academic, for instance, recently transitioned from a career as an applied researcher, while the other had spent a lifetime in academia. The industry professionals, likewise, worked as general manager at a technology provider to mining and head of metallurgy at an African mining company, respectively.

Table 5-3 Experts who participated in the study categorised according to their profession at the time. The mineral design experts are a subset of the total respondent group.

Occupation	**Total numbers**	**Mineral design expert numbers**
Process engineers	4	
Academics	3	2
Applied researchers	3	
Industry professionals	4	2
Specialists*	3	

*Specialists were individuals who had specific expertise, such as experience with cemented paste backfill or soil amendments, and who filled in the questionnaire for only the technology they knew.

The number of experts who participated in the study may seem small, but the sample size is comparable to similar studies in literature (Ball et al., 1998; Beaudrie et al., 2021; Egilmez et al., 2015; Kamble et al., 2017; Nikander et al., 2014). This is because experts tend to be few in number and also be busy people who may not be able to contribute to such a study (Bolger and Wright, 2017). It is also worth pointing out that the aim of the study was not to get an exhaustive understanding of the opinions of all mining and minerals experts in South Africa on the technology alternatives, but rather to get insight as to what the performance of the alternatives is likely to be against certain criteria.

Expert judgements were aggregated mathematically, using simple averaging, in line with Bolger and Wright (2017) and Morgan (2014). Standard deviations were calculated as a measure of variability in the data. To avoid unnecessary inaccuracy, experts were allowed to leave answers blank when they felt that they did not know enough to answer a question well.

5.5.2.2 Interview question selection

To improve our understanding of the underlying reasons for variability in the data and hopefully the distinguishability of alternatives, interviews were conducted with the minerals design experts. During the interviews they were asked to explain their reasoning for assigning certain scores to alternatives on specific criteria. If they wanted to change the score upon further consideration, they were allowed to do so. Conducting interviews on every alternative and criterion would be time-consuming, however, and in some cases superfluous. The minerals design experts were therefore only asked about cases where all the scores were divergent, or where they seemed to disagree with the consensus, as shown in Box 5-3 below. In order to remove the pressure to conform to consensus, as in classic Delphi methods, they were only informed that the question fulfilled one of the criteria for inclusion in the interview.

Box 5-3 Criteria for inclusion of a scoring instance in an interview.

1 Spread - if all the scores for a given processing option on a specific criterion are different (eg. 0, 1, 2, 3), then all the minerals design experts were interviewed on that point.

2 Distinct groupings - if there were two distinct groups for a given processing option on a specific criterion (eg. 1, 1, 3, 3), then all the minerals design experts were interviewed.

3 Distance from average - if the score in question differs by more than 1 from the average for a given processing option on a specific criterion, then the specific minerals design expert only was interviewed.

5.5.2.3 Administering questionnaires and conducting interviews

The process of data elicitation was initiated by sending an email with the project abstract attached. Upon receiving a favourable reply, the decision-support questionnaires were sent along with an information pack and an informed consent form. The information pack aimed to describe the technologies to a similar level of detail, thereby mitigating availability bias. Both the information pack and the information received back from experts can be accessed in the supplementary data[21].

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[21] The data can be found in the *Collection 2 – Design engineers* Excel workbook in the *Time per question* worksheet in the supplementary data at Stander et al. (2022a). Link in Appendix D.

In three cases, the interviews were conducted using Skype, while the fourth interview was conducted in person. Interviews took between 23 min and 210 min each[22]. The questions were selected as discussed in Section 5.5.2.2. The interviewer asked questions like “The previous time you rated this alternative on this criterion you gave it a 3. Do you still agree with that?” This question was then followed up with a request to explain their reasoning.

Desirability of options bias was not considered relevant to this work, since the experts had no stake in which options performed better or worse and were therefore free to give their honest opinions.

5.5.3 Analysis methods

5.5.3.1 Distinguishability analysis

The treatment of the distinguishability analysis here is with the aim of explaining its practical implementation. The theoretical foundations of the approach are outlined in Basson (2004). The original distinguishability analysis used the idea of dispersion thresholds, which quantifies the range within which a criterion value is likely to fall. It is therefore a measure of the criterion value uncertainty and is used by outranking methodologies. In this case a constructed scale was used by multiple experts to rate technologies, the results of which were transformed using value functions and then aggregated using a simple averaging of the values. The standard deviation around the average value of responses[23] therefore gives an indication of uncertainty analogous to the dispersion thresholds used by Basson (2004). Standard deviations were therefore used instead of dispersion thresholds in the distinguishability analysis performed in this paper.

Figure 5-5 shows an illustrative example. It shows by pairwise comparison that technology 1 is indistinguishable from technology 2, 3, 4, 5, and 7, but distinguishable from technology 6. Therefore, in the example table below (Table 5-4), the index blocks that overlap between Technology 1 and Technology 2, 3, 4, 5, and 7 are each labelled with the distinguishability indicator ‘0’ to indicate indistinguishability. The overlap block between Technology 1 and Technology 6 is labelled with the distinguishability indicator ‘1’, to indicate distinguishability between those technologies. The example matrix is then completed by continuing the process for Technology 2 through 7. This process is repeated for all the criteria in the analysis and the average distinguishability between two alternatives can be calculated by averaging their distinguishability indicators for all the criteria.

A distinguishability index (Table 5-5) gives an indication of how distinguishable an alternative is from the other alternatives in the analysis for a single criterion. It is calculated by averaging all the distinguishability indicators associated with a technology (so in this case, the first line of Table 5-4 for the case of Technology 1 and the second line in the case of Technology 2, etc.). This criterion’s distinguishability index shows that Technology 1 is only distinguishable from one other technology, while Technology 6 is distinguishable from 5 others. This indicates that one can only be certain of the distinctness of Technology 6, and to some extent Technology 7, from the other technology alternatives such that they can be differentiated for the purpose of selection.

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[22] The data can be found in the Collection 2 – Design engineers Excel workbook in the Time per question worksheet in the supplementary data at Stander et al.(2022a) in Appendix D.

[23] The standard deviation around the average values of responses is very similar to the margin of error used to calculate 95% confidence interval, assuming a normal distribution, due to the small numbers of data points.

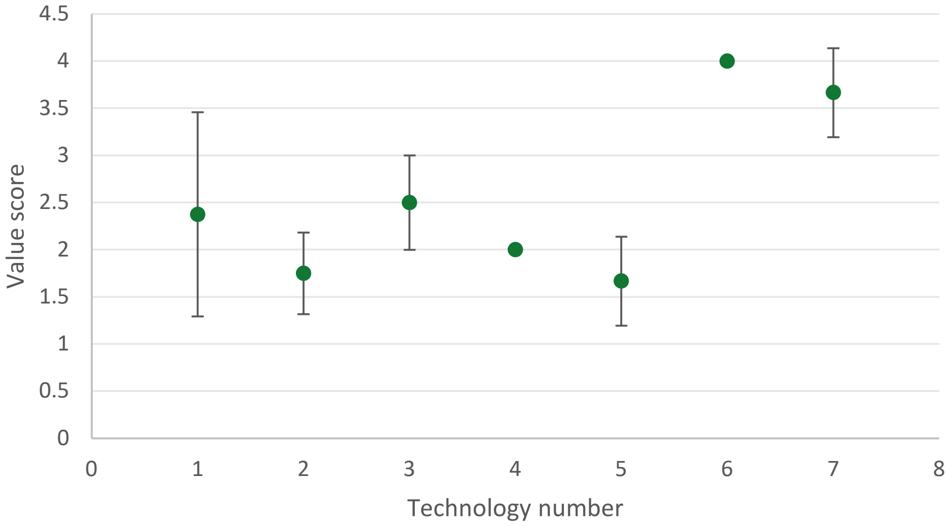

Figure 5-5 An illustrative example for demonstrating distinguishability analysis. The data represents the averages and standard deviations for seven technologies. The data compared is for a single criterion.

Table 5-4 Explanatory distinguishability analysis example matrix populated with distinguishability indicators derived from the data shown in Figure 5-5.

	Tech 1	Tech 2	Tech 3	Tech 4	Tech 5	Tech 6	Tech 7
Technology 1		0	0	0	0	1	0
Technology 2	0		0	0	0	1	1
Technology 3	0	0		0	0	1	1
Technology 4	0	0	0		0	1	1
Technology 5	0	0	0	0		1	1
Technology 6	1	1	1	1	1		0
Technology 7	0	1	1	1	1	0	

Table 5-5 Example distinguishability index for a single criterion.

	Distinguishability index
Technology 1	1/6
Technology 2	2/6
Technology 3	2/6
Technology 4	2/6
Technology 5	2/6
Technology 6	5/6
Technology 7	4/6

To complete the analysis, the process is repeated for every criterion and the distinguishability indexes averaged out to indicate how distinguishable a technology is from the other alternatives, across all the criteria on average. As mentioned in section 5.3.3, Basson (2004) considered 0.5 as the minimum for conducting a ranking exercise – that is, an alternative must be distinguishable from other alternatives more than 50% of the time to be able to be included in a decision support process that looks at the ranking of different alternatives with the aim of taking several alternatives forward for further investigation. While the 0.5 number is not definitive, it is reasonable to expect that an alternative be somewhat distinguishable from the other available alternatives if a ranking or selection exercise is to proceed.

5.5.3.2 *Analysis of interview data*

The interview data (Stander et al. 2022b) allows additional analysis, including the identification of instances of bias, uncertainty and non-ideal interaction with the model, as shown in Table 5-6 below. These instances were identified inductively (i.e. from the interview transcripts) and each instance was subsequently coded per technology alternative and criterion, allowing an overview of obvious sources of variation in the data.

Table 5-6 The thematic codes that were assigned to understand sources of variability.

Thematic code	Description
Model confusion (MC)	Instances where the minerals design expert struggled to keep different criteria separate were coded as model confusion. An example of such a case is where experts were asked to rate technologies on technical simplicity and then made statements such as “the technology is complex, but it is mature, so we know how to deal with that”.
Model ambiguous (MA)	This code was assigned when a technology’s potential implementation context did not neatly fit the constructed scale. An example is the South African deficit of cemented paste backfill – backfill is not something most mines would import or go to extra trouble to obtain, unless it was a commercial imperative, in which case they would use plentiful, cheap material nearby.
Feedstock confusion (FC)	Minerals design experts sometimes temporarily forgot that they were asked about the applicability of the pyrite-enriched coal waste feedstock to the technologies and answered the questions with regards to their preferred feedstocks instead. This was pointed out by the interviewer during the interview, but it may have influenced the previous round’s results. Such cases were marked with FC.
Constructed scale (CS)	There were a few cases where an expert did not base their scores on the constructed scale but rather assigned numbers without consulting the scale. By doing this they effectively reinterpreted the constructed scale to fit their own meaning.
Disagreement (D)	Cases were labelled with a D when experts disagreed regarding the outcomes or mechanism of an effect, leading to different scores.
Uncertainty/not knowing (U)	When experts expressed that they did not know the answer and struggled to assign a score, this was labelled with a U.
Technical details (T)	In many cases experts discussed the technical details of a technology alternative and speculated on aspects that implementation efforts would need to consider. This constituted development guidance and was marked with a T.
No discussion (ND)	Sometimes the expert considered the answer self-evident based on previous discussions and gave only short answers.

This data was then visualised in a technology alternative-criterion grid and overlaid with underlying variability data to allow for comparison. This grid was used to add up instances of each type of variability source. The variability sources were defined as Uncertainty/disagreement, which added up instances where experts expressed uncertainty or disagreed with each other. Model interaction as a source of variability was defined as all the cases where the experts found the model ambiguous, struggled to keep criteria separate, conceptually substituted their own feedstock, or defined their own constructed scales.

5.6 Results

The results section first reports the results obtained from the decision-support process, then the distinguishability analysis, finally followed by interpretation of the interview data.

5.6.1 Outcomes based on application of the decision support tool

The aggregated value scores that represent the decision recommendations are reported in Figure 5-6 below. The error bars on the graph shows that the differences between alternatives are overshadowed by the variation in the data. This illustrates the need for conducting distinguishability analyses to ensure that preference claims can be substantiated when they are derived from the results of decision analyses that are informed by expert judgement input.

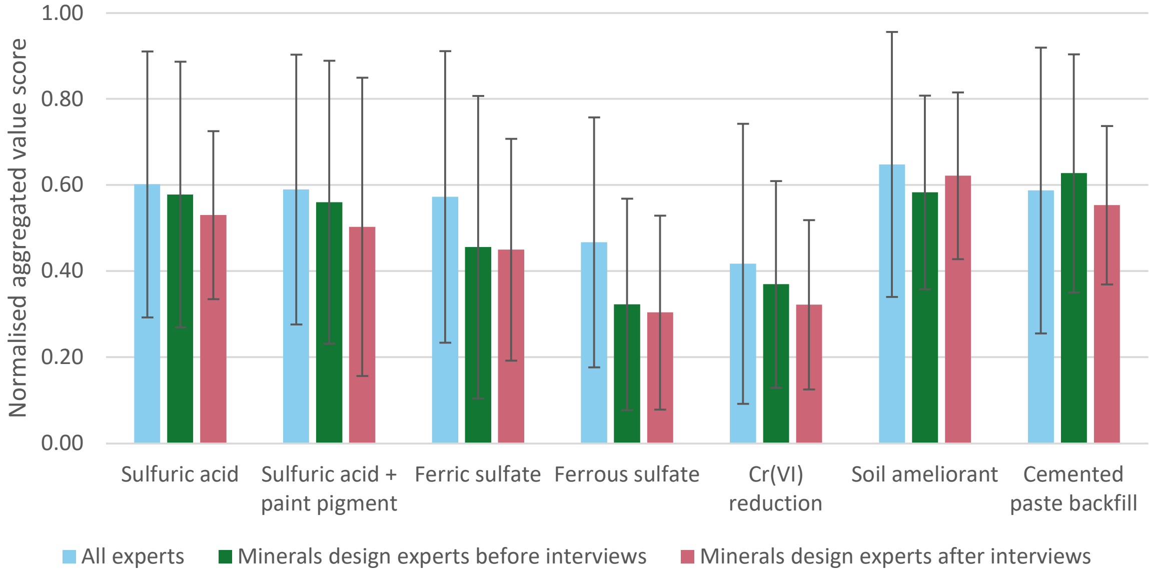

Figure 5-6 The aggregated value scores derived from data provided by all experts, minerals design experts pre-interview and minerals design experts post-interview. The y-axis has been normalised to a maximum of 1.

5.6.2 Distinguishability analysis

Before showing the distinguishability index, which reduces large numbers of data points to a single number, it is helpful to get a sense of the structure of the data through an illustrative example. Figure 5-7 below illustrate the high level of variability in the results by showing the scores given for each alternative by each expert on the *Simplicity of Chemistry and Process Control* criterion. Each mark represents an expert score of an alternative on a criterion and there are very few instances approaching consensus.

The distinguishability indices (Table 5-7) showed that the alternatives are mostly indistinguishable from each other when all experts' data were used, since the best performing technology alternative (Soil ameliorant) only achieved a distinguishability index of 0.17. Isolating the minerals design experts from the rest of the group improved the distinguishability scores (Soil ameliorant now improved to 0.33). Post-interview the distinguishability scores improved further, with the best performing achieving 0.36. The best performer is, however, still well below the 0.5 threshold set by Basson (2004) for conducting a ranking exercise.

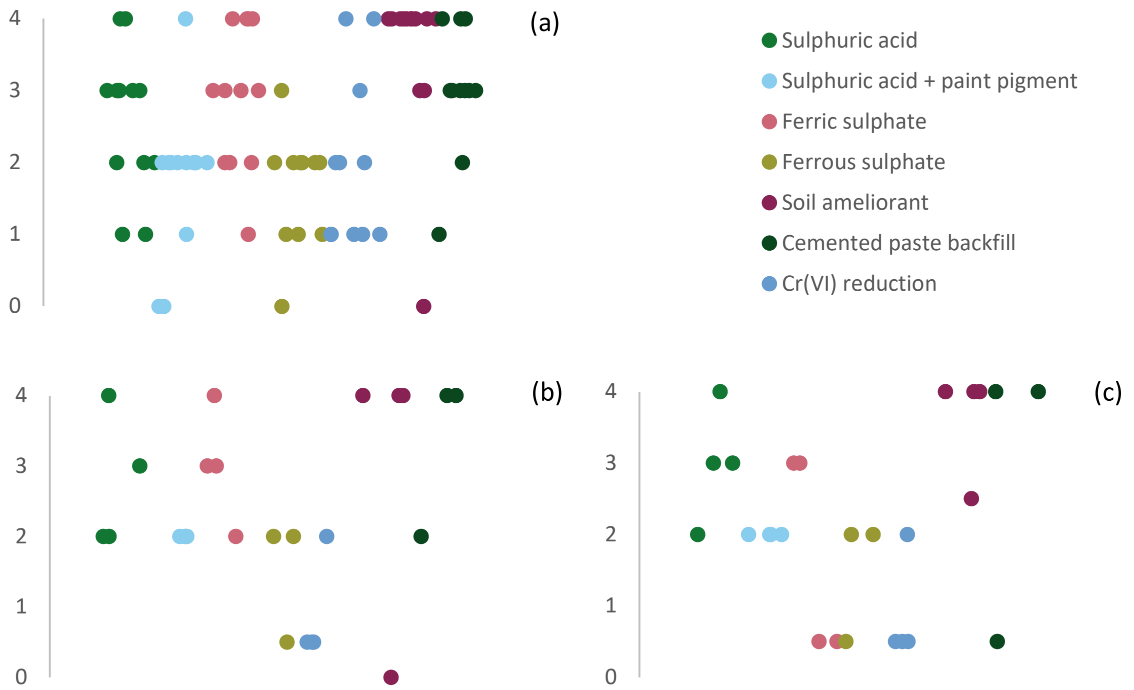

Figure 5-7 The scores that experts assigned technology alternatives based on the criterion simplicity of chemistry and process control: (a) the scores of all experts, (b) minerals design experts' pre-interview scores and (c) post-interview scores. The y-axis is in each case the value score and each dot represents an expert's score.

Even though the overall distinguishability between alternatives were still low after the interviews, individual criteria achieved relatively good distinguishability[24]. *Existing market* and *waste generation*, for instance, had an average distinguishability index of 0.52, while *energy consumption* had an average distinguishability index of 0.67. *System complexity's* average distinguishability index was 0.43, and all other criteria's average distinguishability indexes were below 0.4.

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[24] The data can be seen in the *Collection 2 – Design engineers* Excel workbook, in the *Normalised results* worksheet in the accompanying data file (Stander et al., 2022a). Link in Appendix D

Table 5-7 The distinguishability indices for the greater expert group and the minerals design experts sub-group pre- and post-interviews.

Technology alternatives	All experts	Minerals design experts Pre-interviews	Minerals design experts Post-interviews
Sulfuric acid	0.09	0.14	0.26
Sulfuric acid + paint pigment	0.05	0.20	0.24
Ferric Sulfate	0.01	0.13	0.19
Ferrous Sulfate	0.05	0.18	0.23
Cr(VI) reduction	0.07	0.23	0.33
Soil ameliorant	0.17	0.33	0.36
Cemented paste backfill	0.01	0.20	0.27

5.6.3 Interviews

Minerals design experts were interviewed to understand their reasoning when assigning scores. Interrogation of the interview data led to better understanding of the sources of the divergence. Table 5-8 below classifies issues identified during the interviews, whether technical information was given as well as the standard deviation associated with the technologies for any given criterion before the interviews. Blocks with no entry were not interrogated during the interviews. Areas with high standard deviations often correlate with instances where experts disagreed with one another or when they were unsure of the correct answer. Other sources of variability were found to be model parameter issues and experts' imperfect interaction with the model.

Table 5-9 gives a more quantitative indication of the influence of different contributors on the data variability. The contributors are grouped into indicators of underlying uncertainty/disagreement and the interaction of experts with the model. The former is a function of the decision problem and may not be diminishable by study design, while the latter may be improved by conducting interviews with experts and re-designing a model where misunderstandings or misuse are identified. In cases of high standard deviation, uncertainty/disagreement and model interaction accounted for equal numbers of instances. Table 5-9 also reports the number of instances where technical knowledge was shared during interviews, showing that experts freely discussed technical details for different criteria.

Table 5-8 The standard deviations of each alternative on each criterion with potential sources of variation identified from the literature superimposed.

	Sulfuric acid	Sulfuric acid + paint pigment	Ferric Sulfate	Ferrous Sulfate	Cr(VI) reduction	Soil ameliorant	Cemented paste backfill
Simplicity of chemistry & process control	⬜ D, U, MC, T	🟦 T	⬜ D, MC, T	⬜ _	⬜ _	🟥 U, MC, T	🟥 U, MC, T
System complexity	🟥 D, MC, T	🟦 T	⬜ MC, T	🟦 MC, T	⬜ U	🟦 _	⬜ _
Technical maturity	🟦 T	⬜ T	🟥 FC, CS, MA, T	⬜ FC, T	🟥 U, FC	⬜ _	🟥 FC, T
Job creation	⬜ _	🟦 _	🟦 _	⬜ _	⬜ _	🟦 _	⬜ _
Operating environment health & safety	🟥 CS	🟥 CS	🟥 D, MA	🟥 D, MA	🟦 _	⬜ _	🟥 D
Community health & safety	🟥 D, MA, T	🟥 D, MA, T	⬜ T	⬜ T	⬜ _	🟥 MA	🟥 T
Skills development potential	🟦 _	🟦 _	🟦 _	🟦 _	⬜ _	⬜ D, T	⬜ _
Entrepreneurial activity development	⬜ MA, T	🟥 MA, T	⬜ MA	⬜ MA	🟥 MA, T	🟥 MA	🟥 MA
Expected profitability	🟦 _	🟥 _	🟦 U	⬜ _	🟦 _	🟦 U	🟦 _
Is the product currently sold on the market?	🟦 T	⬜ T	🟥 D, T	🟥 D, T	🟦 _	🟥 U, CS, T	🟥 U
SA deficit	🟥 U, T	🟥 U	⬜ _	⬜ _	⬜ _	⬜ _	🟥 MA
Scale of use	🟦 _	🟦 _	⬜ _	⬜ _	⬜ D, MA	⬜ _	🟦 _
Pollution production	⬜ _	⬜ _	🟥 D, T	🟥 ND	🟥 U	⬜ _	🟦 _
Mineral recovery	🟥 _	⬜ _	⬜ ND	🟥 ND	⬜ MA, T	🟥 T	🟥 _
Energy consumption	🟥 T	🟥 U	🟥 T	🟦 _	🟦 _	🟦 _	🟦 _
Water consumption	🟥 ND	🟥 _	🟥 U, T	⬜ _	🟥 _	🟦 _	⬜ _

Key: D=Disagreement, U=Uncertainty/not knowing, MC=Model confusion (struggling to keep different criteria separate), MA=Model ambiguous (struggling to understand the question or place on constructed scale), FC= feedstock confusion, CS=reinterpreted constructed scale, T=Technical details including development guidance, ND=No discussion

🟦 0 < Std dev < 0.5	⬜ 0.5 < Std dev < 1	🟥 Std dev > 1

Table 5-9 The number of instances of different contributors to data variability identified in the interview data (grouped according to the variability of the underlying data that it describes).

	0 < Std dev < 0.5	0.5 < Std dev < 1	Std dev > 1
Uncertainty/disagreement	2	5	19
Model interaction	1	9	19
Technical information	5	11	19

The interviews did not only reveal reasons for variation, but also allowed the minerals design experts to provide their reasoning and technical input into the design and development process. Box 5-4 below shows some quotes from the interviews to illustrate the value of expert interviews. The quotes were lightly edited for readability.

Box 5-4 Quotes illustrating the value of interviews…

… for improving technical insight:

Expert D on ferric/ferrous sulfate production: "The problem is not so much the kinetics of it, or the size of it. The problem would be that it would generate too much acid as well. So, the pH would go down to 1 and then it would stop, basically. Or when it gets below 1 it would stop. And now if you had something to get rid of that acid [trails off]. There isn't an easy solution for what you're going to do with the acid that's generated. If you neutralise that acid, it's a huge consumption of lime and a huge cost and a bigger tailings than you started out with and then you get a relatively low-grade ferric sulfate."

Expert C on *technical maturity* of cemented paste backfill: "The cemented paste backfill technology may be very well established but if you're looking at it as a way of effectively disposing of your high sulfide component out of your process, in effect then you're looking to use a sort of encapsulated waste product. If you start going that way, then I think that now you'd actually move to a point where it's probably not well understood."

… for illustrating and exploring different points of view:

Expert Q on *community health and safety* of sulfuric acid: "I would say it's low risk because if there was a major failure of the scrubbing system, you would just shut the roaster down. So, for a short while there might be some SO_2 fumes going around but yeah, I'd say it's low risk to me."

Expert H on *community health and safety* of sulfuric acid: "Well, in terms of sulfuric acid production, you've just got to look at the Somerset West site. I mean, that has been a problem for a long, long time and that was due to SO_2 emissions. It was reduced; it was linked to solid waste management"

… for providing market insight

Expert Q on *market* of ferrous sulfate: "Yeah, as I say, Ferrous sulfate - it's almost a problem in this country to get rid of. Ferric sulfate does have a few more uses than ferrous sulfate, but I can't see it being a high value commodity. I'm not sure what the what the market would be for it in South Africa." … "If you suddenly needed ferrous sulfate, I would just go to pigment producers that produce titanium pigments. With them ferrous sulfate is a serious problem, because it discolours the pigment and they produce tonnes of it. You know, they pump it out to the sea unfortunately."

5.7 Discussion

5.7.1 Distinguishability analysis

The data obtained from questionnaires conducted with multiple experts did not lead to information that could be used to differentiate between and select the most suitable technology alternatives for processing and applying sulfide enriched fine coal waste, as evidenced by the very low distinguishability index numbers. The results have shown that the use of questionnaires (without interviews) as a data acquisition method for this type of complex decision problem cannot be accepted without interrogation by a distinguishability index or related method. This is disappointing, but not surprising, since high variability in data derived from expert input was seen in studies with other applications. Indicator valuation by experts, for instance, showed similar variation on expert judgements used for data acquisition and weighting (Darende et al., 2021; Demirkan et al., 2022; Egilmez et al., 2015). Curtright et al. (2008b) reported similarly variable data without interrogation in policy analysis. As Stewart and Glantz (1985) remarked, “The same lack of knowledge that produced the need for a study that relied on expert judgment virtually assures that a group of 'diverse experts' will disagree.”

Table 5-7 also shows that the smaller, more selective group of experts outperformed the larger group. While this may be due to sampling effects (smaller data sets are prone to underestimate the standard deviation of a population, assuming the data follow a normal distribution), the quantum of improvement in the distinguishability index is much larger than would have been expected given purely statistical effects[25]. We believe that this is due to improved data quality, since the minerals design experts sub-group was chosen for its appropriate knowledge and experience and not due to similar bias, since the professional backgrounds of the experts were diverse (see section 5.5.2.1).

Efforts to produce constructed scales where each number is associated with wide linguistic meaning to ‘narrow down’ the results from expert elicitation appeared to be ineffective. Even though the meanings of a score of ‘0’ and a score of ‘4’ were widely different, experts on occasion still assessed the same technology on the same criterion that far apart. According to Table 5-9, such occurrences are in many instances related to cases where the minerals design experts were uncertain of the true score or disagreed with each other. This shows that the use of constructed scales with large ranges of meaning were insufficient for overcoming inherent uncertainty in the decision problem or disagreements between the minerals design experts.

The minerals design experts’ data retained a high degree of variability post-interview. This indicates that excluding the statistical feedback mechanism that Delphi methods often use removes some of the pressure to conformity that Delphi methods are criticised for (Bolger and Wright, 2017; Woudenberg, 1991). The data can therefore retain variability where the disagreements/uncertainties are inherent in the decision problem.

Not all criteria had an average distinguishability score indicating complete indistinguishability, however. For instance, *Waste generation*, the most highly weighted criterion, had a distinguishability index of 0.52. If all the top weighted criteria had similarly high distinguishability analyses, a screening exercise may have been justified assuming extensive sensitivity analyses are undertaken to explore the impact of data variation. In this case, however, the other more distinguishable criteria were ranked much lower (at

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[25] The Monte Carlo analysis showing this analysis can be found in the supporting data (Stander et al. 2022a). Link in Appendix D.

number 5, 9 and 10 respectively[26]) and other highly ranked criteria had low distinguishability index scores (eg. *Community health and safety* at 0.05 and *SA deficit* at 0.19 (Stander et al. 2022a)). This indicates that restructuring of the decision problem would have been unlikely to improve overall distinguishability. Based on preliminary analysis[27], distinguishability can potentially be improved with a larger group of minerals design experts. The group would, however, have to be very large and likeminded to achieve a distinguishability index above 0.5.

Alternatives can be indistinguishable from each other for one of two reasons: In some cases, the means of the aggregated value scores are so close to each other that they are not distinguishable (for example job creation – none of the solutions seems to have been assessed to be large-scale job creators). In other cases, it is not the similarity of the means of the aggregated value scores that cause indistinguishability, but the large variability of the data. Whilst in neither case can one discern between the alternatives in a meaningful way, when all alternatives are rated similarly on a criterion, that indistinguishability is unlikely to be reducible and a case can be made for removing the criterion from the analysis. An example of such a case in this study is the data of the criterion *Skills development potential*. Indistinguishability brought about by high variability, on the other hand, is more likely to be reducible (and in need of reducing) and is where work is required to improve distinguishability. An example of this is the data of the criterion *Water consumption*.

5.7.2 Interviews

Conducting interviews improved the distinguishability index of the minerals design experts' data and provided rich information on the technologies under consideration. Conducting interviews with a few trusted experts therefore appears to be a better use of resources than conducting questionnaires with many experts. This is even though technical interviews can be time intensive: Expert D took three and a half hours to produce 50 data points. This is about 40% of the total data points required for this study. The other experts were faster, but the average time per data point was still almost 3 min. That equates to an average interview length of 6 hours for a decision problem with the same characteristics as this one. The time demands that this places on experts must be borne in mind at the outset of a project. It also makes going back to reconsider and re-design technology alternatives and get input on them again costly.

The interview data in Table 5-8 and Table 5-9 show that, in some cases, the uncertainty in the data can be reduced by well-designed studies that include interviews and can therefore correct some imperfect interactions between the experts and the model, such as feedstock confusion. In other cases, however, the variability in the data is related to inherent uncertainty in the data or disagreement between the experts. This shows that unequivocal results are unlikely to be obtained by conducting interviews alone. In cases of uncertainty and disagreement, data variability may be resolved by conducting quantitative analyses, but these may be expensive in terms of time, money, or other resources.

Alternatively, if more standard quantitative analyses are not an option, the data variability may have to be reduced by enlisting the judgement of the decision team. For instance, which expert's judgement to trust on a specific technology or criterion may be dictated by their professional experience. This approach, however, introduces another set of biases to the analysis: that of the decision team, and may not improve

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[26] The ranking of criteria can be seen in the supporting data (Stander et al. 2022a). Link in Appendix D.

[27] The study can be found in the supporting data (Stander et al., 2023b). Link in Appendix D.

the data accuracy. Alternatively, the decision team could do a sensitivity analysis to see how the differences in judgement are likely to affect the decision outcome. When multiple experts disagree over many alternatives and criteria, this task becomes formidable and may not simplify the decision problem to a point of being able to easily solve it.

It may be possible to achieve lower variability (and therefore better distinguishability), but less accuracy from experts who have a similar background and set of biases. This is analogous to the bias-variability trade-off in machine learning, where over-training an algorithm leads to biases, but under-training it leads to variability in output (Belkin et al., 2019). Machine learning, however, relies on large data sets and in this case expert knowledge is used precisely because of a lack of other trustworthy data. Study designers also have no control over experts' training, in the way that machine learning coders have. The better approach in this context therefore seems to be selecting the best 'quality' experts with the most relevant experience possible, based on their professional achievements and experience. Some diversity in the backgrounds of experts providing data, hopefully reducing bias, is preferable to lower variability in the data.

Despite not reducing data variability appreciably, interviews yielded useful technical background information for future technology development. Points of disagreement and uncertainty can be used to set future development priorities. Expert interviews may therefore still provide useful background information, even if the data they provide do not enable unequivocal decision support.

Two general observations were made about the process of eliciting value function data from experts. Firstly, it appeared that addressing technical criteria first helped the experts to imagine how the technology works before they embarked on scoring the other criteria. There were often long discussions about the technicalities of implementing a solution at the beginning of an interview followed by somewhat faster progress through the other criteria. The second observation is that the specificity of the decision model criteria and constructed scales were a helpful starting point for conversations. They encouraged the experts to think deeply about their assumptions and estimations of how the technology might behave.

Our interviews were not exhaustive, since only cases with high variability and outliers were discussed. More comprehensive interviews may have led to more distinguishable results. For example, when the *Simplicity of Chemistry and Process Control* of ferric sulfate production was rated originally, the scores were 3, 2, 4, and 3. When the interviews were done with the experts who rated 2 and 4, their scores changed to 1 and 1, which increased the standard deviation of the results. If the two individuals who assigned scores of 3 and 3 were also interviewed, clearer results may have been obtained.

5.8 Conclusions

Finding uses for mine waste is important, but very little is typically known about the waste, the novel technologies that might effectively process and apply it, or how the material and the technologies might interact. In this work, we assessed the suitability of overcoming data deficiencies in the early decision-stages of a project by soliciting expert judgements as a data source for formal decision support methods for the case of sulfide-enriched coal waste. The quality of this data was then assessed using distinguishability analysis and interview analysis. The use of distinguishability analysis in the context of expert judgement input is novel since it was originally developed to ascertain the quality of environmental data in the context of industrial process selection.

The distinguishability analysis results from all experts showed that the variability in the data was too great to enable clear distinction between alternatives. Using data from only the minerals design experts improved the distinguishability of the data. This shows that data from larger groups of experts do not necessarily provide more useful data than smaller, more select groups. Furthermore, in the case of the mineral design experts, distinguishability was further improved by conducting interviews in addition to questionnaires, as opposed to questionnaires alone. Interviews also provided additional insights into the technologies which could be useful in further development and design. Despite these mitigation steps, distinguishability remained relatively poor, making it difficult to select alternative technologies with an acceptable degree of certainty. Further analysis indicated that these uncertainties can be attributed to several factors, including the inherent uncertainty in the data or disagreement between experts. A preliminary analysis of the data also indicated that increasing the number of design experts is unlikely to reduce uncertainty to a significant extent.

It is clear from the results of this study that the application of expert judgement to inform MCDA must be treated with caution. This is an important outcome of this work, due to the recent increase in studies using expert elicitation for data acquisition in decision-making for sustainability contexts. Where possible, it may thus be more appropriate to use expert interviews in combination with more quantitative assessment techniques. These include laboratory tests, economic assessments, and LCA.

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5.10 Data statement

The data for this paper are available at (Stander et al. 2022a, 2022b, 2023a, 2023b). The survey and modelling data are freely available. Interview transcripts are embargoed, since expert anonymity cannot be guaranteed given the small pool of minerals experts in South Africa.

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Chapter six – Pre-feasibility study

In line with technology development and process design literature, pre-feasibility studies can be used to validate technology viability and identify development needs before detailed design and development commences. Whilst expert judgement did not provide a definitive answer on the preferred options, soil amelioration was consistently ranked as one of the top three alternatives and had the highest distinguishability index. Soil amelioration was therefore chosen as case study to explore Hypothesis 3 and its associated research questions, which can be seen in the published research paper titled *Using South African sulfide-enriched coal processing waste for amelioration of calcareous soil: A pre-feasibility study*.

To do this, a variety of literature sources were consulted, including technical literature, publicly available data obtained from governmental sources and publicly available navigation data. These data sources were consulted to assess aspects of technology viability that the technology transfer interviews indicated are of key importance. This therefore also forms part of the exploration of Hypothesis 1, key question 3, which considers how insight gained during technology transfer interviews can be used to inform technology design and development. These aspects included an assessment of technical viability, market analysis and rudimentary business case. Environmental, health and safety risks were also assessed to indicate the solutions' overall sustainability.

Hypothesis 3

Pre-feasibility studies which apply publicly available data and first-order calculations can play a key role in supporting the establishment of a sound business case and programme for the systematic development and implementation of mine waste valorisation technologies.

1. Based on requirements identified in the technology transfer work, what data and information are required for a pre-feasibility study to assess the technology viability at the early stages of technology development for mine waste reuse?
2. What input data and methods are suitable to derive this information?
3. How can the information derived from a pre-feasibility study guide design and development?

Paper 3: Using South African sulfide-enriched coal processing waste for amelioration of calcareous soil: A pre-feasibility study

6.1 Abstract

Coal mining in South Africa is an important economic activity but it generates large volumes of pyrite-bearing wastes in the form of fine coal slurry and discards. These pose a significant acid rock drainage risk. Researchers at the University of Cape Town have developed a multi-stage separation process which separates the coal slurry into different fractions: saleable coal, a sulfide-rich fraction, and a sulfide-lean fraction. This was done with a view to enhancing the material value and producing streams suitable for down-stream application to avoid disposal and concomitant environmental risks.

This paper explores the potential for using sulfide-enriched fine coal waste to ameliorate calcareous (enriched in calcium carbonate) and alkaline soils in the South African context, through a pre-feasibility study focusing on technical viability, local market applications and mine-to-market transport costs. Consideration is also given to direct environmental and safety risks and potential local commercial partners. The analysis shows that the solution is likely to be technically feasible, with potential markets in the livestock, field crop and horticulture sectors located in the provinces of the Northern Cape, Western Cape, North West, Free State, Limpopo and Mpumalanga. It was found that fewer than 13 commercial farms could likely be treated with the hypothetical sulfide-enriched coal waste produced in South Africa in a year. The transport costing analysis shows that the solution is likely to be uncompetitive with currently available soil ameliorants, but it may be competitive with waste disposal costs. A research agenda for further development of the solution is put forth.

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6.2 Introduction

The mining industry is known to generate large volumes of waste, which represent a loss of land and valuable resources as well as representing a significant human health and pollution burden (Behum et al., 2018; Chen et al., 2021; Hamberg et al., 2018; Martin et al., 2002; McCarthy and Pretorius, 2009; Owen et al., 2020; Politis et al., 2017; Van Zyl et al., 2002). One important environmental impact associated with mine waste from sulfide-bearing ores is acid rock drainage (ARD), which severely degrades land and water resources and presents health risks to aquatic life, livestock and humans (Geldenhuis and Bell, 1998; McCarthy, 2011; McCarthy and Pretorius, 2009; Park et al., 2019). ARD generation is also a long-term problem with no cost-effective solution once acid generation starts (Leathen et al., 1953b, 1953a; Martin et al., 2002). South African coal ores are sulfide-bearing (Eberhard, 2011), but the sulfide component lowers coal product quality and is therefore washed out with other gangue minerals (Moyo, 2018). Coal processing wastes, including discards and slurry waste, therefore tend to be enriched in sulfide and subsequently present an ARD risk (Fundikwa et al., 2016; Moyo et al., 2019). In South Africa around 2.5 Mtpa of slurry waste is produced[28].

Addressing ARD generation by reusing or repurposing of the sulfide-bearing wastes from ore processing is preferable to improved waste disposal and management practices because it removes the associated risk rather than mitigating it. Reusing mine waste also maximises the value of a mined resource. This is in accordance with resource efficiency and circular economy principles (Bocken et al., 2016; Kirchherr et al., 2017; Nzihou and Lifset, 2010; Suppes and Heuss-Aßbichler, 2021). Mine waste is thereby regarded as a secondary resource.

Researchers at the University of Cape Town's Chemical Engineering Department have therefore developed a process for separating mineral processing waste, such as tailings, into a recovered valuable product stream, a sulfide-lean stream and a sulfide-rich stream (Broadhurst and Harrison, 2015; Hesketh et al., 2010; Iroala, 2014; Kazadi Mbamba et al., 2012), as shown in Figure 6-1. In the application of this process to fine coal wastes, coal collectors such as dodecane or oleic acid are applied in a froth flotation process to recover coal as a saleable product in stage 1, followed by desulfurisation flotation using sulfide collectors such as potassium amyl xanthate (PAX) to generate the sulfide lean and sulfide-enriched stream in stage 2 (Iroala, 2014; Kazadi Mbamba et al., 2012). The coal product stream can be sold, increasing resource efficiency, while the sulfide lean stream can be used in construction, management of coarse mine waste or in the production of technosols (Amaral Filho et al., 2020; Firpo et al., 2015; Kotsiopoulos and Harrison, 2018, 2017). The sulfide-enriched stream, although much reduced in volume, is acid generating and would either need to be repurposed or disposed of at a hazardous waste facility.

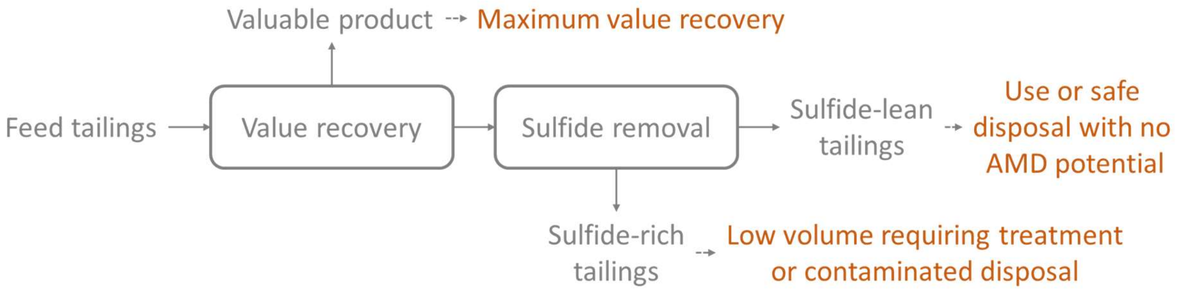

Figure 6-1: The multi-stage separation process for separating sulfidic ultra-fine waste into three streams for repurposing and reuse.

The dominant sulfide component in South African coals is pyrite (Moyo, 2018; Pinetown et al., 2007) and the sulfide-enriched stream may contain up to 16% pyrite, along with gangue minerals and residual coal (Iroala, 2014; Kazadi Mbamba et al., 2012). In a previous study (Stander et al., 2018), a variety of different alternatives for application of the sulfide-enriched material were identified and subjected to multiple criteria decision analysis, as part of a preliminary screening and selection process. One of the preferred options identified is the amelioration of calcareous and other alkaline soils (Stander et al., 2018).

This paper sets out to further explore the potential feasibility of using the sulfide-enriched stream as a soil ameliorant in the South African context. The aim of this pre-feasibility-stage study is not to undertake a

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[28] See Stander et al. (2022d) *Agricultural statistics for South Africa* spreadsheet, *Number of farms* tab in *Calculation for sulfide-enriched stream size* box for calculations. Link in Appendix D.

detailed cost-benefit or risk and economic feasibility analysis but rather to understand some of the context-specific issues associated with the preferred options that will need to be addressed if a solution is to be developed further in laboratory and/or field studies and ultimately implemented. Specific issues to be investigated were identified by a study on the barriers and enablers of transfer of mine waste valorisation technology to the South African coal industry (Stander and Broadhurst, 2021). Of particular importance are technical feasibility, market analysis, the business case, and identification of potential implementation partners (Stander and Broadhurst, 2021). These issues are therefore addressed in this study as well as health, safety and environmental risks. Finally, research and development requirements are identified.

6.3 Background

6.3.1 Characteristics of the sulfide-rich stream

The separation process in Figure 6-1 has been tested on a laboratory-scale, using a variety of coal processing wastes (including ultra-fine slurry wastes and finely ground discards) from different South African collieries (Iroala, 2014; Kazadi Mbamba et al., 2012; Magabane and Naidoo, 2011). The results of the laboratory-scale flotation test work have indicated that the relative deportment of key components (coal, ash and sulfur) to the flotation output streams varies quite significantly according to the mineralogical, petrographic and surface characteristics of the coal wastes, as well as the coal and sulfur collectors used (Broadhurst and Harrison, 2015; Kazadi Mbamba et al., 2012). Performance variabilities notwithstanding, in all case studies the two-stage flotation process resulted in a coal product with reduced ash and sulfur contents; a final tailings fraction with reduced sulfide content and negligible ARD risk potentials; and a sulfide-rich fraction comprising between 1% and 23% of the original slurry and between 32% and 84% of the feed sulfur and <25 % of the ash-forming minerals (Broadhurst and Harrison, 2015; Kazadi Mbamba et al., 2013, 2012). Table 3-1[29] shows the typical compositions of the sulfide-rich fraction derived from the laboratory-scale test work conducted to date. Results published in Fundikwa (2015: 44) and applied to results from Iroala (2014: 49)[30] indicate that between 40% and 50% of the sulfur in the sulfide-enriched stream in a flotation experiment was in the form of sulfide sulfur. Based on literature and in-house work at the University of Cape Town (Moyo, 2018; Pinetown et al., 2007), it can be assumed that the sulfide sulfur is predominantly present as pyrite (FeS2). Assuming that this is true on average, it would place the pyrite content of the sulfide-enriched coal waste stream at between 2% and 16% [31]. Throughout experimental work at UCT, the sulfide-rich stream has consistently been shown to be potentially acid forming (Iroala, 2014; Kazadi Mbamba, 2011).

Table 6-1: Typical sulfur and coal content of the sulfide-enriched material (Howlett and Marsden, 2013; Iroala, 2014; Kazadi Mbamba et al., 2012; Magabane and Naidoo, 2011; Moyo, 2018)**.**

	Sulfur	Coal	Ash
Maximum	19	68	60
Minimum	3	26	27

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[28] See Stander et al. (2022c) in the spreadsheet *Data for characterisation of s-rich*, in the *Flotation test results* tab. The numbers are found in the table labelled *Flotation test results*. Link in Appendix D.

[30] For detailed calculations see Stander et al. (2022c) and see the spreadsheet *Data for characterisation of s-rich*, in the *Flotation Test Results* tab. The results can be seen in the *Sulfur speciation in feed stream* table. Link in Appendix D.

[31] Calculations shown at Stander et al. (2022c) *Data for characterisation of s-rich* in the *Flotation test results* tab in the *Calculation of min & max pyrite expected in s-enriched material* box. Link in Appendix D.

Table 6-1 shows that coal is still a significant component in this sulfide-rich stream. The ash component is likely to consist mostly of kaolinite ($Al_2Si_2O_5(OH)_4$) and quartz (SiO_2) (Iroala, 2014; Kotelo, 2013; Moyo, 2018). For more detail on the composition of the gangue component, see the accompanying data[32]. Given the variable nature of coals and coal processing wastes, and the number of factors influencing the deportment of components, it is difficult to make generalisations about the compositions of the separated fractions, and each coal waste stream will need to be considered on a case-by-case basis. This is due to the variability of minerals between mines and even within the same mine (Moyo, 2018).

Although data on the sulfide-enriched coal waste fractions is limited, analysis of coal processing waste has indicated that these contain several metals in the minor (100-1000 ppm) and trace (<100 ppm) concentration ranges (Moyo, 2018). However, of these only thorium (Th) and Uranium (U) are significantly enriched in coal wastes relative to the average crustal abundance of these elements (Moyo, 2018). Other elements that may be enriched to a lesser extent include Ba, Ce, Mo and Ni. Chemical extraction tests have found, furthermore, that many of these elements are present in relatively inert forms. A preliminary assessment by Moyo (2018) showed that metals in coal processing waste pose a minimal to negligible risk to soil quality.

In terms of physical characteristics, researchers at UCT have encountered particle size distributions with D_{80} of between 220 µm and 68 µm in the slurry waste from coal mines (Iroala, 2014; Opitz et al., 2015). In practice the particle size distributions of sulfidic minerals will be in the range acceptable for flotation (D_{80} < 150µm), due to oversized slurry waste being resized for flotation (Jera, 2013).

6.3.2 Soil Amelioration using pyrite.

The soil required for healthy growth differs between plants, since plants are adapted for specific environments such as wetlands and deserts. Despite this, there are some general soil characteristics that tend to be better for growing a variety of food crops, including good soil structure, sufficient cation exchange capacity, neutral pH, good nutrient content and high organic matter content. The term "soil ameliorant" is generally used to refer to substances or processes that improve the physical properties of soil, such as structure, as well as chemical properties, such as pH and metal toxicity (Bradshaw, 1997; Castelo-Branco et al., 1999; Liebenberg-Weyers, 2010; Wong, 2003). Ameliorants[33] often include plant nutrients as well, as in the case of organic matter, which improves soil structure as well as nitrogen, phosphorus and iron availability (Foth and Ellis, 1996).

6.3.2.1 The role of pyrite in soil amelioration

Pyrite can be used to treat soil that is calcareous (Castelo-Branco et al., 1999; Rai et al., 1982), alkaline or that suffers from iron or sulfur deficiency (Shamim et al., 2010), thereby leading to increased crop yields. Pyrite is useful for soil amelioration according to three mechanisms: (i) it supplies a deficient nutrient to the soil in the form of sulfur (Shamim et al., 2010); (ii) it improves the soil structure by replacing adsorbed

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[32] See the data at Stander et al. (2022c) in the spreadsheet *Data for characterisation of s-rich* in the *Major mineral content* tab. Link in Appendix D.

[33] Ameliorants are as opposed to fertilisers, which tend to refer to concentrated substances that are added to soils to address specific nutrient deficiencies (Abadía et al., 2011; Banath and Holland, 1976; Edis and Norton, 2012; Edmeades et al., 2005; Mortvedt, 1991). Soil ameliorants therefore have a broader function than simply adding nutrients to soil, although they typically do that as well.

sodium ions on clay particles with liberated calcium ions (Somani, 1986; Vlek and Lindsay, 1978); and/or (iii) it makes certain nutrients such as iron in the soil more accessible by reducing the pH of the soil (Castelo-Branco et al., 1999; Rai et al., 1982; Wallace et al., 1976).

6.3.2.1.1 Reducing pH

Alkaline soils tend to be characterised by low nutrient availability, both due to the low solubility of many compounds at a high pH in the case of calcite-induced alkalinity (Foth and Ellis, 1996). Nutrients such as nitrogen, phosphorus and iron are deficient at high pH (Foth and Ellis, 1996). Pyrite can be added to soil to reduce the pH, since sulfuric acid is formed as a product of oxidation reactions, as shown in equations 1-6 below (Ayers et al., 2009; Schippers et al., 1996; Schippers and Sand, 1999; Tao and Dongwei, 2014). The overall reaction (Eq. 1) shows the acid generating nature of the pyrite oxidation reaction, which involves air and water.

$$4FeS_2 + 15O_2 + 14H_2O \rightarrow 4Fe(OH)_3 + 8{SO_4}^{2-} + 16H^+ \quad (1)$$

The oxidation reaction occurs via several intermediate reactions occurring at different rates and giving rise to intermediate products as per the reactions in Eq. 2 to Eq. 6:

Direct oxidation by oxygen to generate soluble Fe(II), sulfate and acid (slow):

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4{SO_4}^{2-} + 4H^+ \quad (2)$$

Oxidation of Fe(II) by oxygen to generate ferric ions (very slow in sterile environments, but accelerated by naturally occurring bacteria):

$$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O \quad (3)$$

Oxidation of pyrite by ferric ions to generate thiosulfate salts (relatively fast in acidic environments):

$$FeS_2 + 6Fe^{3+} + 3H_2O \rightarrow S_2{O_3}^{2-} + 7Fe^{2+} + 6H^+ \quad (4)$$

Oxidation of thiosulfate salts into sulfate (accelerated by *Thiobacillus thiooxidans*):

$$S_2{O_3}^{2-} + 8Fe^{3+} + 5H_2O \rightarrow 2{SO_4}^{2-} + 8Fe^{2+} + 10H^+ \quad (5)$$

Precipitation of ferric ions as ferric hydroxide at weakly acidic, circumneutral and neutral pH ranges:

$$4Fe^{2+} + O_2 + 10H_2O \rightarrow Fe(OH)_3 + 8H^+ \quad (6)$$

In highly calcareous soils, neutralisation may require the application of large volumes of pyrite, due to the buffering effects of calcite, as shown in Eq. 7.

$$H_2SO_4 + CaCO_3 \rightarrow CO_2 + H_2O + Ca^{2+} + {SO_4}^{2-} \quad (7)$$

However, case studies have shown that pyrite still has a positive impact on plant growth, even where the buffering effect of calcite resulted in no change in the bulk soil pH after a number of weeks or years (Castelo-Branco et al., 1999; Shenker and Chen, 2005). To explain this phenomenon, localised neutralisation was postulated, wherein pyrite creates pockets of neutral soil where nutrients are plant available. A method for adding pyrite to soils that takes advantage of localised changes to soil conditions and requires lower application rates is that of band application. Band application is the application of lines, or bands, of ameliorant rather than even distribution across a field. This can improve local nutrient availability without needing to change the bulk soil pH. Band application has been found to be effective in literature for applications for calcareous soils (Marsolek and Hagstrom, 1982; Shenker and Chen, 2005; Wallace et al., 1976).

6.3.2.1.2 Improving soil structure

A good soil structure is important for proper drainage of soil as well as for ensuring that sufficient water and air is retained in the soil for the use of roots, seeds and soil microbes (Foth and Ellis, 1996; Malherbe, 1948). Soil takes on a beneficial structure when clays are flocculated (Abbaslou et al., 2020).

With calcareous sodic soils, however, the high exchangeable sodium content causes soil colloids to deflocculate and disperse, negatively affecting soil structure (Abbaslou et al., 2020; Edelstein et al., 2010; Foth and Ellis, 1996). Gypsum is normally added to improve soil structure in such cases, since it dissolves into soil water and the liberated calcium ions then replace some of the excess sodium ions adsorbed on clay particles, improving clay flocculation and therefore soil structure (Abbaslou et al., 2020; Foth and Ellis, 1996). Similarly, adding pyrite to such soils can liberate calcium ions by way of the neutralisation reaction between calcium carbonate and the sulfuric acid formed, as shown in Eq. 7.

6.3.2.1.3 Addition of sulfur

Since sulfur is a key component of protein, plants, particularly protein-rich plants, need large amounts of sulfur for healthy growth (Malherbe, 1948). Sulfur is absorbed in the form of sulfate ions dissolved in water (Edis and Norton, 2012). Around 3 to 5 mg/ℓ sulfate is normally sufficient for plant growth (Foth and Ellis, 1996). When sulfur is deficient, fertilisers such as gypsum, superphosphate, and ammonium sulfate are added to soils. Several authors have also used pyrite to improve the sulfur availability in soils (Banath and Holland, 1976; Metson, 1972; Shamim et al., 2010; Tiwari et al., 1985).

6.3.2.2 Factors influencing the effectiveness of pyrite

The effectiveness of any specific pyrite-bearing material in ameliorating soils will be influenced by the rate of pyrite oxidation, the application rate, as well as the physiochemical properties of the material.

6.3.2.2.1 Pyrite oxidation rate

Pyrite tends to slow-release the sulfur and iron nutrients to the soil (Banath and Holland, 1976), due to the time involved in oxidation. This is considered advantageous, since it reduces the need for repeated application (Marsolek and Hagstrom, 1982; Metson, 1972). Nevertheless, for pyrite to be an effective soil ameliorant, it needs to oxidise fast enough to achieve circumneutral pockets of soil, because it is the acidity and nutrient release upon oxidation that improves soil properties. Fortunately, pyrite oxidises much faster in soil than would be expected from chemical oxidation alone (Vlek and Lindsay, 1978). It is believed that many of the reactions involved in the oxidative dissolution of pyrite in soils, such as those represented by Eq.'s 3-5 in the Section 6.3.2.1.1, are microbially mediated (Banath and Holland, 1976; Somani, 1986; Vlek and Lindsay, 1978). This is despite alkaline pH values being unfavourable for most known sulfur oxidisers under well-studied environments such as heap leaching and ARD generation (Banath and Holland, 1976; Somani, 1986). The microorganisms' soil microenvironments are thought to be sufficiently acidic for them to function or, alternatively, it is believed that some *Thiobacillus sp* may be tolerant of alkaline environments (Banath and Holland, 1976; Somani, 1986).

The rate of oxidation and dissolution will also be affected by the particle size of the pyrite, the rate increasing with increased particle surface area (Vlek and Lindsay, 1978). Castelo-Branco et al (1999) for instance used material with a D_{80} of 30 µm and Banath and Holland (1976) found that material with a D_{80} of 20 µm released the iron and sulfur at a rate comparable with conventional sulfur fertilisers, such as gypsum, and appreciably quicker than material with a D_{80} of 53 µm.

Pyrite oxidation requires water and oxygen as raw materials for the oxidation reaction and for microbial respiration (Schippers et al., 1996). Application of pyrite should therefore be damp and close to the surface of the soil, since soil aeration reduces with increased depth (Somani, 1986).

6.3.2.2.2 Application rates

The pyrite application rates reported in literature are shown in Table 6-2. Rates of between 5 t/ha and 67 t/ha were used to ameliorate calcareous soil, with higher rates being used for ameliorating cropland than for grazing. Orders of magnitude less of the material (0.2-0.4 t/ha) has been used when it is applied as a sulfur fertiliser.

Table 6-2: Reported pyrite application rates.

Paper	Purpose	Pyrite material application rates
Vlek and Lindsay, 1978	Improving the structure of calcareous sodic soil	26 t/ha[1]
Wallace et al. 1976	Ameliorating calcareous soil for soybean production	Between 34 t/ha and 67 t/ha
Castelo-Branco *et al.*, 1999	Remediating calcareous soil for grazing	5 t/ha
Tozsin and Arol, 2015	Remediating calcareous soil for wheat production	Between 7 t/ha and 23 t/ha
Tozsin, Arol and Cayci, 2015	ameliorating calcareous soil for growing wheat	Between 7 t/ha[1] and 25 t/ha[1]
Sharma and Swarup, 1997	Ameliorating alkaline soil	Between 7 t/ha and 13 t/ha
Banath and Holland 1976	ameliorating alkaline clayey sulfur-deficient soil for growing maize	Between 0.2 t/ha and 0.7 t/ha
Metson 1972	Sulfur fertiliser for grass-clover pasture on fine sand	Between 0.08 t/h and 0.7 t/ha
Tiwari, Dwivedi & Pathak 1985	Sulfur fertiliser for legumes on alkaline sandy-loam	Between 0.1 t/ha and 0.2 t/ha

[1] assuming application calculated for the top 20 cm of a 1.28 g/cm3 soil

As in the case of pyrite, gypsum application rates can also vary widely. For example, Sharma and Swarup (1997) used application rates of 30-40 t/ha for ameliorating alkaline soils, while Banath and Holland (1976) reported a maximum application rate of 670 kg/ha (0.7 t/ha). The table grape industry in Kakamas reportedly uses around 5-6 t/ha of gypsum once or twice per growing season to ensure proper drainage of the soil (personal communication).

6.3.2.2.3 Chemical properties of pyrite-bearing materials

As in the case of most waste streams, pyrite waste streams from mining sources also contain impurities. These could potentially be toxic to plants, depending on the types and levels of impurities and the material application rate. A pilot study in Portugal found that application of pyrite-containing waste from base metal operations at an application rate of 5 t/ha did not lead to toxic runoff, despite elevated levels of Cu, Pb and Zn in the waste (Castelo-Branco et al., 1999). This indicated that elevated metal loads do not necessarily imply environmental hazard, at least over the medium term. Application of this waste also did not have any negative health effects on grazing animals during the three-year trial period (Castelo-Branco et al., 1999).

6.4 Methodology

The review and discussions in Section 6.3 provide evidence of the technical feasibility of using sulfide-enriched coal waste as a soil ameliorant. This study further explores the potential feasibility of this application in a local context. This is done by considering potential market opportunities and costs, as well as health, safety and environmental (HSE) risks, as described in Sections 6.4.1-6.4.3 respectively. Based on the outcomes of a previous study on the barriers and enablers of transfer of waste valorisation technologies to the South African mining industry (Stander and Broadhurst, 2021), these factors are all considered of key relevance to the establishment of a sound business case for the development and uptake of downstream application for bulk mine waste streams. Also shown to be of relevance is the identification of industry partners for the development and implementation of commercial solutions (Stander and Broadhurst, 2021). This is discussed in Section 6.4.1.3.

6.4.1 Market opportunity analysis

The analysis of market opportunities included an identification of potential market applications (Section 6.4.1.1) and size (Section 6.4.1.2), as well as local companies with interests in the soil amelioration business (Section 6.4.1.3).

6.4.1.1 Identification of potential markets

The market for soil ameliorants is agricultural since the soil is improved with the aim of achieving a secondary outcome: increasing crop yield or land's carrying capacity. The first step in the identification of potential market applications entailed the identification and location of soils that might benefit from pyrite addition. This was largely based on the book Soils of South Africa by Martin Fey (2010), which classifies calcareous and other alkaline soils as silicic, calcic or vertic soils.

The agricultural activities taking place on those soils were then identified using agricultural data from the Census for Commercial Agriculture conducted in 2017 by South Africa's national statistics bureau, Statistics South Africa (Statistics South Africa, 2020a). In accordance with this data, agricultural activities were categorised as livestock, field crops and horticultural crops. Only grazing was considered in the livestock category, since farming poultry and pigs do not require large land footprints like cattle-, sheep-, goat- and game grazing do. This data was graphically displayed by colouring provincial maps of South Africa (provided by Municipalities.co.za 2021) on a municipality level based on agricultural data and overlaying those maps on to the soil maps. Agricultural activities in areas that overlap with soils of interest are then suggested as potential markets for the sulfide-enriched stream, based on the understanding that specific agricultural activities' productivity may be increased, or fertilisation regime simplified, by the application of sulfide-enriched materials to appropriate soils.

For the purpose of drawing the agricultural maps of each agricultural category, the data was divided into four groupings based on the land area that it occupies in each municipality, as shown in Table 6-3. Categorisation of a municipality as 'low' in a commodity class means that the commodity class occupies almost no land area in that municipality, while classification as 'high' means that large areas of land in the municipality is occupied by that commodity class. On the maps, the lowest category was kept clear in every case, with each following category becoming progressively darker. Livestock is shown in brown, field crops in yellow and horticultural crops in green. Livestock and field crops tend to use large tracts of land and are therefore reported in ha agricultural land per ha municipal land to avoid letting larger municipalities appear more productive. Horticultural land tends to take up smaller areas and was therefore reported in ha of agricultural land[34].

Table 6-3: Groupings for each agricultural category based on the surface area occupied in each municipality.

Level of land occupation	**Livestock ($ha_{grazing}/ha_{municipality}$)**	**Field crops ($ha_{field\ crops\ land}/ha_{municipality}$)**	**Horticultural crops ($ha_{horticultural\ land}$)**
Low	0-0.4	0-0.02	0-1000
Moderately Low	0.4-0.6	0.02-0.1	1000-4000
Moderately High	0.6-0.8	0.1-0.2	4000-7000
High	>0.8	>0.2	>7000

6.4.1.2 Comparing potential product and market sizes

The area of land that could be treated per annum (ha/a) was calculated based on the maximum amount of sulfide-enriched coal waste that could be generated by the coal mining industry per annum (t/a) and the application rate of this material (t/ha), in accordance with Eq. 8.

$$\begin{aligned} &Land\ area\ treated \\ &\qquad = Dry\ mass\ of\ sulfide\ enriched\ fine\ coal\ waste\ generated \\ &\qquad \div Dry\ application\ rate \end{aligned} \tag{8}$$

The number of farms that could potentially be serviced by the hypothetical annual production of sulfide-enriched soil ameliorant was subsequently calculated with Eq. 9, based on an average farm size of 1441 ha, as calculated from Statistics South Africa's 2017 Census of Commercial Agriculture (Statistics South Africa, 2020a)[35].

$$Number\ of\ farms\ treated = Land\ area\ treated \div Average\ farm\ area \tag{9}$$

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[34] For a more in-depth explanation of this approach, see the appendix at Stander et al. (2022d). Link in Appendix D.

[35] Calculations are shown in the data to be accessed at Stander et al. (2022d), in the *Agricultural statistics for South Africa* spreadsheet in the *2017 Detailed commodity stats* tab at the bottom of the table. Link in Appendix D.

6.4.1.2.1 Mass of sulfide-enriched material generated

The mass of sulfide-enriched coal waste generated was calculated from an estimation of the total mass of ultra-fine waste generated by the coal sector per annum (t/a dry basis) and the fraction of this amount expected to deport as sulfide-enriched tailings during subsequent separation flotation, based on available experimental results. This calculation is shown in Eq. 10 and the parameters used are shown in Table 6-4.

$$\begin{aligned} &Dry\ mass\ of\ sulfide\ enriched\ fine\ coal\ waste\ generated \\ &\quad = Dry\ mass\ of\ coal\ waste\ produced\ per\ year \\ &\quad \times fraction\ of\ waste\ reporting\ to\ slurry \\ &\quad \times recovery\ rate\ of\ sulfide\ enriched\ material \end{aligned} \tag{10}$$

Table 6-4: The parameters used to calculate dry mass of sulfide-enriched coal waste.

Parameter	Number	Reference
Coal waste produced per year	62.5 Mt	(SACRSC 2011: 126) Averaged between 60 Mt and 65 Mt
Waste reporting to ultra-fine slurry	4 %	(SACRSC 2011: 46)
Recovery rate of sulfide-enriched material	0.8 % - 23 %	See Stander et al. (2022b) in the *Data for characterisation of s-rich* spreadsheet, in the *Flotation test results* tab, in the table called *Flotation test results*

6.4.1.2.2 Application rates

The application rate of sulfide-enriched coal waste (t waste/ha) was calculated based on the estimated pyrite application rate (t pyrite/ha) from literature, the estimated content of pyrite (dry basis) in the waste (% pyrite), and the estimated moisture content of the waste material (%), as shown in Eq. 11.

$$\begin{aligned} &Dry\ application\ rate \\ &\quad = pyrite\ application\ rate \\ &\quad \div (pyrite\ content\ of\ coal\ waste\ \times\ 0.01) \end{aligned} \tag{11}$$

To calculate the mass of pyrite that will be required to ameliorate a hectare of farmland is difficult, since in practice this will depend on individual soil needs and the rate of pyrite oxidation, which in turn is influenced by the soil chemistry, environmental conditions, and characteristics of the sulfide-enriched material, including particle sizes. Some simplifying assumptions were thus made, as summarised in Table 6-5.

Table 6-5: The parameters used to calculate application rates for sulfide-enriched coal waste (dry basis).

Parameter	Number	Reference
Application rate for pyrite: field crop	15 t/ha	(Tozsin et al., 2015; Tozsin and Arol, 2015)
Application rate for pyrite: grazing	5 t/ha	(Castelo-Branco et al., 1999)
Pyrite content of sulfide-enriched stream	16 %	From section 6.3.1.

For pyrite application rates, it is assumed that application rates similar to literature will be appropriate within different South African conditions: 5 t pure pyrite/ha for grazing, following Castelo-Branco et al. (1999) and 15 t pure pyrite/ha for field crops, following Tozsin and Arol (2015). Assuming that pilot and industrial processes will be able to achieve similar pyrite content to what UCT researchers have been able to achieve on a lab scale, it would place the pyrite content of the stream at between 2% and 16%. Since the two-stage flotation process has not been optimised, a pyrite content of 16% was assumed. The sulfidic minerals will most likely not be dry: it is a flotation concentrate stream and as such will be in slurry form after flotation.

6.4.1.3 Identifying potential partners

Bulk agricultural chemicals of interest and their suppliers were identified from an industry publication by Grain SA (Smit et al., 2021). This was done because distributors of such chemicals already have the market access and infrastructure in place to effectively add sulfide-enriched material to their product offering. Finding such partners is an approach recommended by Stander and Broadhurst (2021).

6.4.2 Costing

To assess the potential cost or profitability of the solution, several assumption and simplifications were made. The first important assumption is that, even though several processing steps will likely be required to transform the sulfide-enriched stream into an agricultural product (see Figure 6-2), the overall costs will be dominated by the costs of transport. Due to the long distances between economic centres in South Africa, transport cost is a very important consideration when evaluating the economics of product-to-market options. For instance, gypsum market research indicated that the transport costs were between 3 and 7.5 times higher than the production cost of the product (OTM 2009). Freight transport within South Africa is limited to road and rail transport with pipelines being used for large volume oil transport (Simpson, 2013; Viljoen, 2013). Rail transport tends to be more cost effective and more energy effective, but due to the limited capacity of the South African rail network, road transport is extensively used in South Africa (Simpson, 2013; Viljoen, 2013). The cost of road transport is therefore considered as a first step to understanding the economics of the solution.

Figure 6-2: Steps in the waste-to-market mechanistic chain.

6.4.2.1 Transport costs

The costs of transporting sulfide-enriched coal waste to the identified application locations (R/ha) were calculated based on road transport costs (R/t.km), distances between mines and application locations (km) and calculated application rates (t/ha), as shown in Eq. 12. This cost is then compared with the all-in cost of the main competitor product, gypsum.

$$\begin{aligned}&Transport\ cost\ per\ hectare\\&\quad = Road\ transport\ cost \times distance\ travelled\\&\quad \times wet\ application\ rate\end{aligned} \tag{12}$$

6.4.2.1.1 Road transport costs

Road transport costs are a function of several factors, including truck utilisation, the kind of truck used, fuel price as well as the state of repair of roads (Viljoen, 2013). In this study a generic value of R1.28 /t-km is used based on an industry publication made available for the reference and benchmarking of logistics operators (Braun, 2019). It is the number used for a truck with 50% utilisation and was adopted in this analysis, since it is uncertain whether another appropriate commodity can be found to fill the truck on the return trip.

6.4.2.1.2 Distances travelled

The distance that the sulfide-enriched material must travel is dependent on the location of the source of the material as well as the market. The market locations were identified as indicated in Section 6.4.1.1. The source of the material is coal mines. South Africa's largest coal mining area is located in the Central Basin with mines near Witbank, Ermelo and Middleburg in Mpumalanga (Eberhard, 2011; McCarthy and Pretorius, 2009). Limpopo coal fields are emerging and set to grow in the future, as the Central Basin gets depleted (Eberhard, 2011), making this a significant future source of sulfide-rich material.

Not all coal mines produce slurry waste, but only coal mines that wash their coals for export or metallurgy (Eberhard 2011; SACRSC 2011). Only such beneficiating mines that produce more than 3 Mtpa are considered in this analysis, since they are more likely to produce enough fine coal waste to beneficiate economically. The locations of these mines are shown in Figure 6-3. Most mines are in the Emalahleni-Middelburg area, except for the large Grootegeluk mine near Lephalale in Limpopo and the small Savmore mine near Piet Retief. Transport distances will therefore be calculated from Emalahleni and Lephalale, whichever is the nearest to the agricultural market municipality in question.

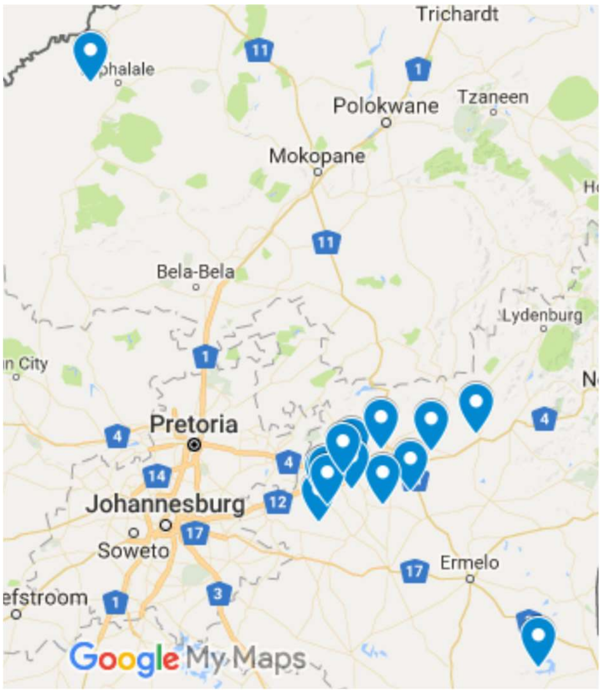


Figure 6-3: The locations of beneficiating coal mines (>3 Mtpa) in South Africa. (Google and AfriGIS (Pty) Ltd, 2019; Prévost, 2011).

To estimate the market location, the municipal seat was used as a proxy for agricultural regions in a specific municipality. The distance to market was therefore estimated as the distance between the nearest coal fields and the municipal seat since the locations of the specific farms with soils of interest are unknown. This gives rise to the anomaly of sulfide-enriched material from Lephalale not having to travel at all.

6.4.2.1.3 Wet application rates

It is assumed that the sulfidic mineral stream will contain 15% water, since filtration of waste streams prior to disposal is becoming common practice in order to improve water efficiency and waste disposal (Fundikwa et al., 2016; Jera, 2013). The wet application rates were thus calculated from the dry application rates, calculated in Eq. 11, and the moisture content using Eq. 13.

$$Wet\ application\ rate\ = dry\ application\ rate\ \div (1 - water\ content\ \times 0.01) \tag{13}$$

6.4.2.2 *Competitor product costs*

Gypsum was used for comparison to the transport cost of the sulfide-enriched material. This is because it is the main competitor product for use as a soil ameliorant in calcareous sodic soils and because it is a bulk chemical with some industrial sources (OTM 2009). The all-in gypsum cost (R/ha) was calculated on the basis of the gypsum price (R/t), the transport cost associated with moving the gypsum from the depot to the farming area in question (R/t) and the application rate (t/ha), as shown in Eq. 14.

$$\begin{aligned} &Cost\ per\ hectare\ of\ gypsum \\ &\quad = (Gypsum\ price \\ &\quad + Road\ transport\ cost \times distance\ travelled) \times application\ rate \end{aligned} \tag{14}$$

In each case the gypsum price and transport cost from the depot closest to the farming area was used for the calculation. Transport costs were calculated like that of coal waste (Eq. 12), with the same base road transport cost. An application rate of 11 t/ha per season is in line with the current application rates in Kakamas, an important horticultural town in the Northern Cape Province, (private communication) and was therefore used in these calculations. The gypsum prices found on the SAKG website, shown in Table 6-6, were used, since no other producers were willing to make their prices public.

Table 6-6: Gypsum prices at different locations in South Africa (Kalkor (Pty) Ltd, 2019).

Gypsum source location	Gypsum price
Phokeng (North West Province)*	R 235 /t
Potchefstroom (North West Province)	R 360 /t
Middelburg (Mpumalanga)	R 240 /t
Phalaborwa (Limpopo Province)	R 190 /t
Chloorkop (Gauteng Province)	R 315 /t

*Gypsum to the Northern Cape will most likely be supplied from Phokeng, near Rustenburg, since it is better priced at R 235 /t than the Potchefstroom gypsum at R 360 /t (Kalkor (Pty) Ltd, 2019).

6.4.2.3 *Sensitivity analysis*

The sensitivity analysis was conducted by changing the variables in Eq.'s 12 and 13, while keeping 'distance travelled' at one, for comparison. Road transport cost (Eq. 12) was varied according to truck utilisation rate as well as inflationary increases that results from fuel price changes and changes in maintenance costs (Statistics South Africa, 2021). For Eq. 13 which calculates the application rate number used in Eq. 12, pyrite application rate and pyrite content of the coal waste were varied, keeping the water content of the material constant, since it is simply a function of the dewatering regime chosen and not a main concern in this paper. The application rate numbers that were used compared the grazing and field crop application rates with the highest application rate used in literature. Table 6-7 shows the parameters considered and their ranges.

Table 6-7: Parameters considered in the sensitivity analyses and the ranges within which they were considered.

Parameter changed	Parameter base value	Parameter range
Truck utilisation rate	50 % utilisation	100 % utilisation (+100% of base case)
Road transport cost	R 1.28 /t.km (2019 transport figure: it is the last data point)	R 1.17 /t.km (2017 figure @ -9% of base case) to R 1.4 /t.km (projected 2023 number @ +10% of base case)
Pyrite application rates	15 t/ha (Application rate for field crops)	4.5 t/ha (grazing application rate @-70% of base case) to 30t/ha (@100% of base case)
Pyrite content of the fine coal waste	15.8 % (Max achieved pyrite content)	2.3% (Min achieved pyrite content @ -70% of base case) to 31.6 % (@100% of base case)

6.4.3 Potential health, safety and environmental risks

Assessment of a technology's sustainability performance requires assessment on a wider range of issues than traditional techno-economic assessments. Based on triple bottom line thinking (Elkington, 1998), social and environmental issues must be considered in addition to a technology's economic characteristics. In this pre-feasibility study the analysis focuses on the potential safety, health and environmental risks associated with the material handling and use. No consideration was given to impacts across the life cycle of the product, such as greenhouse gas emissions or risks associated with material transport.

6.5 Results and discussion

6.5.1 Market Opportunity Analysis

The assessment of market potential was based on the identification and locations of appropriate soils (Section 6.5.1.1) and agricultural activities (Section 6.5.1.2) and the extent to which these coincide (Section 6.5.1.3), as well as potential market demand vs production considerations (Section 6.5.1.4). Potential distribution partners are identified in Section 6.5.1.5.

6.5.1.1 Identification and location of appropriate soil types

The soils that may benefit from pyrite application are classified as silicic, calcic and vertic soils. This section draws heavily on *Soils of South Africa* by Fey (2010) and information is from that work, unless otherwise referenced.

6.5.1.1.1 Silicic soils

Silicic soils, shown in Figure 6-4, are particular to dry areas in South Africa since they require arid environments to form. Silicic soils are located mainly in the central and western areas of the Northern Cape Province. There are also small pockets of silicic soils in the Eastern Cape and Western Cape.

These soils have a subsurface layer called hardpan which is either hard or very hard, having been cemented by silica. Silicic soils tend to have a pH between 7.5 and 9, although values between 5 and 10 are not unknown. They tend to have low electrical conductivity and high amounts of exchangeable sodium and, often, calcium. Due to the elevated pH plant-available iron tends to be low, while the available boron tends to be so high "that it is toxic to agricultural crops".

The hardpan layer in these soils must be ripped for planting crops. These soils will benefit from application of sulfide-enriched material both by improving iron and phosphate-availability and reducing available boron by reducing the soil pH. These soils will also benefit from improved soil structure, due to calcium released in acid neutralising reactions, which can then replace sodium on clay particles' cation exchange sites, thereby improving soil structure.

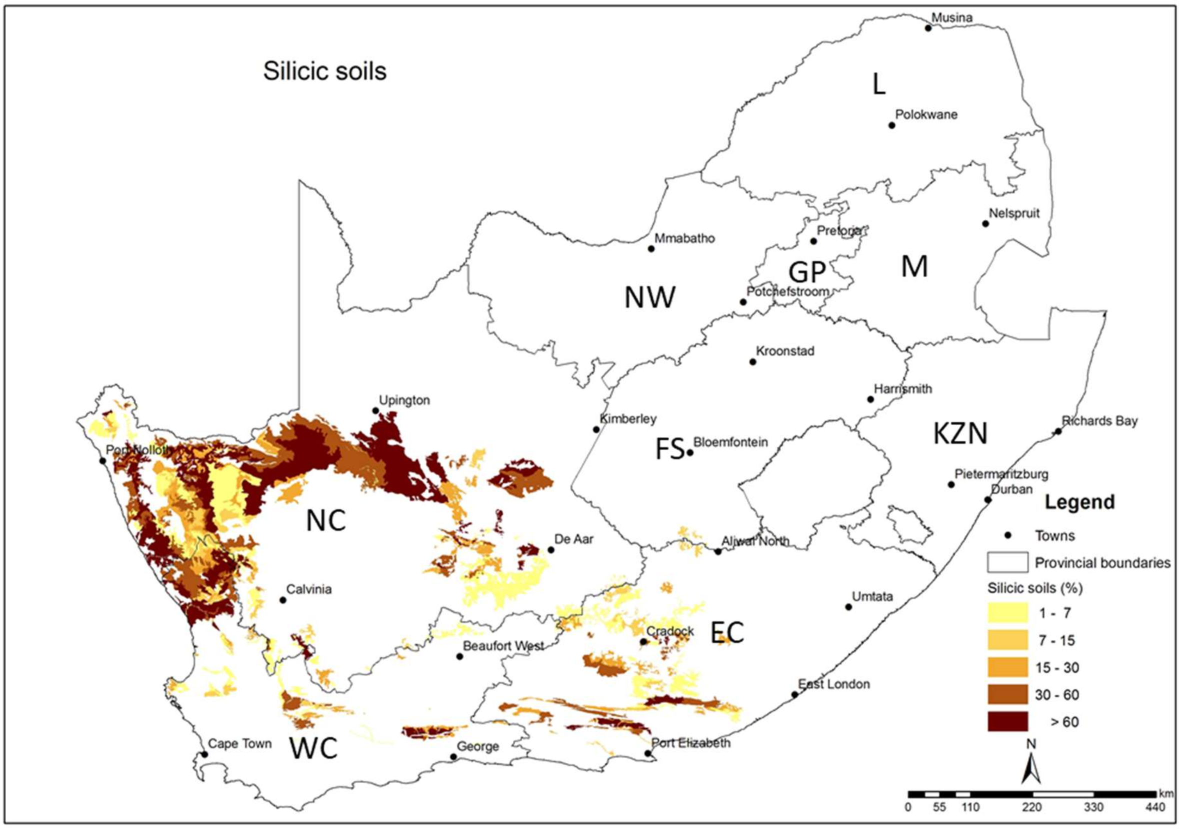


Figure 6-4: Location of silicic soils in South Africa (Agricultural Research Council -Institute for Soil Climate and Water, n.d.)**. EC: Eastern Cape Province, FS: Free State Province, GP: Gauteng Province, KZN: KwaZulu-Natal Province, L: Limpopo Province, MP: Mpumalanga Province, NC: Northern Cape Province, NW: North West Province, WC: Western Cape Province**

6.5.1.1.2 Calcic soils

Calcic soils can mostly be found in the central and north-eastern region of the Northern Cape Province and into the south-western region of the North-West Province, as shown in Figure 6-5. These soils are typically described as calcareous, or rich in calcium carbonate, but this grouping also includes soils that have a magnesium carbonate element or are formed by gypsum, rather than lime. The topsoil layers tend to have a crumb or granular structure and medium to fine texture. The subsurface layers are cemented by calcium carbonate rather than silica, as is the case with silicic soils. The soil has a neutral pH in the topsoil, but in the lower layers the pH increases to between 8 and 8.5. The soil is base-rich, which means that there is ample capacity for neutralising acid. As such the soils have low nutrient availability, especially with respect to iron and phosphate. The soils also suffer from plant-toxic boron levels, high salinity and stoniness.

The hardpan layer in these soils must be ripped before planting crops and alkalinity thereby finds its way to the topsoil. When ripped, these soils can benefit from application of sulfide-enriched material due to their neutralising effect, which increases the root-available nutrients, notably iron and phosphate. Due to the soil's high base status it is unlikely to be acidified by judicious application of sulfide-enriched material.

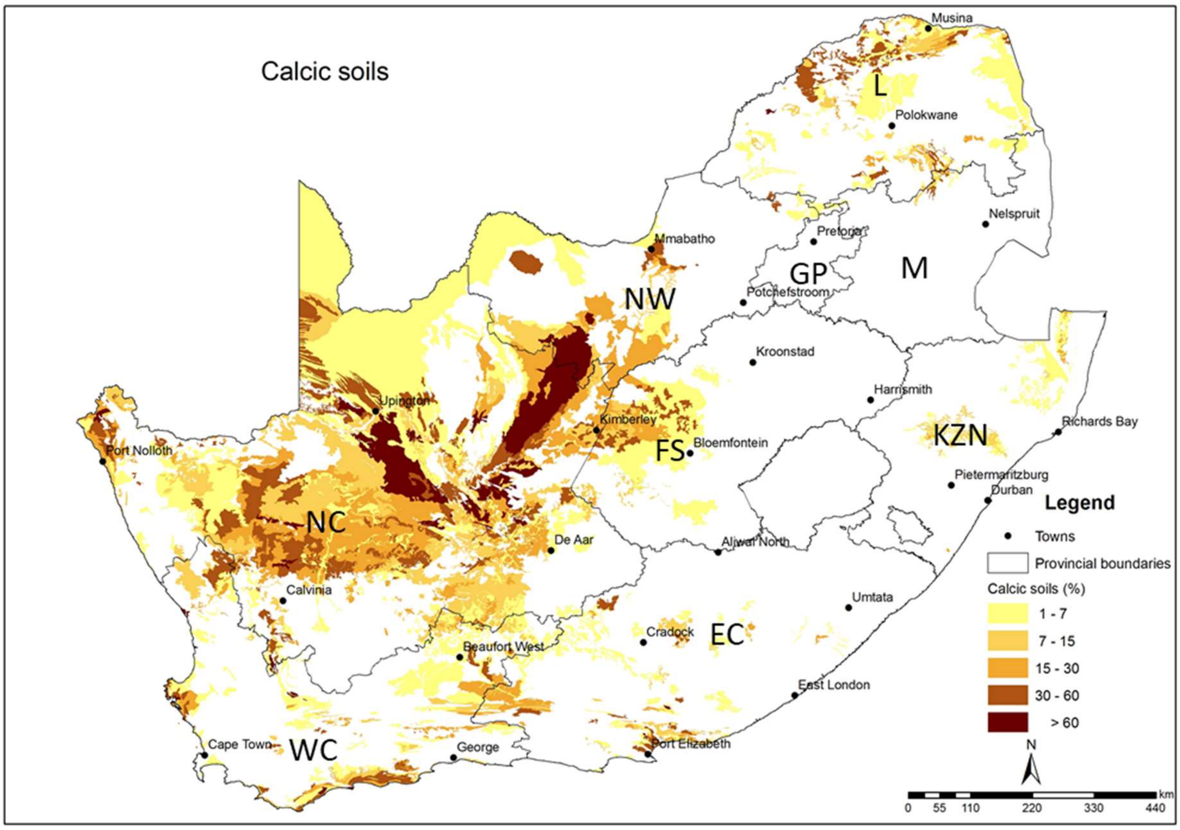


Figure 6-5: the location of calcic soils in South Africa (Agricultural Research Council -Institute for Soil Climate and Water, n.d.). **EC: Eastern Cape Province, FS: Free State Province, GP: Gauteng Province, KZN: KwaZulu-Natal Province, L: Limpopo Province, MP: Mpumalanga Province, NC: Northern Cape Province, NW: North West Province, WC: Western Cape Province**

6.5.1.1.3 Vertic soils

Vertic soils, shown in Figure 6-6, occur in the north of the Free State Province and south-west of Mpumalanga with some found in areas of the north-east of the North West Province and south-west of Limpopo. These soils are clayey, with a strong tendency to swell in damp conditions and shrink when dry. Vertic soils can have high levels of calcium carbonate, gypsum or halite, and have a high base status, pH between 6 and 8,5 and a high cation exchange capacity. Vertic soils present challenges to agriculture, since they can be hard when dry, but too wet and sticky when wet.

Alkaline versions of this soil can benefit from sulfide-enriched material application by acidifying pockets of the soil and thereby creating nutrient availability. The high base status of the soils means that they are unlikely to be completely acidified by judicious application of sulfide-enriched material.

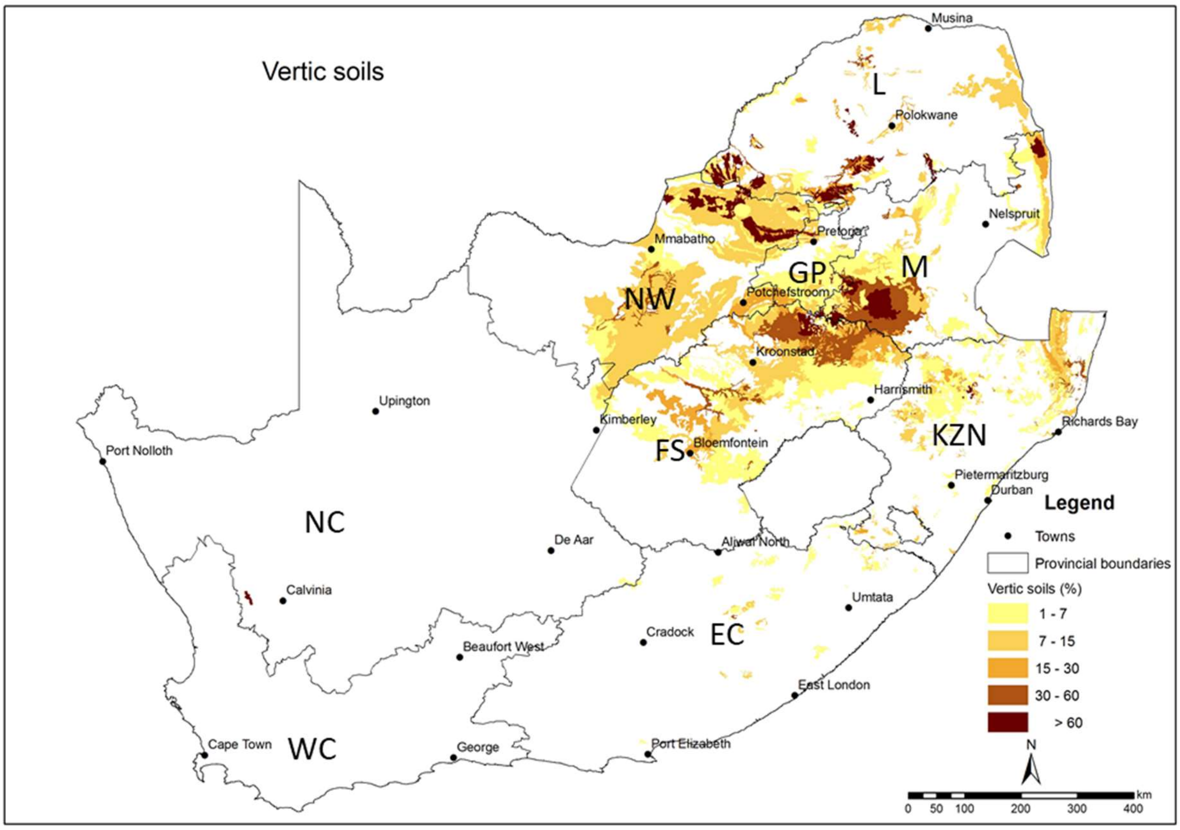


Figure 6-6: the location of vertic soils in South Africa (Agricultural Research Council -Institute for Soil Climate and Water, n.d.)**. EC: Eastern Cape Province, FS: Free State Province, GP: Gauteng Province, KZN: KwaZulu-Natal Province, L: Limpopo Province, MP: Mpumalanga Province, NC: Northern Cape Province, NW: North West Province, WC: Western Cape Province**

6.5.1.2 Identification and location of agricultural activities

Maps of the agricultural activities taking place in the same areas where relevant soils (mentioned in section 6.5.1.1) are found are shown in Figure 6-7, and the top products in each agricultural activity for each province summarised in Table 6-8. Livestock grazing towards the north of the country is mainly cattle with sheep predominating towards the south. Goat farming is a minor activity practiced towards the west and the north of the country. Only grazing was considered in the livestock category, since farming poultry and pigs do not require large land footprints like cattle-, sheep-, goat- and game grazing do. Field crops are grown mostly towards the east of the country where maize, soybeans, and sorghum predominate. Maize is an important field crop throughout the field crop growing regions shown, with soybeans, sunflower seeds, wheat and sorghum also forming part of the staples.

Horticultural commodities of interest towards the west of the country are grape farming, both table grapes and wine grapes, with some vegetables and nuts. Another rich horticultural region is towards the north, where vegetables, citrus fruit and deciduous fruit are grown. This analysis excludes areas to the south-west of the maps since these are used for rooibos production which requires deep, sandy, acidic soil. The soils in this analysis have a high base status and therefore endeavouring to make them wholly acidic is unrealistic.

Table 6-8: The top agricultural commodities in each category (Statistics South Africa, 2020b, 2020c, 2020d, 2020e, 2020f, 2020g).

	Livestock	**Field crops**	**Horticulture**
Northern Cape	Sheep, cattle, goats	Maize, wheat, fodder	Grapes, vegetables, pecan nuts
Western Cape	Sheep	Wheat	Grapes
North West	Cattle, goats, sheep	Maize, sunflower seeds, soya beans	Vegetables, citrus fruit, tree nuts
Free State	Cattle, sheep	Maize, soya beans, sunflower seeds	Vegetables
Mpumalanga	Cattle, sheep	Maize, soya beans, sorghum	Vegetables, tree nuts
Limpopo	Cattle, sheep, goats	Sunflower seeds, sorghum, maize	Vegetables, citrus fruit, deciduous fruit

The maps in Figure 6-7 also show that horticultural crops tend to cover the smallest land footprint, although they generate the highest income per land area. Field crops span larger land areas and can therefore potentially absorb more sulfide-enriched material. Livestock farming uses larger land areas than either field crops or horticulture and consistently generates the most income. As mentioned before, however, ripping is necessary to prepare silicic and calcic soils for horticulture and field crops and ripping is what releases calcite in calcic soils and makes them alkaline. Ripping land is, however, expensive (GRDC 2009) and therefore unlikely to be undertaken on the vast expanses required for grazing. The hard-pan layer itself also presents a barrier to plant growth, even if the topsoil pH is neutral. This means that silicic soils' livestock carrying capacity can be improved by pyrite application, but that the hardpan layer will still present a barrier. For calcic soils, direct pyrite application to the topsoil will likely not improve the land's grazing carrying capacity. Grazing on vertic soils can therefore comparatively benefit the most from pyrite application, unless the technical challenge associated with the hardpan layer can be solved. The livestock activity on calcic soils is nevertheless shown for the purpose of completeness.

6.5.1.3 *Identification and location of potential markets*

The agricultural regions map of Figure 6-7 were superimposed on the different soil maps in Figure 6-8, Figure 6-9 and Figure 6-10 to show where areas of high agricultural activity and specific soils overlap.

Figure 6-8 shows that there are few areas where agricultural activities are practiced near or on silicic soils. Some overlap with livestock grazing is found to the south-east of the Northern Cape province, where sheep farming takes place (Statistics South Africa, 2020d). Field crop farming also overlaps with silicic soils to the east of the Northern Cape province. Horticulture is the only agricultural activity extensively practiced on silicic soils. In the central Northern Cape grape farming is practiced on the banks of the orange river, where the soils are silicic, and in the north of the Western Cape province grape cultivation takes place in silicic soil areas.

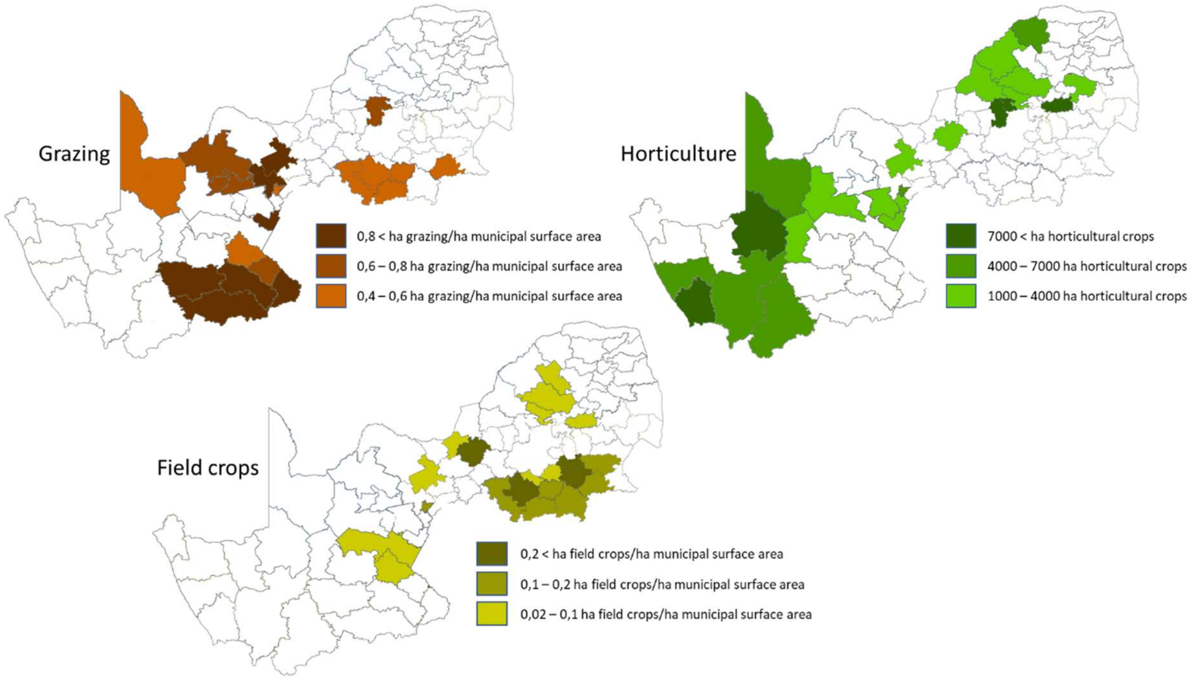
Figure 6-9 shows where calcic soils affect agricultural activities. Some cattle farming areas towards the north of the Northern Cape province and North West province are found near or on calcic soils. Small areas of calcic soils are also found within sheep farming areas towards the south. As noted before, sulfide-enriched material may be of limited value on these soils when used for the purpose of grazing, due to the hardpan layer. Field crop production and calcic soils can be found in the same municipalities towards the east of the Northern Cape province and central North West province. Horticultural activities take place in the same municipal environments where calcic soils are found in the Northern Cape as well as Limpopo provinces.

Figure 6-10 indicates that vertic soils affect grazing mostly in the Free State and Mpumalanga, with small areas being affected in the North West province. Field crop areas in the north of the Free State province and south west of Mpumalanga are affected by vertic soils. Lastly only small areas in the horticultural areas south of Limpopo and north of the North West province are affected by vertic soils.

The locations of potential markets for sulfide-enriched coal waste as a soil ameliorant within south Africa are summarised in Table 6-9.

Table 6-9: Potential market opportunities for sulfide-enriched coal waste as a soil ameliorant (Agricultural Research Council -Institute for Soil Climate and Water, n.d.; Statistics South Africa, 2020b, 2020c, 2020d, 2020e, 2020f, 2020g).

Province	Municipality	Soil types	Agriculture
Northern Cape	Thembelihle	Silicic soils; Calcic soils	Field crops, grazing
	Emthanjeni	Silicic soils; Calcic soils	Grazing
	Kai! Garib	Silicic soils; Calcic soils	Horticulture
	Dawid Kruiper	Calcic soils	Horticulture, grazing
	Siyancuma	Calcic soils	Field crops
	!Kheis	Calcic soils	Horticulture
	Dikgatlong	Calcic soils	Horticulture
	Kareeberg	Silicic soils; Calcic soils	Grazing
	Tsantsabane	Calcic soils	Horticulture
Western Cape	Matzikama	Silicic soils; Calcic soils	Horticulture
North West	Naledi	Calcic soils	Field crops, horticulture, grazing
	Mahikeng	Calcic soils	Field crops
	Madibeng & Moretele	Vertic soils	Grazing, horticulture
	Thabazimbi	Vertic soils	Horticulture
Limpopo	Bela-Bela	Vertic soils	Horticulture, Field crops
	Lephalale	Calcic soils	Horticulture
	Blouberg	Calcic soils	Horticulture
	Lekwa	Vertic soils	Field crops
Mpumalanga	Dr. Pixley Ka Isaka Seme	Vertic soils	Field crops, grazing
	Govan Mbeki	Vertic soils	Field crops
	Diplaseng	Vertic soils	Field crops
	Ngwathe	Vertic soils	Grazing, field crops
Free State	Mafube	Vertic soils	Grazing, field crops
	Metsimaholo	Vertic	Field crops



Grazing

Horticulture

Field crops

Figure 6-7: The surface areas of different types of agricultural activities in municipalities where soils that can benefit from sulfide-enriched material are found. Grazing and field crops tend to cover a large land area and is therefore shown in units of ha/ ha municipal surface area, to account for the different sizes of municipalities. Horticulture tends to be more concentrated and is therefore shown in ha, since it is less sensitive to the size of the municipality. (Statistics South Africa, 2020b, 2020c, 2020d, 2020e, 2020f, 2020g) **These maps were created based on municipal maps from Municipalities.co.za.**

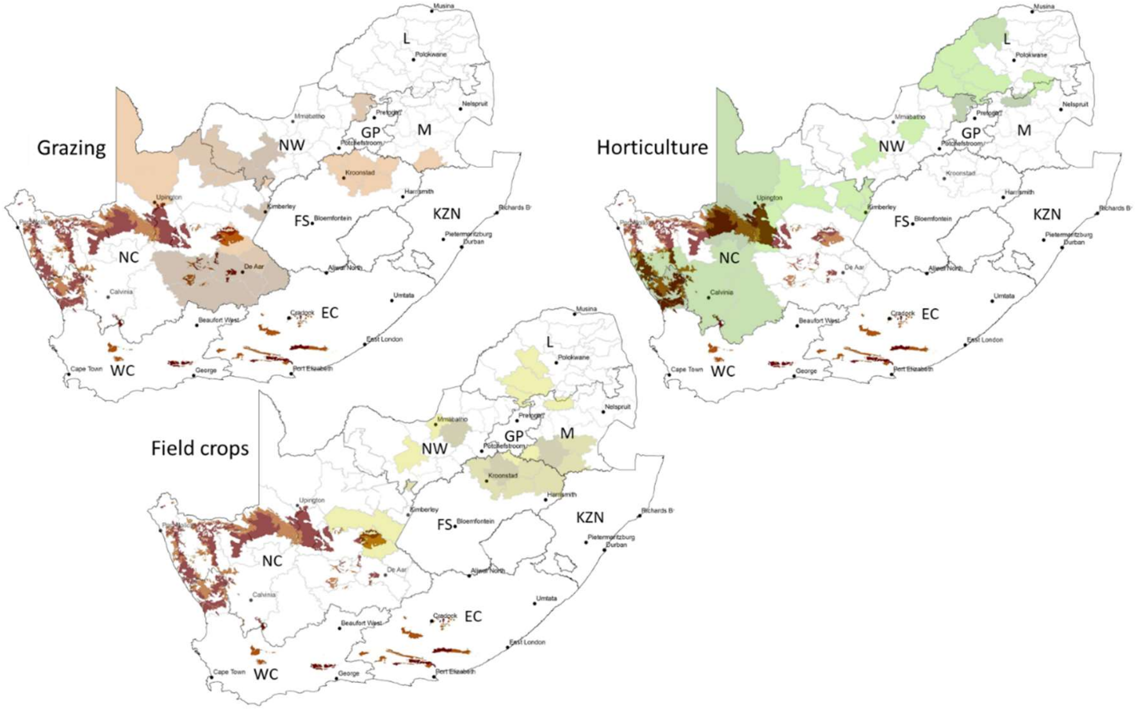


Figure 6-8: Silicic soil maps with the agricultural outputs of different municipalities (Figure 6-7) superimposed on it. (Statistics South Africa, 2020b, 2020c, 2020d, 2020e, 2020f, 2020g)**. Areas of overlap indicate agricultural regions of interest for a specific soil and commodity type. The province abbreviations are as follows: NC – Northern Cape, NW – North West, GP – Gauteng province, L – Limpopo, M – Mpumalanga, FS – Free State, KZN – KwaZulu-Natal, WC – Western Cape, EC – Eastern Cape. Agricultural maps were created based on municipal maps from Municipalities.co.za and soil maps are from the Agricultural Research Council -Institute for Soil (n.d).**

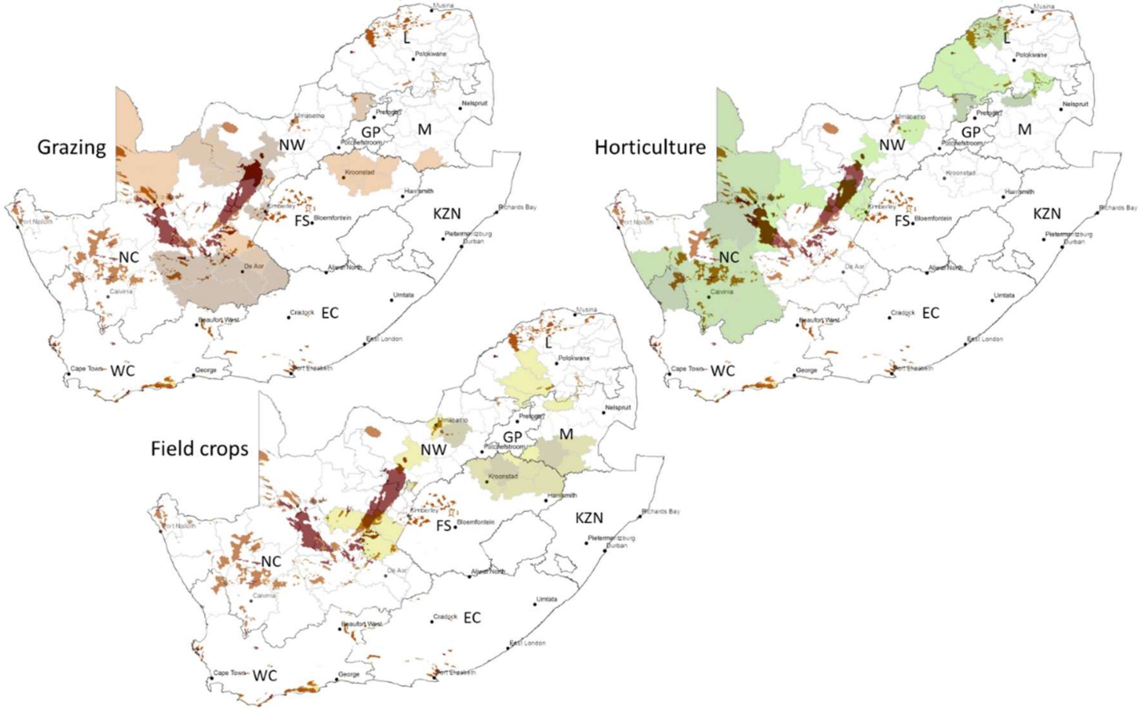


Figure 6-9: Calcic soil maps with the agricultural outputs of different municipalities (Figure 6-7) superimposed on it. (Statistics South Africa, 2020b, 2020c, 2020d, 2020e, 2020f, 2020g)**. Areas of overlap indicate agricultural regions of interest for a specific soil and commodity type. The province abbreviations are as follows: NC – Northern Cape, NW – North West, GP – Gauteng province, L – Limpopo, M – Mpumalanga, FS – Free State, KZN -KwaZulu-Natal, WC – Western Cape, EC – Eastern Cape. Agricultural maps were created based on municipal maps from Municipalities.co.za and soil maps are from the Agricultural Research Council -Institute for Soil (n.d).**

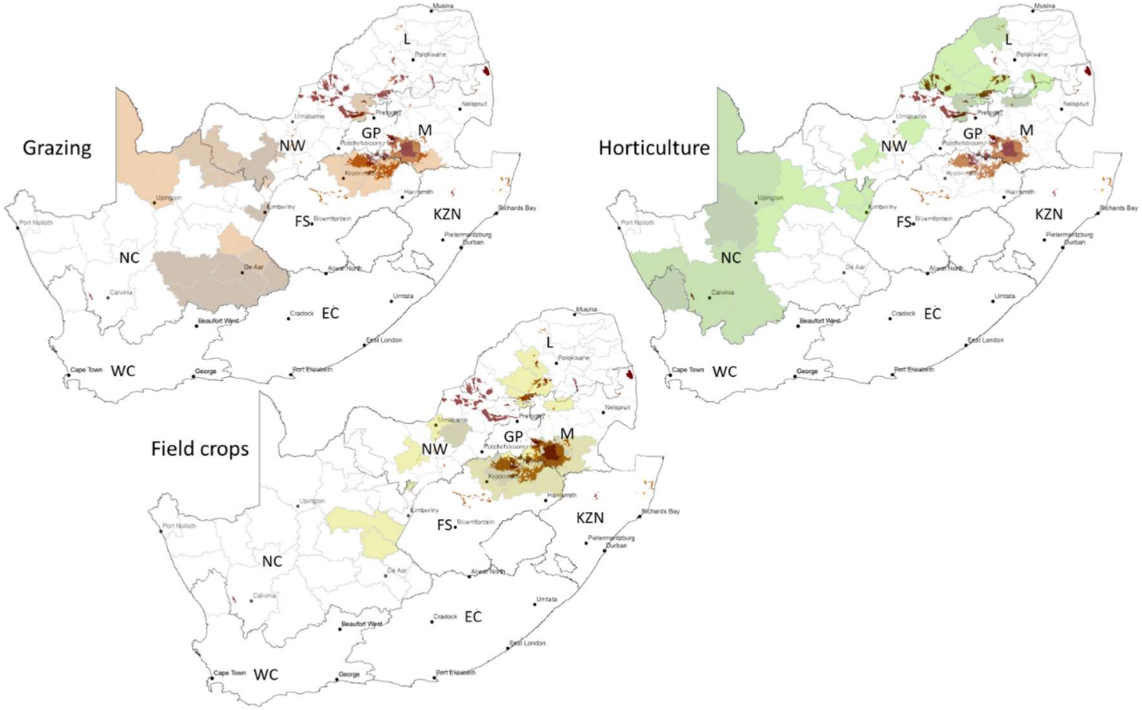


Figure 6-10: Vertic soil maps with the agricultural outputs of different municipalities (Figure 6-7) superimposed on it. (Statistics South Africa, 2020b, 2020c, 2020d, 2020e, 2020f, 2020g)**. Areas of overlap indicate agricultural regions of interest for a specific soil and commodity type. The province abbreviations are as follows: NC – Northern Cape, NW – North West, GP – Gauteng province, L – Limpopo, M – Mpumalanga, FS – Free State, KZN – KwaZulu-Natal, WC – Western Cape, EC – Eastern Cape. Agricultural maps were created based on municipal maps from Municipalities.co.za and soil maps are from the Agricultural Research Council -Institute for Soil (n.d).**

6.5.1.4 Comparison of potential product and market sizes

Given a coal slurry production rate of 2.5 Mtpa[36], the total sulfide-enriched stream production (dry basis) is likely to be between 20 ktpa and 575 ktpa, depending on the relative deportment of ultrafine coal processing waste during flotation separation. At calculated dry application rates of 31 t/ha for grazing and 97 t/ha for field crops and assuming an average farm size of 1441 ha, this equates to between 0.1 and 13 farms being serviced by sulfide-enriched material annually, as shown in Table 6-10. The numbers are low so fresh coal slurry production can easily be absorbed by agriculture. There is therefore also opportunity for including historical slurry and reground fine discards in the production process, which may help address more of the fresh, and some of the legacy, coal mining waste. The small annual production on its own is unlikely to justify capital cost expenditure or a large marketing campaign, so including legacy slurry may be important for achieving economies of scale.

Table 6-10: The number of farms that can be serviced by the hypothetical annual production of sulfide-enriched soil ameliorant[37].

	Min total sulfide-enriched stream size (20 ktpa)	**Max total sulfide-enriched stream size (575 ktpa)**
Grazing application rate (36 t/ha)	654 ha 0.5 farms	18797 ha 13 farms
Field crop application rate (114 t/ha)	207 ha 0.1 farms	5948 ha 4 farms

6.5.1.5 Potential partners

Distributors of agricultural commodities such as calcite, lime and gypsum were identified as potential distribution partners, since they already have relationships with farmers and have the business processes in place to market, package and distribute bulk soil ameliorants. Agricultural distributors of these have been identified in a report by Grain SA (Smit et al., 2021) and are listed in Box 1. Suppliers only active in the Western and Eastern Cape provinces were not included in this list since high transport costs prohibit supply to this region.

Box 1: Distributors of agricultural gypsum, lime and calcite (Smit et al., 2021)**.**

SA Lime and Gypsum
H. Pistorius & Co
Kalkor
LimeCrop
Limecor
Bastion Lime
Agrilime
PBD Boeredienste

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[36] For calculations see the data at Stander et al. (2022d) in the *Agricultural statistics for South Africa* spreadsheet in the *Number of Farms* tab. Link in Appendix D.

[37] For calculations see the data at Stander et al. (2022d) in the *Agricultural statistics for South Africa* spreadsheet in the *Number of Farms* tab. Link in Appendix D.

6.5.2 Costing of soil amelioration

6.5.2.1 Base case costing

In this section the logistical cost of transporting sulfide-enriched material for ameliorating farming land used is considered. Table 6-11 shows the costs of transporting sulfide-enriched coal waste from collieries to the nearest and farthest identified agricultural locations in each province as a function of application type and compares that with the all-in (sale price plus transport) cost of gypsum in the area. This is intended to give the range within which transport costs are likely to fall within a certain province and compare that with the costs of a bulk soil ameliorant commonly used. The table shows that transporting the material over large distances, such as to the Northern or Western Cape provinces, is likely to be prohibitively expensive. Assuming application rates similar to that of field crops, the cost per hectare for the furthest town in the Northern Cape is R 160,000 /ha, more than ten times the R 15,000 /ha for gypsum. Grazing application rates reduced the cost of application to R 49,000 /ha, which is closer to parity, but still more than three times more expensive than gypsum application. Likewise, in the North West grazing application rates is twice to three times that of gypsum. Even in areas near mines, like Limpopo and Mpumalanga, most of the application rates for most of the locations have higher transport costs than the all-in cost of gypsum, although the transport costs in these regions are closer to parity. Therefore, the transport costs alone in most regions far outstrip the prices that farmers may be used to paying for soil ameliorants.

Table 6-11: Comparison of the highest and lowest transport costs for sulfide-enriched material in each province as well as all-in gypsum price. Distances are from Google Maps.

Province	Municipal seat	Distance (km)	Grazing (cost/ha)	Field crops (cost/ha)	Gypsum distance (km)	Gypsum (cost/ha)
Northern Cape	Barkley-West	648	R 29,850	R 94,328	485	R 9,414
	Carnarvon	1,073	R 49,427	R 156,194	883	R 15,018
Western Cape	Vredendal	1,462	R 67,347	R 212,820	276	R 6,526
North West	Brits	171	R 7,877	R 24,892	87	R 3,810
	Taung	546	R 25,151	R 79,480	389	R 8,062
Limpopo	Lephalale	0	R 0	R 0	320	R 7,971
	Senwabarwana	199	R 9,167	R 28,968	386	R 8,900
Mpumalanga	Secunda	99	R 4,560	R 14,411	111	R 4,203
	Volksrust	199	R 9,167	R 28,968	199	R 5,442
Free State	Sasolburg	214	R 9,858	R 31,152	103	R 4,915
	Parys	253	R 11,654	R 36,829	157	R 5,676

Parameters: Transport cost: R1.28 /t-km; Grazing pyrite application rate (wet basis): 36 t/ha; Field crop pyrite application rate (wet basis): 114 t/ha; Gypsum application rate: 11 t/ha; Gypsum price: Table 6-6.

Regular re-application of sulfide-enriched material should not be necessary as with gypsum, however. The calcium that is added by adding gypsum washes out with irrigation and rains, while the sodium minerals intrinsic to the soil continually dissolve, leading to poor soil structure a few months after gypsum application. With the application of the sulfide-enriched material, calcium will be replenished through continuous neutralisation reactions between calcite and the acidity generated by oxidation of the pyrite. A large once-off application will therefore continue to be effective for longer than smaller, frequent gypsum applications (Metson, 1972). This provides advantages to farmers in terms of labour efficiency and soil preservation over several growing seasons, which may convince them of the solution's value.

This data shows that it is unlikely that the solution will be profitable to mines on an all-in basis. It may, however, be more cost-effective to them than long-term storage and remediation of the material.

6.5.2.2 *Sensitivity analysis*

Sensitivity analyses were conducted to assess the impacts of different assumptions on the outcome. In Figure 6-11 the sensitivity of the cost for transporting enough material to treat a hectare of soil is graphed relative to the pyrite content of the sulfide-enriched material, the truck utilisation rate and the application rates used and road transport cost. Results indicate that the variable with the largest potential to increase the cost is pyrite content of the material. If the 16 % pyrite content cannot be achieved on an industrial scale, transports cost may become prohibitively expensive. The curve shape is due to the inverse relationship between the transport cost /ha.km and the pyrite content of the material, where 0% pyrite content represents an asymptote. Increased pyrite application rates also increased the transport cost, but this relationship is linear with a slope of 1. The range of application rates in literature varies considerably, which will impact cost. Finding the right application rate is therefore not simply a technical- and risk-related issue, but a financial one as well.

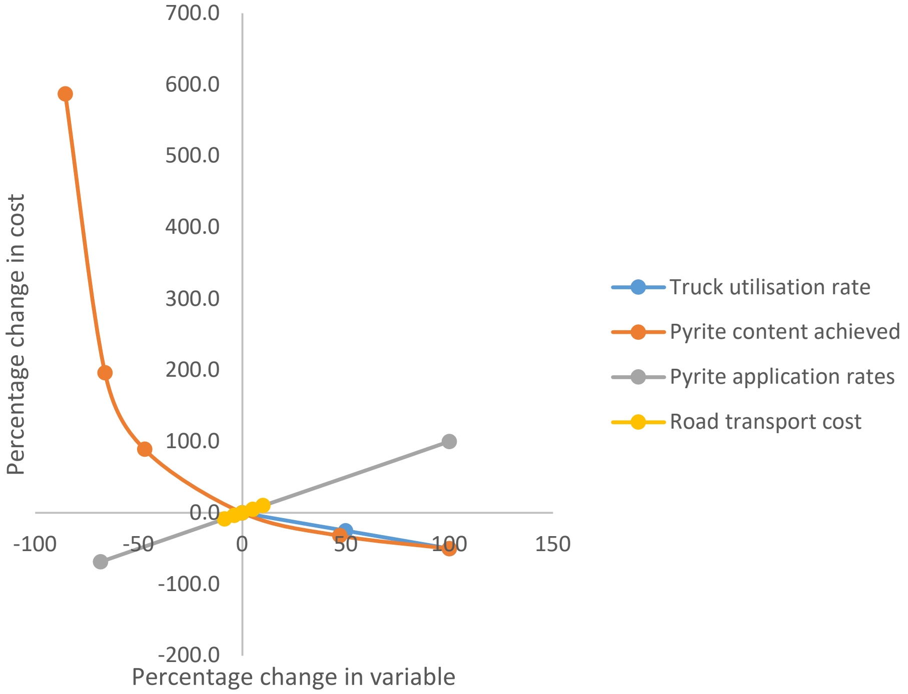

Figure 6-11 Sensitivity analysis showing the impact of different variables on the transport cost of sulfide-enriched coal waste (R/ha.km).

The curve for the inflationary changes in road transport cost is on top of the application rates curve since both variables have a slope of 1. Its range is much smaller, however, indicating that the inflationary increases in road transport cost will have a relatively small impact on costs. The truck utilisation has a bigger impact on transport costs, having a slope of -0.5: a truck full on both legs of a journey will reduce the transport cost by half. The large economic advantage of sharing transport costs warrants investing cost and effort into finding commercial partners to fill trucks on the return journey.

6.5.3 Potential safety, health and environmental risks

As in the case of most waste materials, the sulfide-enriched coal waste streams are comprised of several components which may pose a safety, health or environmental risk during handling and application.

6.5.3.1 Coal

Application of this material to agricultural soil carries some risk, associated with both the pyrite component and the non-pyrite components. One set of risks are associated with the coal component of the sulfide-enriched material. It could present spontaneous combustion risk on the storage pad due to the high coal and pyrite content. In the agricultural application of sulfide-enriched material, the significant coal content of the stream could increase the risk of runaway farm fires. The effect of coal on the growth and development of plants is also unclear and would need to be tested. Here also lies potential opportunity, however. If the coal can be transformed into humic substances (soil organic matter that increases fertility) (Erdogan et al., 2007; Fong et al., 2007), that would improve the desirability of the stream greatly.

6.5.3.2 Flotation chemicals

Another example of substances that may be present in the sulfide-enriched material are xanthates. Xanthates are toxic substances (Okibe and Johnson, 2002) that have been used in the second stage of the two-stage flotation process as a sulfide collector and will therefore be concentrated in the sulfide-enriched material (Broadhurst et al., 2015; Fundikwa et al., 2016). Xanthates tend to degrade rapidly and the degradation products, rather than the xanthates themselves will therefore likely be chemicals of environmental concern. Nevertheless, a life cycle assessment study by Kunene (2014) found that toxicity effects related to these are small compared with the impacts of not treating base metal mine waste. Similarly, other pyrite streams used for soil amelioration in literature were also produced using flotation (Banath and Holland, 1976; Metson, 1972) and flotation chemicals did not cause obvious adverse effects for plants or animals in those cases. The use of xanthates is never explicitly mentioned in these papers, however, and the effect of flotation chemicals on pyrite oxidation and plant growth needs to be investigated before application.

6.5.3.3 Minor and trace elements

There may also be some environmentally hazardous minor and trace elements present in the material, the mobility and impact of which will have to be assessed on a case-by-case basis. Initial indications are that trace elements should not pose a significant risk. In a study by Moyo (2018), sequential chemical extraction tests on a sample of Witbank coal slurry waste and Waterberg coal slurry wastes indicated that whilst these wastes contain a number of elements in elevated concentrations relative to the average crustal abundance (including Se, Sb, Mo, As, U, Ba, Sn and Th), their mobility is relatively low and the material posed little risk to soils under neutral and acid leach conditions (Moyo 2018: 142). Elements that were identified as potentially posing a moderate risk to water sources under oxidative leach conditions included Mn, Pb, As, Sb, Al, and Hg (Moyo, 2018).

If any trace elements are present in very high amounts, plants grown on soil treated with sulfide-enriched material may be enriched in these and pose health risks to people ingesting them. Grazing animals may also directly ingest some of the sulfide-enriched material. As discussed in the previous paragraph, this risk is relatively low, due to the low availability under neutral and acid leach conditions, but field trials will nonetheless be needed for confirmation.

6.5.3.4 Pyrite

Whilst the pyrite has beneficial properties for alkaline soil, injudicious application of the sulfide-enriched material may lead to acidification of previously alkaline soils. Due to the high base status of the soils of interest, the risk of acidification is relatively low, but cannot be excluded. Salinisation is also a risk related to injudicious application of sulfide-enriched material to soils, especially since many calcic soils already suffer from salinity. Oxidation of pyrite releases sulfate ions, which can build up and lead to soil conditions that are inhospitable to plants. In agricultural areas in Mpumalanga and the northern areas of the Free State the proximity to industrial sulfur sources, such as power plants, means that soils may already have high sulfur levels. Sulfur is released into the air by power stations and other industry (Barber, 1984; Foth and Ellis, 1996). The underlying soil sulfur levels should also be taken into consideration along with soil neutralisation capacity when deciding how much sulfide-enriched material to apply to soils.

6.6 Conclusions

The literature review has indicated that it is likely to be technically feasible to apply pyrite-enriched material, such as that generated from the treatment of fine coal processing wastes, as an ameliorant for alkaline and calcareous soils found in the drier regions of South Africa. The mapping study identified users that will potentially benefit from application of the material in South Africa: field crop producers of the Free State, North West, Northern Cape and Mpumalanga; livestock farmers of the Northern Cape, Free State, and Mpumalanga; and the horticultural producers of the Northern Cape, Limpopo and Mpumalanga. Potential implementation partners were identified as existing lime and gypsum distributors in the areas of interest.

The costing study showed that due to the long distances between sources of sulfide-enriched material and potential market regions as well as the relatively low pyrite content of the material, the transport costs are high. It is unlikely that application as soil ameliorant will be profitable to mines. A comparison with the market price of alternative soil ameliorants such as gypsum indicates that the direct application of pyrite to soils is unlikely to be financially competitive. The advantages will rather be in the avoiding the costs and liabilities of land disposal.

A preliminary assessment of health, safety and environmental implications has indicated potential spontaneous combustion risks associated with the residual coal content, as well as potential toxicity risks due to residual xanthate reagents used in the desulfurisation process. In general, environmental and health risks associated with minor and trace elements are likely to be low to negligible, due to low concentration levels and/or inert nature.

6.7 Future work

More studies are needed to give a definitive answer as to the viability of this solution. Firstly, studies on the compositional variability of fine coal waste are needed to understand the true variability of the material and develop an understanding of the technical challenges associated with producing a product with a predictable composition and characteristics. The impact of this material in larger scale application of the material on agricultural settings is also imperative for driving the solution toward implementation. Lastly, studies on the safety, health and environmental risks associated with the solution, such as spontaneous combustion of the material on farms in arid regions, as well as their mitigation is needed.

The business case for implementing the solution must be explored in more detail and compared with disposal costs and risks associated with the material. This will provide an important basis for engaging with potential stakeholders and development partners. To facilitate implementation of the solution, engagement with potential development partners must be started as a matter of priority (Stander and Broadhurst, 2019).

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Chapter seven - Conclusions and recommendations

Despite the potential advantages of mine waste valorisation, few examples of commercial implementation of such technologies exist. More mine waste valorisation technologies must therefore be developed to enable improved resource utilisation and reduced environmental impacts. Development of these technologies has historically mostly taken place at universities and research institutions. This project was therefore undertaken to propose a process for universities and research institutions to use in developing mine waste valorisation technologies with the aim of increasing the likelihood of successful development and implementation. To do this, a structured generalised approach for the early stages of design and development of mine waste valorisation technologies was developed in Chapter 2, as shown in Figure 7-1, by drawing on chemical process design, technology development, and innovation literature. The approach was then applied in Chapters 4, 5 and 6 to the case study of South African sulfide-enriched fine coal waste, which was selected due to the environmental risks associated with pyrite-bearing coal waste and the associated risks posed in terms of a just transition away from coal-based energy. This study addresses both technology transfer and data deficiency in the early stages of technology design and development, and is based on qualitative data and literature, consistent with early-stage design.

This chapter summarises the key findings in terms of the hypotheses and key research questions (Section 7.1), before drawing final conclusions (Section 7.2) and making recommendations for further research and development (Section 7.3).

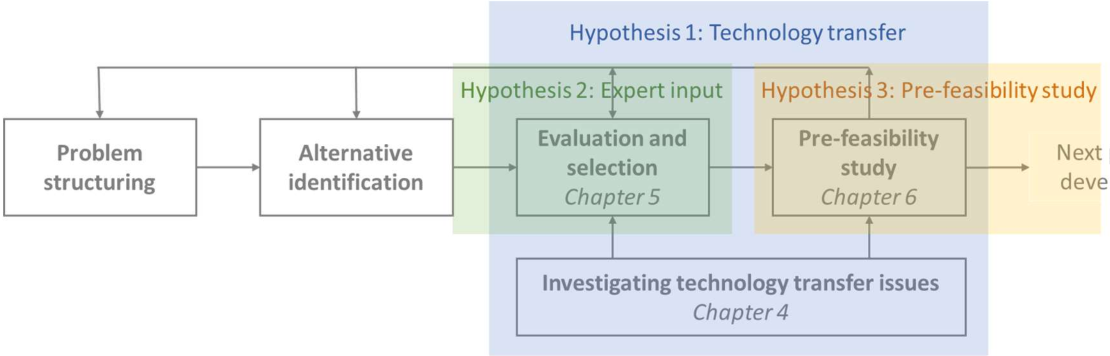

Figure 7-1: The generalised approach for the early-stage design and development of mine waste valorisation technologies.

7.1 Key findings

The key findings are discussed based on the hypotheses and key questions formulated in Chapter 2 and shown in Figure 7-1.

7.1.1 Hypothesis 1

Transfer of technology is important, but it is particularly challenging for universities developing novel technologies. Conventionally, technology transfer is only included in the final stages of technology design and development, but literature has shown that considering technology transfer from the early stages of the process increases the likelihood of transfer. It is within this context that Hypothesis 1, represented by the blue box in Figure 7-1, states that ***technology transfer considerations identified through interviews with industry stakeholders can play a key role in guiding the early stages of design and development of technologies for waste reuse**.* To test this hypothesis, three key questions were formulated and explored through the application of the sulfide-enriched coal processing waste case study. The first two research questions (Section 7.1.1.1 and 7.1.1.2) were interrogated using interviews with South African coal mining industry participants/stakeholders, and the results reported in the journal paper presented in Chapter 4. Sixteen Industry participants were interviewed, and the transcripts were inductively analysed using thematic analysis from a semantic realist perspective to give a rich description of the data. The third research question (Section 7.1.1.3) explored how a knowledge of technology transfer can inform subsequent steps in the early-stage design and development framework, specifically technology evaluation and selection (the subject of the journal paper presented in Chapter 5) and the pre-feasibility study (the subject of the journal paper presented in Chapter 6).

7.1.1.1 Key question 1

What are the potential key enablers and barriers to technology transfer for mine waste valorisation technologies?

During the interviews, several important factors to consider during the design and development of mine waste valorisation technologies for implementation in the South African coal mining industry were identified, as shown in Table 7-1. Firstly, a compelling techno-economic business case is needed for a project to receive funding in competition with the other projects a company considers. This means that the technology must be beneficial in a techno-economic sense for all commercial partners. Respondents noted that reduction in disposal costs or liabilities for the mines can supplement the business case. Business cases are often calculated in terms of internal rate of return (IRR). For relatively immature technologies the expected hurdle IRR might be very high (in the range of 17,5%-30%) and therefore difficult to achieve. This difficulty might be exacerbated, according to the industry participants, by difficulties in achieving economies of scale on environmentally significant, but commercially small, waste heaps.

The business case for waste valorisation technologies was furthermore considered to be predicated on there being a market for the product. Ensuring that a viable market exists, or working towards establishing one, is therefore important even at the beginning of a technology development project.

Participants mentioned that mature technologies are more easily accepted. This is unsurprising since technology development and scale-up is expensive, uncertain, and potentially stretches over long timelines. Mature technologies therefore carry much lower technology risk. Four respondents mentioned that mining companies would prefer to buy well-supported technologies off-the-shelf from trusted technology providers. Proof of concept for individual mines was still considered necessary for mature technologies, however, due to the chemical and physical variability inherent in mine waste.

A related barrier to transfer of waste valorisation technology to the South African coal mining industry is entrenched ideas. The dominant conception of waste valorisation, for instance, was that of burning coal with little reference to other value that could be realised from the material. Some respondents mentioned that the mining industry must be aware of new technologies and see examples of them working for entrenched ideas to change.

Table 7-1 The salient enablers and barriers to mine waste valorisation technology implementation in the South African coal mining industry.

	Enablers	Barriers
Business case	• Business case: lower expenses and liability • Business case: increased income • Having a market	• Technology development is expensive • Technology development takes time • Business risk • Coal juniors have tight budgets • Economies of scale • Ownership of mine waste
Technology development and demonstration	• Industry awareness of technology success • Mature/off-the-shelf technologies • Pilot and demonstration plants that are accessible	• Piloting or scale-up is difficult/effort • Technology must be proven on a mine's own waste • Technology risk • Mine waste heterogeneity • Lack of technical expertise at mines
Corporate values and culture	• Top management aligned in the process • Public and NGO pressure to improve environmental footprints • Improving industry perspectives towards sustainability	• Pre-conceived negative ideas about technology effectiveness • Compliance with legislation is enough to be responsible • Pre-conceived negative ideas about waste • Universities are outsiders to the coal industry • Bureaucracy
Regulatory environ-ment	• Stricter environmental legislation • Good relationships with government by responsible stewardship	• Government entities blocking/not supporting waste valorisation efforts • Some legislation a barrier to implementation of value-from-waste technologies

Respondents mentioned that South African environmental legislation regulating waste disposal has become more stringent, significantly increasing the cost of waste disposal. This improves the business case for any mine waste valorisation technologies that avoid disposal. Despite the advantages that more stringent environmental regulations hold for transfer of mine waste valorisation technologies, some mining-related legislation was considered likely to be a draw-back. An example that was mentioned is the necessity of requesting permission from government departments when activities on a mine site are added or changed. Legislation around liability for, and ownership of, waste is also likely to stifle collaboration between mines.

7.1.1.2 Key question 2

What key partnerships must be developed to expedite technology design, development and transfer?

The technology transfer interviews yielded several important insights that are pertinent to the partnerships that are needed for the transfer of technologies to the South African coal mining industry. A key finding of this study is that mines may not be the most suitable mine waste valorisation technology development partners for universities, due to their core-product-related business strategies and their lack of technical depth. It was mentioned that mining companies, by and large, focus on their core business strategies, producing minerals and metals, and have consequently disinvested specialised technical functions. Several respondents noted that mines are not in the technology development business and would prefer to buy well-supported technologies from trusted original equipment manufacturers (OEMs), as mentioned in Section 7.1.1.1.

Several respondents also noted that the relatively small profit streams likely to be achieved from waste valorisation may lead to neglect of that aspect of the business and therefore perceived failure. Mines also do not have the business strategy of producing other products such as electricity or construction materials, and so do not have structures such as marketing set up for other products. This makes adoption of waste valorisation technologies by mines more difficult. OEMs and commercial waste processors were identified as potentially better development and implementation partners. They already have the business strategy, experience, technical skills, contacts, and credibility with industry to be able to commercialize technologies successfully. The case for partnering with OEMs is strengthened by the fact that one of the ‘technology implementers’ interviewed was in fact an executive at an OEM that was operating and maintaining their technology on behalf of coal mines. Also, in the one example that was mentioned of a waste heap that was worked away, the company doing the reprocessing was external to the mine. Neither OEMs nor commercial waste processors were included as a class of participant in the original study design. Future work should address this research gap.

This does not mean that mines can be ignored during technology development, however. Interviewees noted that they are the owners of the wastes as well as the associated liabilities, which is an important legal issue. Mines are also likely to benefit the most from reduced or avoided disposal costs and liabilities. They are therefore important stakeholders to the technology development process, but unlikely to be active partners.

Respondents suggested that research partnerships with applied research institutions such as the CSIR and Mintek would also be helpful for advancing technology development, because they focus on later-stage development work, while universities tend to focus on lab-scale work. They may therefore provide beneficial contributions to the development process along with commercial partners.

The study has shown the importance of checking assumptions around which organisations are likely to be key development partners. While the ideal partners are likely to vary between technology development contexts, this study shows that OEMs and boutique waste processors are well-placed to help commercialise mine waste valorisation technologies.

7.1.1.3 Key question 3

How can knowledge of potential technology transfer issues inform the early stages of mine waste valorisation technology design and development?

During the decision support process, it is important to consider the values and opinions of stakeholders to the decision to ensure that aspects of value to a group are not missed or ignored. In the case study applied here, criteria for process selection were developed using generic techno-triple bottom line criteria, due to the early-stage nature of this study and the fact that many stakeholder groups remain unidentifiable. Nevertheless, the elicitation of coal industry representatives' perspectives made it possible to probe the completeness and sufficiency of the generic criterion set with regard to their concerns.

For instance, as discussed in Section 7.1.1.1, some of the values that were underscored by respondents were the preference for profitable business cases when selecting capital projects, procuring technologies from external providers and technical maturity. South African coal mining companies would prefer not to spend resources on technical de-risking of novel technologies. The information from the interviews confirmed the significance of criteria related to the business case, including *Profitability*, *Existing market* and *Technical maturity*.

The *Technical maturity* criterion, however, presented a point of conflict during the weighting process, since universities and research institutions are well-placed to develop novel technologies, while industry actors prefer to work with mature technologies. Academics are therefore likely to weight the criterion lower than industry participants. Due to the identified need for novel technologies, however, the university perspective was used during the decision support process.

The same aspects that were used to check the completeness of the criteria were then also focussed and expanded upon in the pre-feasibility study. The business case was investigated by doing preliminary costing of transport due to the long distances products would have to travel by road in South Africa. So too an investigation of potential markets, technical maturity, as well potential risks of an environmental and health nature. Based on the finding that OEMs, specialist waste processors and applied research institutions are likely to play key roles in the development of mine waste valorisation technologies, the pre-feasibility study also identified such organisations in the local industrial contexts of the selected waste valorisation technologies. Yet other aspects arising from the interviews with industry stakeholders were more appropriate for consideration in future work. Examples include investigating the effect of economies of scale, studying environmental legislation, and conducting piloting and demonstration studies.

It is also interesting to note that the act of conducting interviews with industry participants has already started to impact the identified issues of industry awareness and industry perspectives on waste. During the interviews industry stakeholders were made aware of the work that is being done within the University of Cape Town on coal mine waste valorisation. Future publication and distribution of that academic work would be advantageous for advancing this effort.

7.1.2 Hypothesis 2

Application of multi-criteria decision analysis (MCDA) for the early-stage evaluation and selection of mineral processing technology alternatives is characterised by low data availability. This is exacerbated in the case of mine waste, which tends to be heterogeneous and poorly characterised. It is within this context that Hypothesis 2 states that ***expert interviews and questionnaires can support technology selection and contribute positively to early-stage technology design and development for mine waste valorisation in line with sustainable development principles.*** This hypothesis was tested by using expert judgement input of the potential performance of seven mine waste valorisation technologies for sulfide-enriched fine coal waste against several criteria. It formed the basis for the journal paper presented in Chapter 5 of the thesis. In this study, judgement input was elicited using a survey, followed by interviews with selected respondents, and the variability of the performance scores subsequently interrogated using distinguishability analysis. Distinguishability analysis quantifies the extent to which an alternative is distinguishable from the other alternatives being considered and a distinguishability index of 0.5 or higher is considered appropriate for decision support aimed alternative screening (Basson, 2004). Three key research questions were formulated to explore this hypothesis, and the findings for each outlined below (Sections 7.1.2.1 – 7.1.2.3).

7.1.2.1 Key question 1

Does conducting surveys with technical experts lead to the acquisition of data of adequate quality to enable defensible technology selection?

The first part of the study employed linguistic constructed scales, which were later transformed to value functions. Seventeen experts from the minerals and chemical processing industries and research institutions completed the survey. The data of a sub-group of 4 minerals design experts were also evaluated separately. When applying distinguishability analysis to the general expert data obtained for this work, the distinguishability indexes were consistently below 0.2 (see Table 7-2), indicating that the data are inadequately distinguishable to enable defensible decision support. As Stewart et al. (2003) noted: "The ability to make meaningful design decisions is informed by the quality of support information available."

Table 7-2 Distinguishability indexes of all experts and the minerals design experts sub-group.

Technology alternatives	All experts	Minerals design experts
Sulfuric acid	0.09	0.14
Sulfuric acid + paint pigment	0.05	0.20
Ferric Sulfate	0.01	0.13
Ferrous Sulfate	0.05	0.18
Cr(VI) reduction	0.07	0.23
Soil ameliorant	0.17	0.33
Cemented paste backfill	0.01	0.20

To see whether the ‘quality’ of the experts improved the data’s usefulness, the data of a subset of minerals design experts that were highly regarded by the decision-makers were isolated. The distinguishability indexes of the minerals design experts were indeed higher than that of the general expert group (the highest distinguishability achieved improved to 0.33). This is believed to be due to increased accuracy of the group as a whole, rather than similarity of backgrounds and biases, since their backgrounds were diverse and they were not given the opportunity to discuss their opinions. A Montecarlo analysis also showed that the effect is unlikely to be this pronounced if it is simply an artifact of sampling size. The distinguishability indexes indicated that the data are, however, still not suitable for reliable decision support in the context of alternative screening.

In summary, the expert judgement survey data obtained for multi-criteria technology selection using the value function method did not show sufficient agreement to enable defensible technology selection. The results have shown that the use of surveys (without interviews) as a data acquisition method for this type of complex decision problem must be used with care and cannot be accepted without interrogation by a distinguishability index or similar method. These results also indicate that, should expert judgements be used as data for process selection, securing 'high quality' experts to provide judgement inputs is a priority.

7.1.2.2 Key question 2

Does the supplementation of technical expert judgement surveys with interviews improve data quality?

To test whether conducting interviews improved the quality of the expert judgement input data for technology selection, interviews were conducted with the subset of minerals design experts. The interviews used the same survey questions that were used in the unaided questionnaires mentioned above, but only focused on the instances where the greatest data variability was found. This was done to save time and was considered sufficient since the data that did not exhibit great variability ostensibly did not need improvement. The experts were asked for their reasoning for assigning a specific value and given an opportunity to change the value if they wanted. They were, however, not told what values the other experts assigned or whether their opinions were outliers or not. This was done to avoid any pressure to change a value to conform with the group, and to ensure that the assigned values were well-reasoned. Additionally, the interviews were aimed at trying to understand the reasons for data variability between experts.

The results were again analysed using distinguishability indexes. The results (Table 7-3) showed that the distinguishability indexes further improved, indicating that soliciting judgement inputs should be done within an interview context, as opposed to experts providing their judgements without guidance and discussion. The post-interview data was still, unfortunately, unsuitable for reliable decision support since distinguishability indexes were consistently below 0.4.

Table 7-3 Distinguishability indexes for minerals design experts after interviews.

Technology alternatives	Minerals design experts Pre-interviews	Minerals design experts Post-interviews
Sulfuric acid	0.14	0.26
Sulfuric acid + paint pigment	0.20	0.24
Ferric Sulfate	0.13	0.19
Ferrous Sulfate	0.18	0.23
Cr(VI) reduction	0.23	0.33
Soil ameliorant	0.33	0.36
Cemented paste backfill	0.20	0.27

Not all criteria had an average distinguishability score indicating complete indistinguishability after the interviews, however. For instance, *Waste generation*, the most highly weighted criterion, had a distinguishability index of 0.52. If all the top weighted criteria had similarly high distinguishability indexes, a screening exercise using only the high-weighted and high-distinguishability index criteria may have been justified. In this case, however, the other more distinguishable criteria were ranked much lower in terms of their weight (at number 5, 9 and 10 respectively) and other high-weighted criteria had low distinguishability index scores (eg. *Community health and safety* at 0.05 and *SA deficit* at 0.19). This indicates that restructuring of the decision problem would have been unlikely to improve overall distinguishability. Whilst distinguishability could potentially be improved with a larger group of minerals design experts, a preliminary analysis indicated that this group would have to be very large and like-minded, with the concomitant risk of including disciplinary bias, to achieve a distinguishability index above 0.5.

The interviews indicated that the sources of variability included inherent uncertainty in the decision problem; disagreements between experts; interactions between experts and the model (reinterpretation of the given constructed scales or feedstocks); and model-related issues (model ambiguity and criteria confusion).The two top-weighted criteria with low average distinguishability indexes were characterised by disagreement and uncertainty in addition to being affected by model ambiguity and constructed scale reinterpretation. This means that the full extent of the variability of their data is unlikely to be easily resolved.

7.1.2.3 Key question 3

How can data derived from interviews with technical experts add additional value to the technology design and development process?

As mentioned in the previous section, interviews with the minerals design experts allowed for the analysis of interview transcripts to identify reasons for the data variability observed in the survey data as well as technical insights shared by the experts.

This knowledge is useful in several ways. Firstly, in instances where uncertainty, differences of opinion or differences in values are the reason for the variability in the data, it is likely that fundamental uncertainties exist that must be investigated. Further research via modelling or laboratory work may therefore be warranted, especially when the affected criteria are high-weighted. Knowledge of misunderstandings, assumptions and confusion can also be useful for shaping future versions of the decision support instrument to be more user-friendly.

In addition to providing evidence on the reasons for variability within the decision support questionnaire data, interviews also provided other useful information. The experts interviewed were generous in providing technical insight, market intelligence, and projections. For instance, Expert D mentioned the technical difficulty around neutralising the acidity produced in the production of ferric and ferrous sulfate and the large volumes of lime that would be required. They also mentioned that large volumes of gypsum waste is likely to result. This provided insight into at least one technical hurdle that must be cleared before these technologies can be commercially implemented. Likewise, Expert Q commented on how the market for ferrous sulfate is saturated. They mentioned that it is easily obtainable from titanium pigment producers, which provides a point of departure for further investigating the markets for both ferrous and ferric sulfate. The semi-structured, criteria-driven interviews also ensured that all the aspects of importance were covered in some technical detail, providing justification for the use of criteria in technical judgement elicitation interviews.

Hence, although interviews with technical experts did not yield data of sufficient quality and appropriate for reliable technology selection, it did provide useful information which can guide the development of technologies into the future. Conducting interviews with a few trusted experts therefore appears to be a better use of resources than conducting questionnaires with many experts.

7.1.3 Hypothesis 3

While technology selection using MCDA approaches focuses on generic aspects of importance for further design and development, the successful implementation of such technologies also depends on local and context-specific factors. Pre-feasibility studies can potentially provide a framework for investigating these factors in a non-data-intensive way. For this reason, the third hypothesis states that ***pre-feasibility studies which apply publicly available data and first-order calculations can play a key role in supporting the establishment of a sound business case and programme for the systematic development and implementation of mine waste valorisation technologies.*** This hypothesis was explored through a desktop study on the application of sulfide-enriched coal waste for the amelioration of alkaline soils and formed the basis of the journal paper presented in Chapter 6.

7.1.3.1 Key question 1

Based on requirements identified in the technology transfer work, what data and information are required for a pre-feasibility study to assess the technology viability at the early stages of technology development for mine waste reuse?

Local factors strongly influence the viability of a solution. These do not necessarily only consider the impacts such as governance systems, logistics networks and industrial capacity at a local community level, but also at the meso-scale of province and country. The impacts of local issues must be identified, analysed, and incorporated into a pre-feasibility study to ensure that the business case is defensible.

Based on the outcomes of the technology transfer interviews (Section 7.1.1.1), technical viability, economic viability and market factors are key considerations for implementation of mine waste valorisation technologies in the South African context. The early identification of implementation partners was also considered important. These factors must therefore be considered in the early phases of design and development to increase the likelihood of eventual technology transfer. Due to the background of the project, with a strong sustainability focus, it was acknowledged that environmental and social impacts were also key.

In the specific context of this particular case study, and given the absence of an established market for agricultural pyrite in South Africa, the potential markets for the material had to first be identified based on the technical parameters of the solution. For instance, pyrite (the major form of sulfide present in the coal processing waste) is only beneficial for the amelioration of alkaline soils, especially those with iron and sulfur deficiencies. The areas in South Africa that are likely to be covered by alkaline soils were therefore identified and the types of agriculture practiced on those soils, in that climate, also had to be identified. Also of key relevance to markets is the quality of the likely end-product. For instance, in the case of amelioration, pyrite content (the active ingredient) is important in terms of application rates of product required, whilst particle size distribution is also a key parameter controlling the rate of oxidation and thereby the release of acidity and soil nutrients. The extent to which appreciable oxidation continues over several growing seasons also determines whether regular re-application is needed, contributing to the value proposition to potential customers.

The financial viability of a solution is a vital consideration, as shown by the importance placed by South African coal industry participants on having a convincing business case. In the case of the pre-feasibility study, the costing exercise was simplified to the calculation of one cost-item, road transport costs, due to the long distances between economic centres in South Africa and the poorly developed rail infrastructure. To calculate whether transport costs alone allowed for profit, these were compared with the all-in pricing (product plus transport cost) of the current industry alternative to pyrite, gypsum. The quality of the final product also has a bearing on the financial viability. In the case of the soil amelioration case study, the pyrite-content in the coal waste determines the amount of product that is required per application unit, and hence the transport costs.

Given that waste streams generally contain several components in varying concentrations, the potential environmental, safety and health risks associated with different components during processing and/or application likewise needed consideration, based on the constituents of waste material. In the case of the application of sulfide-enriched waste material, the constituents of interest include residual coal, residual flotation chemicals, and minor and trace elements.

7.1.3.2 Key question 2

What input data and methods are suitable to derive this information?

The findings in Section 7.1.3.1 discussed the type of information that can be generated when conducting a pre-feasibility study. In integrating such studies into early-stage design, it is equally important that data and resource requirements (including time, money, equipment and infrastructure) for such studies remain manageable. This is particularly important in the case of mine waste valorisation, due to the significant data deficits typically encountered. In the case study explored here, use was made of publicly available data, such as Google Maps and Statistics South Africa reports, industry publications and academic literature.

Academic literature on soil amelioration using pyrite provided a starting point for assessing the technical feasibility of the solution as well as the potential health and safety impacts. This was sufficient for the pre-feasibility study since it provided insight into the available science of the solution. It also provided information on the maturity of the technology, as well as the developmental requirements. The data needed for doing the market analysis included identification of types of alkaline soils found in South Africa (Silicic, Calcic and Vertic soils), where these are located as well as agricultural production data for these areas. Soil types were identified through literature and located using soil maps from the Agricultural Research Council of South Africa. Relatively recent agricultural production data was obtained from Statistics South Africa's 2017 census of commercial agriculture. Although aggregated to a municipality level, the data was sufficient to provide a starting point for analysis. It allowed for the identification of commodity types of interest in specific regions, providing a basis for identifying specific farmers that could benefit from the material. It also enabled the calculation of rough travel distances. Overlaying the soil and agricultural data on top of each other facilitated the identification of potential key markets. The potential size of the market was also compared with the production of sulfide-enriched coal waste, thereby estimating the size of the market that might be serviced. Potential implementation partners were identified as an important consideration during the technology transfer component of the work and distributors of agricultural chemicals were identified as key marketing partners. These were identified from agricultural industry publications.

As transport costs were identified as one of the key economic factors, the pre-feasibility assessment of financial viability was simplified to a comparison between the product transport cost and all-in competitor product cost. It proved to be a useful starting point to assess the financial viability of the solution. Transport costs were calculated per hectare to create a common basis for comparison despite different application rates for pyrite and gypsum. To calculate transport costs, the following parameters were used: distance, travel cost per tonne and kilometre (an industry metric), and application rate information for both sulfide-enriched fine coal waste and gypsum. This necessitated obtaining data on the distances between sources of sulfide-enriched coal waste and potential markets. This was done using the market information obtained in the previous section to identify the potential destinations of trucks as well as the sources of sulfide-enriched coal waste. The distances between these locations were then obtained using directions information from Google Maps. The cost per tonne and kilometre of truck transport was found from industry publications and pyrite application rates from literature were assumed. This significantly simplified the problem and still provided enough information to comment on the potential viability of the business case. The transport cost per hectare of sulfide-enriched fine coal waste was in most cases far above that of the product and transport cost of gypsum.

Finally, the application of a simple sensitivity analysis provided a useful method for assessing the importance of the different aspects of the pre-feasibility study to the business case. The sensitivity analysis has, for instance, shown that a lower pyrite content of the sulfide-enriched coal waste material leads to precipitous increases in transportation costs. This indicates that the technical factors of pyrite recovery and selectivity during flotation are key if the material is to be used as a soil ameliorant in South Africa. Other aspects, such as truck utilisation factors were also shown to be important.

7.1.3.3 Key question 3

How can the information derived from a pre-feasibility study guide design and development?

The pre-feasibility study, as employed in this study, provided several lines of information: technical, costing, market, and environmental, health and safety information. Each of these identified key aspects that influence the technology's viability within the South African context and that require further investigation to de-risk the technology.

The pre-feasibility study showed, for instance, that the most important issue affecting the financial viability of the logistics is the long distances that the material must travel to market. The distance between the source and the largest potential markets can be more than a thousand of kilometres. There are, however, small pockets of alkaline soils located closer to mining areas. This knowledge can be used to prioritise development of soil ameliorant tailored to the requirements of farmers located near mines. While the potentially alkaline soil areas near mines are small, the analysis showed that large land areas may not be needed to absorb all the sulfide-enriched coal mine waste produced in a year. These areas can potentially be identified with the help of the bulk agricultural chemical suppliers in the region.

In addition to the long distances, the sensitivity analysis showed how severely lower sulfide recovery rates can affect transport costs. Every kilogram of material in the product that is not pyrite increases transport costs. The effectiveness of the flotation separation process therefore plays an important role in creating a viable business case and therefore must enjoy priority in future technology development efforts.

Reducing the loading rate will also reduce the amount of material that needs to be transported. For instance, the extent to which the material is effective over multiple growing seasons will play an important role in determining the acceptable transport cost and therefore the justifiable distances to market.

Currently, however, the application of such waste as a soil ameliorant, and the technical factors affecting efficiency, remains largely unexplored. The pre-feasibility study indicated that there are a number of important factors that require further empirical investigation. For instance, the effectiveness of the sulfide-enriched coal waste for improving plant growing conditions on different local alkaline soils must be investigated. The importance of particle size distributions on pyrite oxidation rates has been demonstrated, but the 'requisite' particle size ranges for South African sulfide-enriched fine coal waste in the field are unknown. The optimal application rates for different soils and different agricultural commodities must be investigated. Lastly, it is also necessary to establish the robustness of the application. The literature investigation into material properties underscored the variability of mine wastes. The extent of their variability and their contaminant content post-separation are important factors determining the technical viability of the solution for large-scale implementation. Apart from demonstrating technical feasibility, these studies will also provide useful data for a more detailed study of the business case, considering both the CAPEX and OPEX, product pricing, and incorporate the consideration of avoided disposal costs.

The environment, health and safety assessment as part of the pre-feasibility study identified several risks associated with the application of the material to soils, including the risk of spontaneous combustion. Investigations into the risks associated with the residual coal content, minor and trace element content and degrading flotation chemicals are needed. This must be done both on a laboratory scale and tested in pilot applications of the materials in agricultural settings. Efforts should also include improving separation specificity for coal flotation, due to the fire risks associated with coal.

7.2 Concluding remarks

This thesis set out to develop a generalised approach that universities and research institutions can use for the early-stage design and development of mine waste valorisation technologies. Reusing mine waste in a way that utilises, or at least neutralises, its inherent risks has the potential to create value in addition to removing risk. Reusing mine waste is consistent with resource efficiency and circular economy principles and can be used to support the wider sustainable development project. The aim of the generalised approach was to provide a structured and scientifically rigorous approach to the early stages of design and development of such technologies. This was done by combining the theories of sustainable chemical process design, technology development and innovation, and incorporated technology transfer activities, MCDA-based decision support for technology selection and a pre-feasibility study. The generalised approach was applied to the case study of the valorisation of sulfide-enriched fine coal waste, but it can readily be extended to other waste streams.

7.2.1 Concluding remarks regarding generalised early-stage mine waste valorisation design and development approach

The generalised approach for the early-stage design and development of mine waste valorisation technologies included consideration of technology transfer from academic and research institutions to industry in the early stages of the technology design and development process. This enabled the testing of assumptions about who the academics' key partners are likely to be as well as building an understanding of industry priorities and motivators. In so doing, it provides a basis for the design and development of waste valorisation technologies to increase the likelihood of implementation.

The procurement of data to score different options in accordance with the selection criteria, however, remains problematic. The MCDA approach to technology selection using expert judgement input obtained through either surveys, or surveys combined with interviews, did not provide data appropriate for defensible technology alternative selection. This is despite efforts at conducting a rigorous, theoretically founded decision support process. These results show that there may therefore be value in questioning the bases of traditional design decision-making tools such as Pugh matrixes and quality function deployment. These early-stage decision approaches also make use of technical experts' judgement input as data, but practitioners tend to make less of an attempt at creating common understanding, well-defined criteria, or theoretically founded results than for more formal MCDA methods (Ayag and Özdemir, 2009; Bertoni et al., 2017). An improved approach to technology selection for early-stage design and development of waste valorisation technologies is therefore still needed.

Obtaining expert judgement input on technical matters can, nonetheless, be very useful for technology design and development. The experts provided insight into technologies, including potential problems and advantages. This information can enable the setting of experimental priorities and development trajectories.

Involving technical experts, especially from relevant areas of industry, in this phase of technology design and development is also a form of creating industry awareness, which the technology transfer interviews have shown is necessary for expediting technology transfer. It may also be a useful tool for assessing potential industry partnerships and help create a sense of ownership in industry partners. Technical interviews can therefore be a technology transfer activity in their own right. The efficacy of this approach was not the focus of this work and must therefore still be investigated.

Pre-feasibility studies, traditionally a tool for making investment decisions, was repurposed in this study for assessing the practicalities of implementation into a specific context. This complements the MCDA-based selection step during which the technologies are evaluated in a generic sense. It is not certain, however, that the selected technology will be useful in the location and context where the mine waste is being generated. In the pre-feasibility study, the technology appropriateness is tested by considering local factors relevant to implementation and the relative impact of different factors is tested using sensitivity analysis. This provided useful information on the factors likely to influence commercial viability and uptake of preferred options for specific geographical contexts and cases, which can be used to guide further R&D studies with a view to de-risking. The pre-feasibility study scope was, however, guided strongly by the views of industry and industry-support representatives on technology transfer concerns and barriers, which emphasised techno-economic aspects, as opposed to social aspects.

In conclusion, the generalised approach for design and development of waste valorisation technologies developed in this thesis can support universities and research organisations in structuring the early-stage design and development of technologies with the aim of bringing effective technologies to market. This has the potential to improve the development rate and implementation success of waste valorisation technologies and thereby reduce the mining industry's negative environmental and social footprint.

7.2.2 Concluding remarks regarding the case study

Apart from testing and demonstrating the generalised approach, the case study on the valorisation of sulfide-enriched fine coal waste has stand-alone significance due to the associated environmental impacts that emanate from both current and historical coal mine waste facilities. The coal industry is a sunset industry, which will likely continue a slow and steady decline. This underscores the importance of addressing environmental impacts sooner rather than later to avoid a scenario where legacy coal waste facilities continue to affect nearby landscapes and communities, but where the resources for addressing these issues have run dry. Addressing the negative environmental legacy of coal mining is therefore an important step towards ensuring a Just Transition to renewable energy. The interviews conducted with industry representatives in this study have, furthermore, shown that the coal industry considers itself to be under threat. This makes it more risk averse and less inclined to be innovative, which was reflected in the interviews on barriers and drivers for technology transfer.

It should be noted that, although the outcomes of the MCDA method based on expert judgment needs to be treated with caution due to the high uncertainty, several alternative valorisation technologies for sulfide-enriched fine coal waste were consistently more highly ranked than the others. These included soil amelioration, cemented paste backfill and sulfuric acid production. While the further development of these options may not continue with the same level of confidence that it might otherwise enjoy, they nevertheless present the most likely avenues for gainful further development based on the available information.

Soil amelioration was considered further in this study and it was shown that, due to high transport costs, the viability of the solution is strongly dependent on identifying potential markets near to the waste-producing mines. If the material can be shown to slow-release S and Fe, thereby avoiding the need for repeated applications, further transport distances may nevertheless be justified. The pyrite content of the final material was also shown to strongly affect transport costs. The efficacy and safety of the material for agricultural application remain two important aspects to investigate.

7.3 Recommendations

This section considers both recommendations for further development of the generalised early-stage mine waste valorisation design and development process and the future development of the case study.

7.3.1 Recommendations for improving the generalised approach

The value of a systematic approach to the early-stage design and development of waste valorisation has been demonstrated. The study has nevertheless also highlighted several challenges. Recommendations for further developing and improving the generic approach are outlined below:

Alternative identification: While alternative identification is foundational to any technology design and development work, it was not a focus in this study. The challenge with finding data on which to assess the identified alternatives nevertheless also makes it difficult to identify or create innovative mine waste valorisation technology alternatives. Approaches for improving the innovativeness of identified mine waste valorisation technology alternatives would therefore be a useful field of study.

The role of interviews with industry representatives: The interviews with technical experts can be construed as a technology transfer activity in its own right, since they provide opportunities for industry participants to become familiar with the different technical options available for valorising a specific mine waste. The interviews can also potentially help create industry interest in the preferred solutions and create a sense of ownership from industry. Similarly, the efficacy and appropriateness of employing technical decision support or development-related interviews with industry participants as tools for enabling technology transfer must be tested. This may be a particularly convenient approach for academics looking to design and develop mine waste valorisation technologies, since it achieves three objectives (obtaining technical insight, creating industry awareness and identifying future development partners) in one task. Assurance of the approach's efficacy would therefore be helpful for future technology development efforts.

Evaluation and selection of alternatives: The approach of using expert judgement input as data for MCDA-based process selection has been shown to not be sufficiently rigorous for this case study and potentially for other contexts as well. The judgement input of technical experts and the results from the pre-feasibility study did, however, provide some measure of demonstration of the technology alternative's appropriateness for implementation into the South African context. Van Vliet et al. (2020) showed that expert judgement input and modelling studies provide different and potentially complementary perspectives in risk assessments for low-carbon transitions. A decision support and technology development approach that uses both expert input and pre-feasibility modelling may therefore provide a defensible basis for process selection. The approach may include an additional screening step to reduce the number of alternatives considered, followed by interviews with subject experts based on specified criteria. These interviews would not aim to obtain scores based on constructed scales, but rather a judgement of the technical, social, environmental and economic issues that might accompany a technology. After this, pre-feasibility studies can be conducted, using the leads obtained from experts as a starting point. The results of the pre-feasibility studies and expert interviews can then be combined and used to motivate for the selection of technologies for further development. This approach would hopefully allow for the consideration of known technical issues without being constrained by entrenched ideas. It would also allow for the inclusion of a wider range of concerns from a societal perspective as well. Refinement and testing of this approach may result in a more satisfactory decision support method for early-stage mine waste valorisation technology selection.

Distinguishability index: The outcomes of the alternative evaluation and selection step used the distinguishability index threshold suggested by Basson (2004) for conducting a screening exercise (0.5). The relevance of this distinguishability index threshold in technologies for valorising mine waste has not been rigorously tested to date. Arguments for both a higher or lower threshold value are plausible. Further research into the allowable distinguishability index threshold is therefore needed.

Engagement with a broader set of stakeholders: The input from coal industry participants into aspects of importance for technology transfer contributed to ensuring the completeness of selection criteria. While the importance of the input of other stakeholders, such as community members and governmental bodies, is well recognised, the approach by which to ensure the completeness of the criterion set regarding these stakeholder groups, who are less easy to include in the early stages of technology design and development, remains a challenge. Corder (2015) suggested canvassing employees or other individuals who are from the affected stakeholder groups or might hold or sympathise with similar values. In the absence of such individuals, for instance future inhabitants of the as yet unknown area of implementation, obtaining stakeholder values in the problem structuring phase and the exploration of technology transfer remains a problem. In this study, important factors affecting communities were identified through generic techno-triple-bottom-line sustainability criteria. Expansion of approaches for including the concerns of various stakeholders, and their efficacy will be valuable. In particular, it is recommended that future pre-feasibility studies include consideration of potential community and end-user concerns as well as regulator concerns around risk and benefits. These issues are important, since community opposition to the implementation of a proposed technology can prevent such a project from continuing.

Case studies of successful implementation of mine waste valorisation technologies: While outside the scope of this study, case studies of successful implementation of mine waste valorisation technologies in other countries and in other sectors (e.g., agriculture and civil engineering applications) will be useful for improving the understanding of what the determinants of successful implementation are. The outcomes of such studies can be used to expand and refine the generalised approach put forward in this thesis.

7.3.2 Recommendations for development of the case study

In terms of the case study of the valorisation of sulfide-enriched fine coal waste, several recommendations are appropriate.

Technical and business case-related research: The technology transfer interviews identified aspects requiring further research. These include exploring the business case, particularly the effect of economies of scale and the variability of South African fine coal mine waste. The importance of achieving economies of scale was also mentioned during the technical decision support interviews. This was not investigated at the pre-feasibility study stage since public mine waste characterisation data sources were unavailable, but it is an important consideration for any mine waste valorisation technology being developed.

The pre-feasibility study has furthermore shown that some knowledge gaps must be addressed in future development work to be able to give clear guidance as to the viability of the solution. Firstly, a more thorough investigation is required to establish whether avoiding high disposal costs would provide sufficient incentive for mines, OEMs and other companies to partner with universities in developing soil amelioration as a mine waste valorisation technology. Furthermore, the impact of this material in larger scale application in agricultural settings and its efficacy over multiple growing seasons must also be investigated in a piloting study. Lastly, studies on the safety, health and environmental risks associated with the solution, as well as mitigation of any such risks, is needed. An example is spontaneous combustion of the material on farms in arid regions. Insight into these issues will provide an important basis for engaging with potential stakeholders and development partners.

Progress with regards to commercial partners: One of the key outcomes of this study was the potential importance of partnering with OEMs and boutique waste processors. Future work must therefore identify issues of significance to OEMs and boutique waste processors, specifically within the South African coal mining industry, and consolidate this understanding with the results discussed in Hypothesis 1. The pre-feasibility study noted potential marketing and development partners (the companies who already sell bulk agricultural chemicals), but not mining technology providers who already have relationships with mines. This is an area of research that must be addressed to facilitate implementation of viable technologies.

Engagement with a broader set of stakeholders: The further development of options needs to include engagement with the broader set of stakeholders to ensure that any concerns that may have arisen in the pre-feasibility study and potential barriers to implementation are addressed. In the soil amelioration case study, these would include commercial farmers, farm employees and dwellers, subsistence farmers, transporters, regulators and local government. A potential avenue for engaging and building relationships with stakeholders is to run the pilot studies as "living laboratory" projects which would include stakeholder visits and workshops. Such a programme would also serve to create greater awareness of opportunities around waste valorisation to a wider audience.

Local context: The technology transfer interviews identified that the South African regulatory environment provides both support and headwinds for mine waste valorisation technology implementation. While an attempt has been made to understand the impacts of the South African regulatory environment on mine waste valorisation (Haywood et al., 2019), a more comprehensive study is needed. An approach for technology developers to overcome regulatory headwinds must also be created.

Other valorisation options: While the pre-feasibility study focused on soil amelioration as an option for the reuse of sulfide-enriched coal mine waste, other technologies are also potentially viable contenders. These include sulfuric acid production and cemented paste backfill. Further consideration of these technologies must not be neglected.

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Appendix A Mine waste valorisation research institutions

Table A 1 shows a selection of the institutions that have contributed to or conducted mine waste valorisation research, based on the available literature. This shows that, while commercial funding is not unheard of, mine waste valorisation research is conducted mostly with public funds. Commercial partners in conducting the research itself is also not common.

Table A 1 A selection of papers on beneficially using mine waste.

Authors	Author affiliations	Type of mine waste	Suggested uses	Industry participation /funding
(Acordi et al., 2023)	Universidade Federal de Santa Catarina, Brazil Universidade do Extremo Sul Catarinense, Brazil	Coal mine waste	Bricks Cement Concrete Road construction Soil amendment	Public grant funding
(Allard et al., 2022)	Université du Québec en Abitibi-Témiscamingue (UQAT), Canada University of Sherbrooke, Canada SLN—Société le Nickel,	Sulfide concentrate	Re-mining, reuse of gangue for mine waste covers or construction	**Contribution to funding by "Industrial partners" is mentioned. Presumably they are referring to SLN.** **Public grant funding**
(Amaral Filho et al., 2020)	University of Cape Town, South Africa Federal University of Rio Grande do Sul, Brazil	Coal mine waste	Production of a fabricated soil for mine rehabilitation	Public grant funding
(Barati et al., 2020)	Shiraz University, Iran Shiraz University of Technology, Iran	Iron tailings	Road construction	Funding by academic institution
(Bellenfant et al., 2013)	French Geological Survey (BRGM)	Survey of tailings facilities in France	Screening for tailings re-mining	Public funding
(Benahsina et al., 2022b)	Cadi Ayyad University, Morocco Chouaib Doukkali University, Morocco Mohammed VI Polytechnic University, Morocco	Copper mine waste rocks	Aggregate in concrete	None mentioned

(Binnemans et al., 2015)	Katholieke Universiteit Leuven, Belgium	Phospho-gypsum Bauxite waste	Recovery of target minerals (rare earths, iron, aluminium) Cement Gypsum plaster Fertiliser	Public grant funding & Funding by academic institution
(Blasenbauer et al., 2020)	European cooperation in science & technology Technische Universität Wien, Austria	Global mine waste facilities	Characterisation for re-mining	Public grant funding
(Chugh, 1992)	Southern Illinois University, USA *University of North Dakota, USA *Energy and Environmental Research Center, USA *Electric Power Research Institute, USA *U.S. Bureau of Mines *U.S. Department of Energy *U.S. Environmental Protection Agency *Purdue University, USA *Pennsylvania State University, USA *Baker, Inc. *Radian Corporation	Coal combustion products	Gypsum wallboard Construction materials Backfill Cement Recovery of target minerals Catalysts Mine reclamation Highway construction Agriculture	Public grant funding
(Colling et al., 2011)	Universidade Federal do Rio Grande do Sul, Brazil	Coal tailings	Producion of ferric sulfate from pyrite inherent in waste	**A combination of (presumably) industry body funding (Brazilian Coal Net) and public funding**
(Fan et al., 2014)	China University of Mining & Technology Xinjiang University, China	Coal mine waste	Backfilling Underground roadways Brick making Electricity generation Rehabilitation of land subsidence	Public grant funding
(Fleming et al., 2010)	SGS Group	Gold tailings	Re-mining and de-risking	Company sponsored – the company provides risk management services to the mining industry.

(Golev et al., 2022)	University of Queensland, Australia University of Geneva, Switzerland Federal University of Minas Gerais, Brazil	Iron ore tailings	Sand replacement in construction	**Vale (mining company) funded the research**
(Haibin and Zhenling, 2010)	China University of Mining &Technology (Beijing) Henan University of Technology, China	Coal waste	Waste partitioning and reuse	Public grant funding
(Helser et al., 2022)	KU Leuven, Belgium University of Oulu, Finland	Base metal mine waste	Ceramics and construction materials	Public grant funding
(Kazadi Mbamba et al., 2013)	University of Cape Town, South Africa	Coal tailings	Re-mining and reuse of benign fraction.	Public grant funding
(Khaldoun et al., 2016)	Mohammed V University, Morocco	Gold-mercury tailings	Cemented paste backfill	None mentioned
(Li and Han, 2006)	Wuhan University of Science and Technology, China	Coal mine waste	Advanced ceramic powders, Refractory materials Cement and concrete	None mentioned
(Li and Hitch, 2016)	University of British Columbia, Canada University of New South Wales, Australia	Nickel waste rock	Carbon sequestration	Public grant funding
(Maroušek et al., 2023)	Montanuniversität Leoben, Austria GKB-Bergbau GmbH	Lead-zinc waste rock	Characterisation for re-mining	One of the authors is employed by a mining consultant cum construction company operating in historic mining areas Public grant funding
(Menezes et al., 2017)	Universidade do Oeste de Santa Catarina, Brazil Universidade Federal do Rio Grande do Sul, Brazil Faculdade Meridional (IMED), Brazil	Coal tailings	Producion of ferric sulfate from pyrite inherent in waste	**A combination of (presumably) industry body funding (Brazilian Coal Net) and public funding**
(Meyer et al., 2014)	University of Cape Town, South Africa	Platinum group metals tailings	Carbon sequestration	Pubic grant funding

(Nwaila et al., 2021b)	University of the Witwatersrand, South Africa Luleå University of Technology, Sweden PG Techno Wox (Pty) Limited Tolmay Enterprises University of Johannesburg, South Africa University of Würzburg, Am Hubland, Germany University of Cape Town, South Africa	Hypothetical copper-cobalt tailings	Characterisation for re-mining	Two of the authors are consultants Public grant funding
(Pactwa et al., 2020)	Wrocław University of Science and Technology, Poland	Coal mine waste	Power generation from low-grade coal	Public grant funding
(Riina et al., 2014)	Lappeenranta University of Technology, Finland	Base metal tailings	Re-mining	**The project was partly funded by public grant funding, but partly funded by original equipment manufacturers**
(Segura-Salazar and Franks, 2023)	University of Queensland, Australia	Gold and copper mine tailings	Use as sand	**Project funded by Newcrest Mining**
(Stolboushkin et al., 2016)	Institute of Thermophysics, Novosibirsk, Russia Siberian State Industrial University, Russia	Coal mine waste	Ceramic bricks	Public grant funding
(Suppes and Heuss-Aßbichler, 2021)	RWTH Aachen University, Germany Gesellschaft für Consulting, Business und Management mbH Ludwig-Maximilians-Universität München, Germany	German tailings facilities	Screening for tailings re-mining	One of the authors had ties to a commercial consulting and training company. Public funding
(Taha et al., 2022)	Mohammed VI Polytechnic University, Morocco University of Cadi Ayyad Morocco	Coal mine waste	Shales for brick production Aggregate in concrete Sand replacement	Public grant funding

(Veetil et al., 2015)	Institut national de la recherche scientifique, Canada The University of Melbourne, Australia	Iron ore	Carbon sequestration	Public grant funding
(Veiga Simão et al., 2022)	Central Laboratory for Clay Roof Tiles, Belgium KU Leuven, Belgium VITO NV, Belgium ETH Zürich, Switzerland	Base-metal mining waste	Production of bricks	One of the authors is employed by an independent research organisation Public grant funding
(Vigânico et al., 2011)	Universidade Federal do Rio Grande do Sul, Brazil	Coal tailings	Production of ferrous sulfate heptahydrate from pyrite inherent in waste	**A combination of (presumably) industry body funding (Brazilian Coal Net) and public grant funding.**
(Zhang et al., 2014)	University of Arizona, USA Chinese Academy of Sciences	Copper tailings	Geopolymerised construction materials	**Research chair funding from Freeport-McMoRan Copper & Gold**
(Zhou et al., 2019)	Tianjin University, China	Bayer red mud (aluminum tailings)	Recovery of alkali	Public funding
(Žibret et al., 2020)	Geological Survey of Slovenia French geological survey (BRGM) Technical University of Madrid, Spain SERENGEO Srl University of the West of England Cardiff University, Wales Mining and Geological Survey of Hungary Universidade de Lisboa, Portugal	European mine waste facilities	Screening for re-mining of mine waste or reuse as construction materials	One of the authors has ties to a geoengineering services company Public grant funding

*Not author affiliations, but institutions conducting coal combustion waste valorisation research

Appendix B Process development and design

B.1 Chemical process design schematics

This section shows the schematics used to describe chemical process design steps in various literature sources.

Figure A 1 "Normal 'linear' models for design process" by Dym et al. (2009).

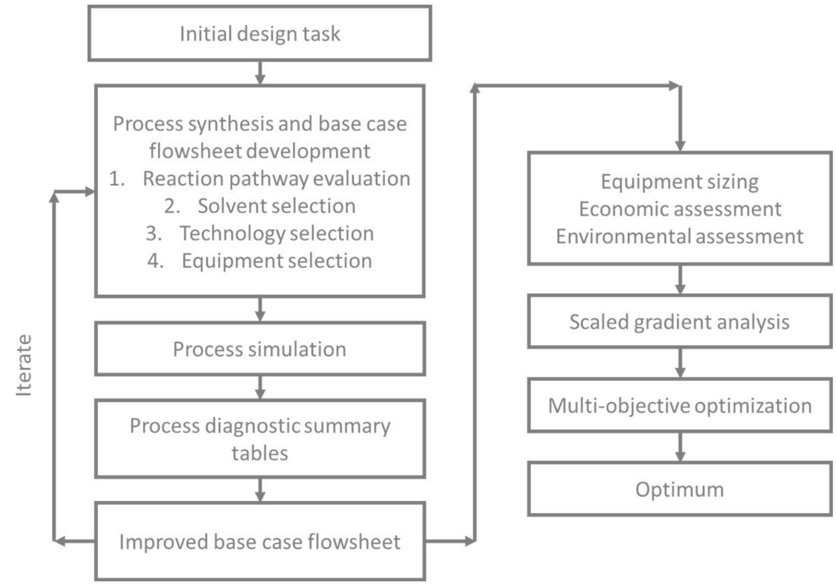
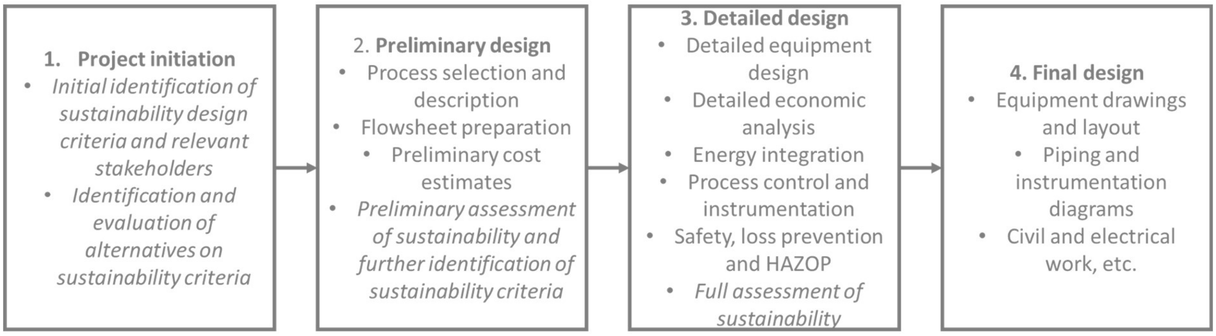


Figure A 2 "Framework for environmentally conscious process design" by Chen and Shonnard (2004).



Text in italics represent design stages related to sustainability
Normal text represent stages in traditional design

Figure A 3"Stages in process design for sustainability" by Azapagic et al. (2006).

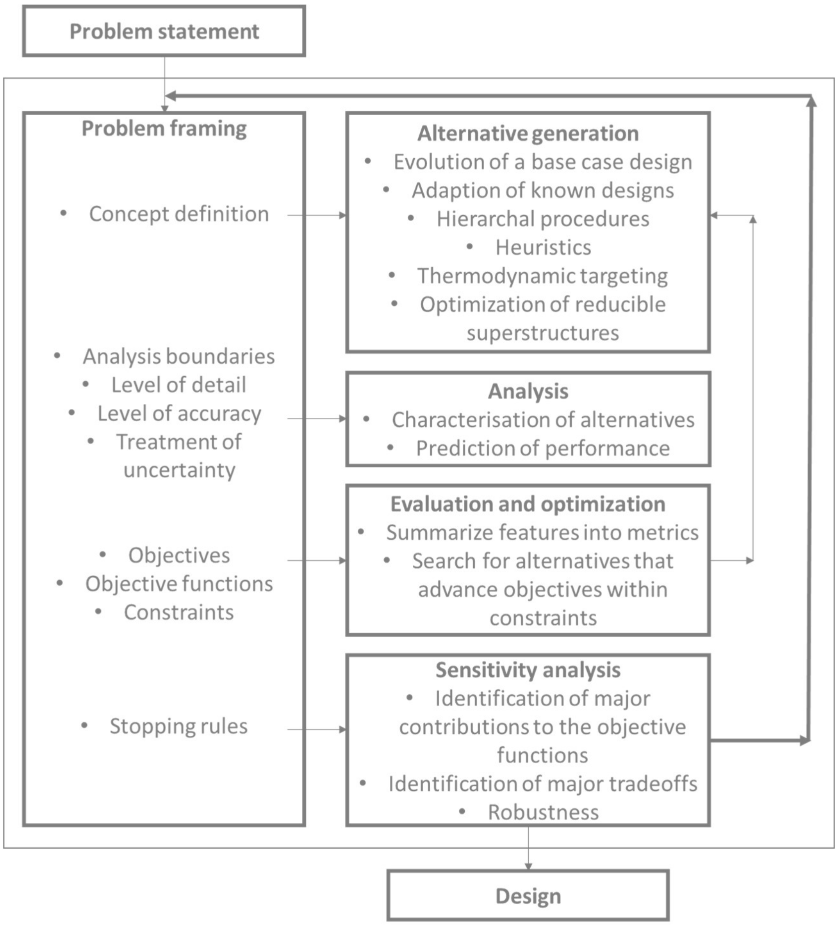


Figure A 4 "The design process" by Cano-Ruiz and McRae (1998).

Figure A 5 "The structure of a chemical engineering project" by (Towler and Sinnott, 2008).

Table A 2 An example of the integrated design hierarchy decision sequence (Douglas, 1988; Stewart et al., 2003)**.**

Design stage	Step	Design hierarchy decision
Project selection	A	Process selection
Initial design	0	Input information gathering
	1	Batch vs continuous
	2	Input-output models
	3	Recycle structure
Detail design	4	Separation systems
	5	Energy integration

B.2 Technology development schematics

B2.1 Problem-driven technology development approaches

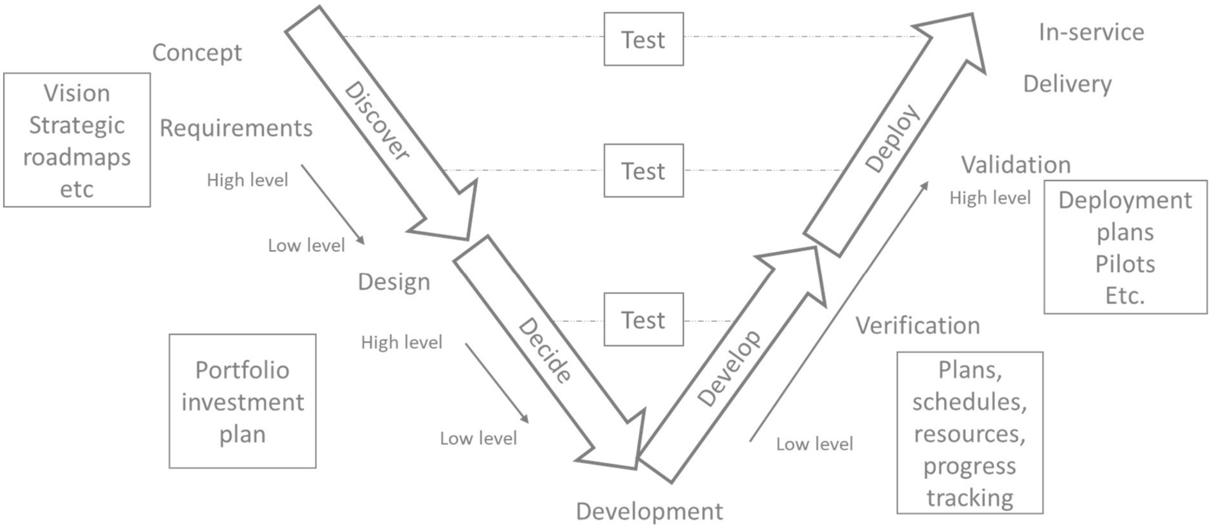


Figure A 6 "Global enterprise technology system" (Lind, 2006)

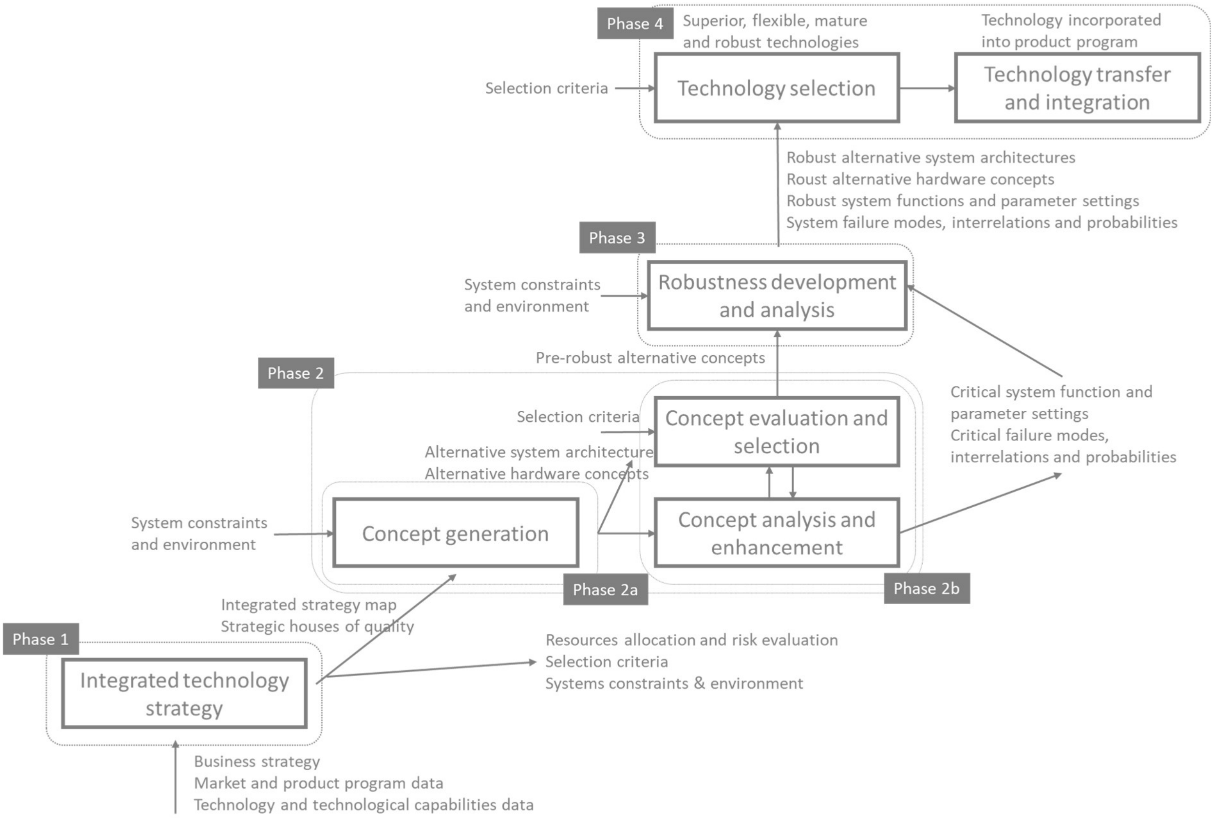


Figure A 7 "Total technology development model" (Schulz et al., 2000)

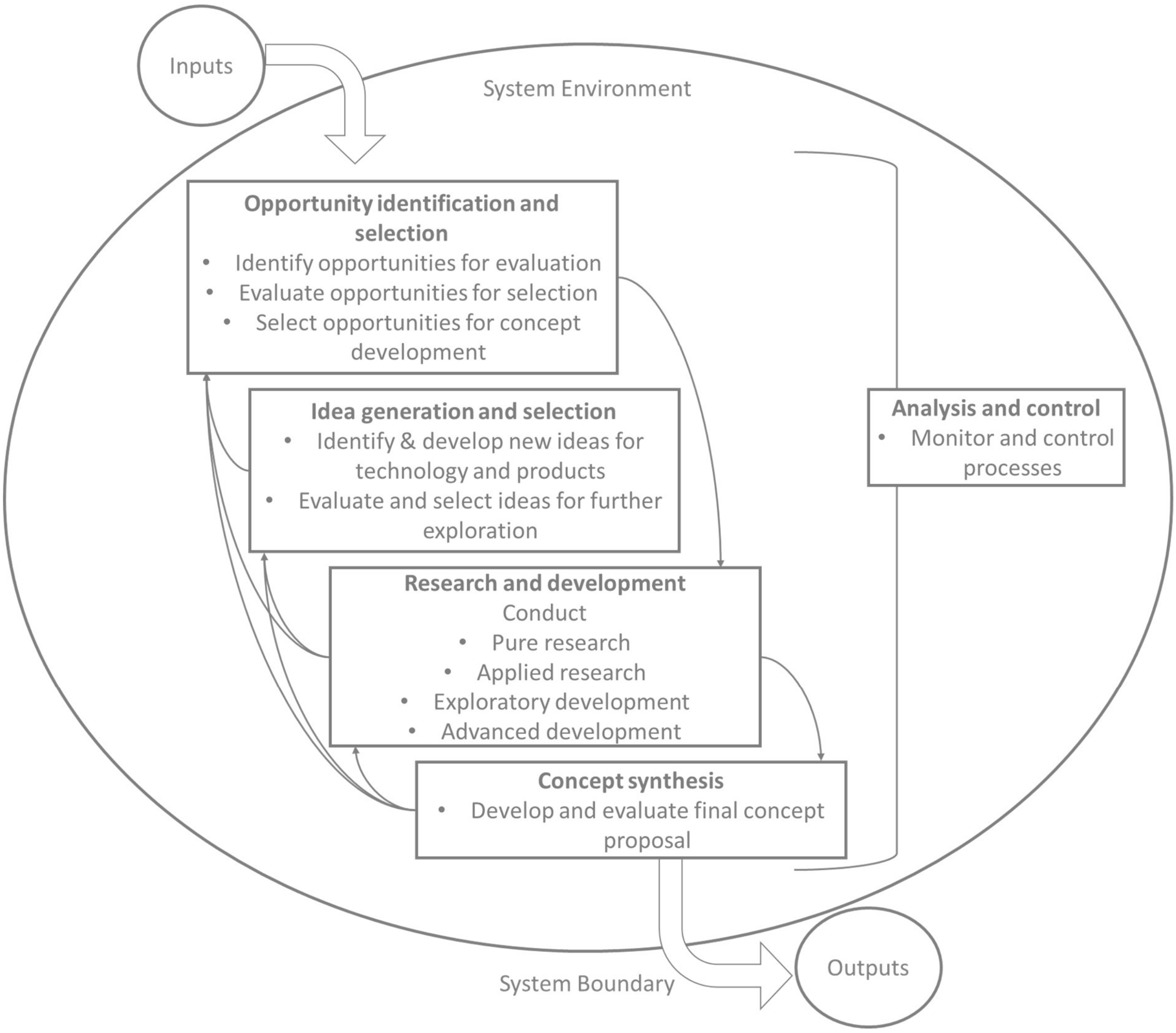


Figure A 8 "The technology development model is a system of processes within the R & D manager's domain" (Whitney, 2007)

B2.2 Idea-driven technology development approaches

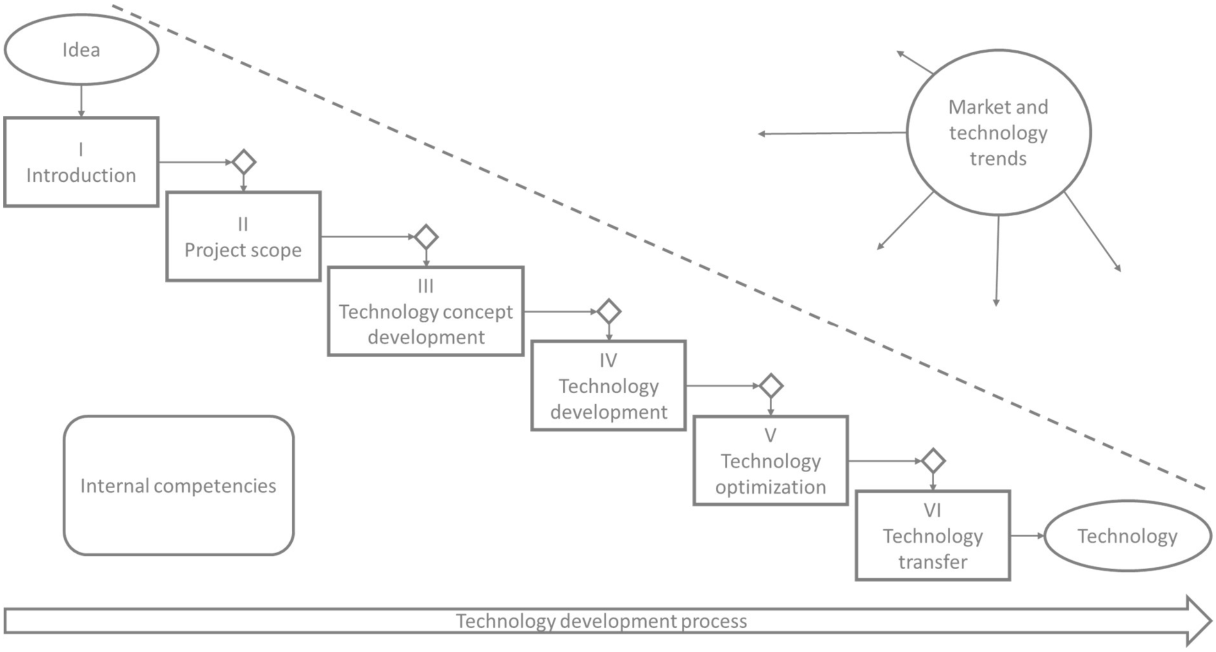


Figure A 9 “Theoretical model of technology development process” (Caetano et al., 2011)

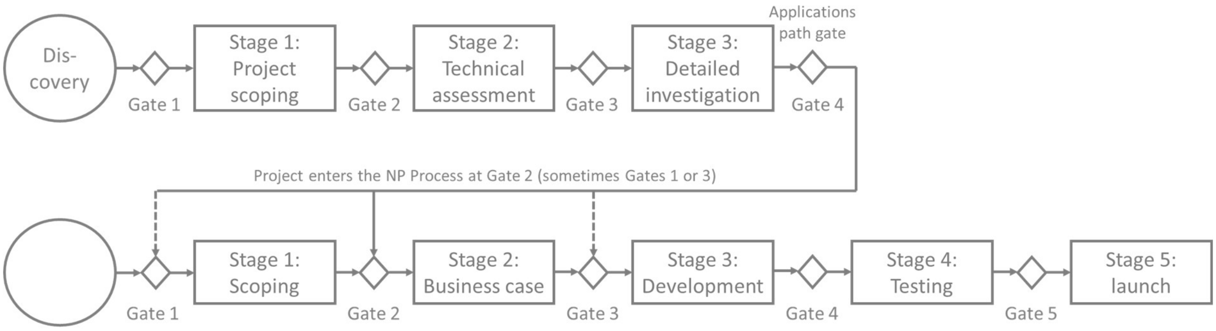


Figure A 10 “The typical technology development (TD) process spawns multiple “commercial projects” that can feed the new-product process at Gates 1, 2 or 3” (Cooper, 2006)

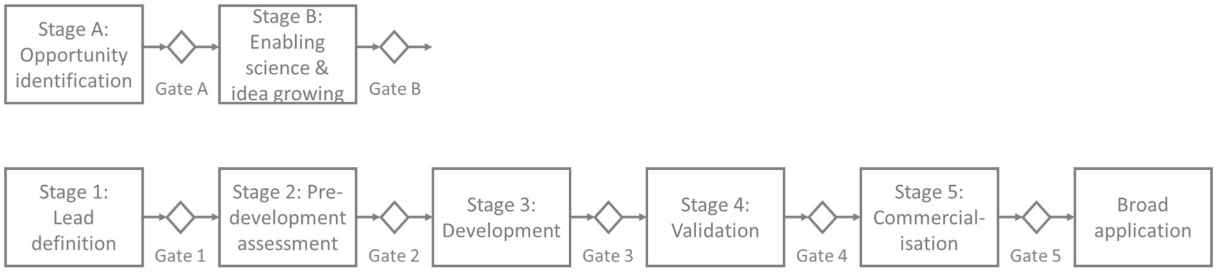


Figure A 11 “The ERE stage-gate system builds on the Exxon Chemicals Product Innovation Process by adding early stage-gates for the basic research phases of technology advancement” (Yapps Cohen et al., 1998)

B.3 Innovation approaches

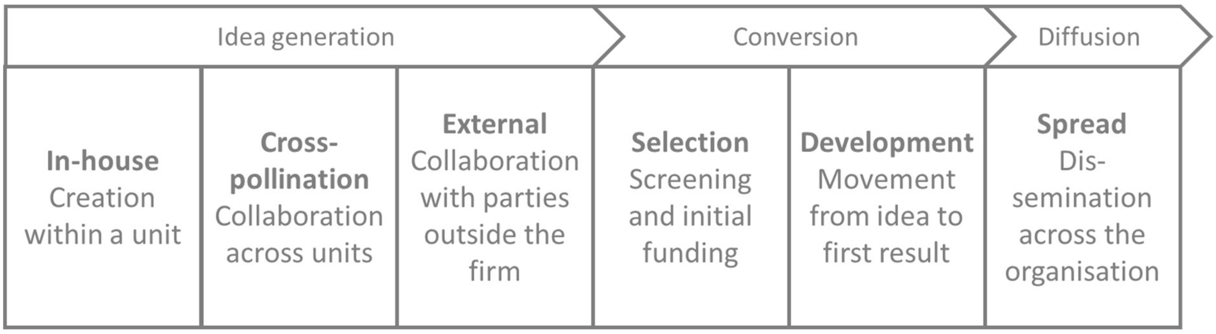


Figure A 12 "The innovation value chain" (Hansen and Birkinshaw, 2007)

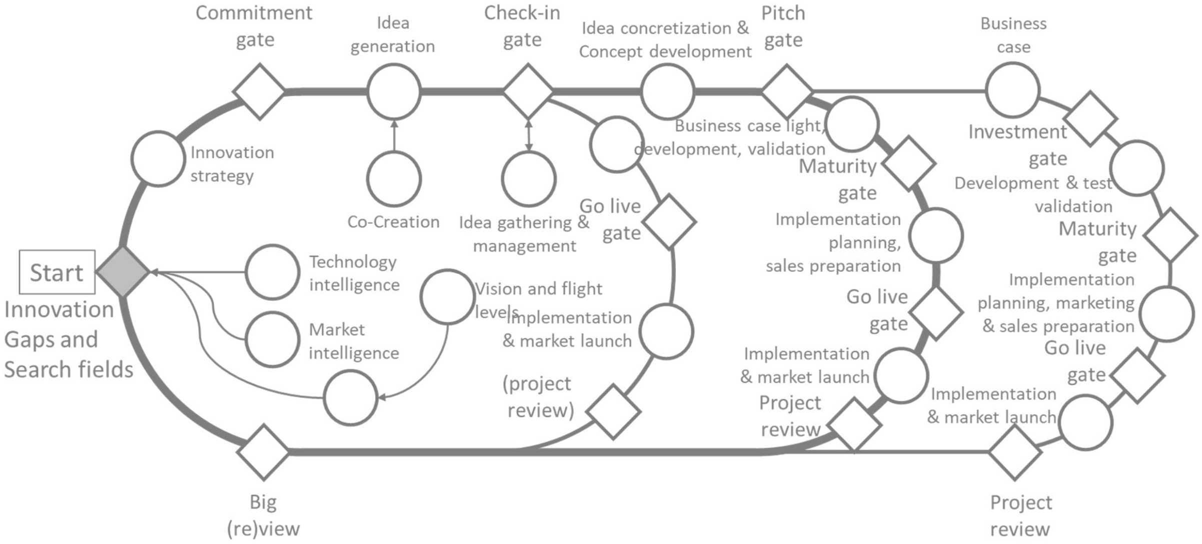


Figure A 13 "BIG picture innovation model (Lercher, 2016)**"**

Appendix C Sustainability criteria, weighting and aggregation for analysis and selection of early-stage process design alternatives

C.1 Introduction

Criteria are the key factors to consider in a multiple criteria decision-making process. The performances of alternatives based on the relevant criteria are evaluated and form part of the process for determining which alternative is likely to be most beneficial within a decision context. The selection of preferred technology options for reusing South African sulfide-enriched fine coal waste, therefore, also required the development of an appropriate set of criteria.

This appendix considers what criteria and indicators from literature could potentially be used for early-stage process selection. These include techno-economic indicators (Gnansounou and Dauriat, 2010; Swanson, 2009; Wright et al., 2010) that are routinely used for process selection, indicator sets popularly used for monitoring organisations (Bare, 2012; Clifford, 2003; Global Reporting Initiative, 2013; IChemE, 2002; IMA, 2001) as well as from academic sustainability literature (Azapagic et al., 2006; Corder et al., 2010; Othman et al., 2010; Ouattara et al., 2012; Sikdar, 2003). This section also provides guidance on how to select suitable criteria for specific applications. A list of criteria is then developed for the case study of technology selection for value-from-waste reuse in the South African coal mining industry. This set of criteria is not intended to be an exhaustive list, since as Petrie et al. (2007) cautioned, it is impossible and unwise to try to produce an exhaustive list of criteria for every application.

For criteria to be operationalised, the evaluations of alternatives on a specific criterion must have consistent meanings to make the results between alternatives comparable (Belton and Stewart, 2002). Constructed scales were therefore created to ensure consistency in technology evaluations and these are reported along with the relevant criteria.

Comparison between criteria must also be formalised and weights are assigned to do this. The weighting method used for comparing the mine waste reuse technology alternatives based on the identified criteria is then discussed and the weights reported. The aggregation method used is also discussed.

C.2 Criteria

C2.1 Indicator sets from literature

It is helpful to look at indicator sets from literature to ensure the completeness of a set of criteria. The next two sections look at techno-economic criteria that have traditionally been used to assess projects when making investment decisions and more holistic sustainability criteria.

C2.1.1Techno-economic criteria

For early-stage process selection techno-economic criteria are traditionally used for process analysis and selection (Azapagic et al., 2006; Corder et al., 2010; Sinnott, 2005). Criteria that have been used for optimising process design are shown in Table A 3. More holistic economic indicators will be shown and discussed in section C2.1.2.

Table A 3 Techno-economic criteria commonly used in assessing processes.

Indicator	Source	Comments
Economic		
Capital costs	(Azapagic et al., 2006; Sinnott, 2005; West et al., 2008; Wright et al., 2010)	The cost of constructing the process equipment
Uncertainty in capital costs due to untested equipment	(Wright et al., 2010)	
Operating costs	(Azapagic et al., 2006; Sinnott, 2005; West et al., 2008; Wright et al., 2010)	The cost of operating the process equipment
Raw material costs	(Cano-Ruiz and McRae, 1998; Gnansounou and Dauriat, 2010)	
Utilities costs	(Cano-Ruiz and McRae, 1998)	
Cost minimisation	(Cano-Ruiz and McRae, 1998)	
Profitability	(Azapagic et al., 2006; Cano-Ruiz and McRae, 1998; Sinnott, 2005; West et al., 2008; Wright et al., 2010)	Normally measured in terms of net present value or internal rate of return.
Valuable by-products	(Gnansounou and Dauriat, 2010)	
Technical		
Commercial readiness/technical maturity	(Swanson, 2009; Wright et al., 2010; Wunderlich et al., 2021)	How much development is still needed? Often measured in technology readiness levels (TRL's)
Number of new process areas/steps	(Wright et al., 2010)	
Conversion efficiency (Yield)	(Gnansounou and Dauriat, 2010; Wright et al., 2010)	
Complexity	(West et al., 2008; Wright et al., 2010)	Number of consecutive process steps
Scale of plant	(Gnansounou and Dauriat, 2010)	
Impurities	(Wright et al., 2010)	Impurities in the process
Controllability	(Chen and Shonnard, 2004)	
Flexibility	(Chen and Shonnard, 2004)	
Number of unit operations	(West et al., 2008)	
Availability feedstock	(Gnansounou and Dauriat, 2010)	
Availability of markets	(Gnansounou and Dauriat, 2010)	
Waste disposal	(Wright et al., 2010)	
Feasibility at practical feed rate	(Swanson, 2009)	Will the plant be feasible at a practical raw material feed rate?
Transport of product	(Swanson, 2009)	The product should be compatible with existing fuel transportation infrastructure

C2.1.2 Sustainability indicators

Pre-developed sustainability indicators are often focussed on measuring organisational sustainability. The most well-known and important of these indicator sets is the Global Reporting Initiative (GRI). It was founded in 1997 and has since worked on formulating and improving indicators for assessing the sustainability performance of organisations (Global Reporting Initiative, 2016). The all-encompassing nature of the GRI reporting means that many operational aspects of an organisation is included. For example, the "Equal Remuneration for Women and Men" indicator must be considered by existing companies' management teams, but it cannot be assessed for a project that is still conceptual. The full indicator set can therefore not be used as the criteria for early-stage process selection without some adjustment.

The Institute of Chemical Engineers (IChemE) has published its own guidelines on sustainability reporting in 2002 (IChemE, 2002) with the purpose of supporting the sustainability assessment and improvement of chemical processes and supply chains. The indicators are based on triple bottom line thinking and is applicable to the operational phase of a project like the principles put forward by the GRI. IChemE indicators are, however, more process-specific and therefore more useful to early-stage process selection although some indicators have operational aspects which must be adjusted for use in process selection. The IChemE has also given guidance on how to calculate values for some of the more difficult environmental indicators (IChemE, 2002).

The Industrial Minerals Association in Europe (IMA-EU) has endeavoured to report on the sustainability of their members' operations in a 2001 sustainability report (IMA, 2001). The indicators used were selected to give a broad overview of the extractive minerals industry's performance. They are therefore mining-specific, which is useful, but there are also operational indicators included.

In 2012 the United States Environmental Protection Agency (EPA) put forward the 2.1 version of the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) (Bare, 2012). It is a computer program that was designed to support a variety of sustainability-related applications such as life cycle impact assessment, industrial ecology and process design impact assessment. It uses the same impact categories and method for measurement as life cycle assessment and is therefore focussed mainly on the environmental aspects of sustainability.

Academics have also added their voices to the consideration of organisational sustainability indicators. Falck and Spangenberg (2014) have identified and weighted 59 indicators for monitoring mining-related social and environmental impacts with input from stakeholders of a South African coal mine, Slovakian lignite mine and a Kyrgyz gold mine. The 59 indicators are a comprehensive list of social and environmental indicators, but economics and technical issues are not considered. Kretschmann and Amiri (2015) identified and ranked 32 social, environmental and economic indicators. These indicators are very location- and context-specific, however, and no indication of how to operationalise them is given. Diniz da Costa and Pagan (2006) has used four environmental indicators to measure the performance of four coal fired power plants. Azapagic and Perdan (2000) has developed generic indicators for measuring the progress of industry towards sustainability. In 2006, Azapagic et al. (2006) suggested a list of 30 criteria that may be of use in the early stages of process selection. Even so no indication of what requirements there are for a set of criteria or how to adapt the list for specific purposes were given.

A compilation of the indicators that are potentially useful for developing criteria for early-stage process selection is shown in Table A 4. This excludes all exclusively operational indicators and includes suggestions on how the indicator could be adjusted to become a useful criterion for early-stage process selection. It is possible for sustainability criteria to be grouped under social, environmental and economic headings, reflecting a recognition of the triple bottom line of sustainability (Azapagic and Perdan, 2000; Elkington, 2004; Sikdar, 2003) and this convention was followed here.

Table A 4 "A list of indicators from literature that could be used in early-stage process selection."

Indicator	**Source**	**Comments**
Environmental		
Energy usage	IChemE; IMA; GRI; WAR (Azapagic & Perdan, 2000)	Usage of energy (in its different forms, such as electricity and fuel oil) per year or per unit product. One can make provision for energy sourced from renewables
Energy usage of inputs or outputs	GRI	Usage of energy upstream or down-stream from this process
Material usage	IChemE; GRI; (Azapagic & Perdan, 2000(Azapagic et al., 2006))	The total usage of materials per unit product.
Hazardous material usage	IChemE; IMA	Use of hazardous materials in tonnes or in kg per unit product
Recycled material usage	IChemE; GRI	Recycled materials used per unit product
Material recyclability	(Azapagic and Perdan, 2000)	How easily can the product be recycled
Water usage	IChemE; IMA	Water used in production of product
Product durability	(Azapagic and Perdan, 2000)	How long a product can be used
Service intensity	(Azapagic and Perdan, 2000)	What is the product's capacity factor/what percentage of the time is the product in use?
Land occupation	IChemE; IMA	Land used in all the company's operations.
Land rehabilitation	IChemE; IMA	A measure of the rate of restoration
Air Emissions	GRI; TRACI; (Cano-Ruiz and McRae, 1998)	Specifically the emissions of NOx, SOx, persistent organic pollutants, volatile organic compounds, hazardous air pollutants and particulate matter.
Land emissions	IChemE; TRACI (Azapagic et al., 2006)	
Water emissions	IChemE; TRACI (Azapagic et al., 2006)	
GHG emissions	GRI; IChemE; LCA; WAR (Azapagic et al., 2006; Ouattara et al., 2012)	The emissions of greenhouse gasses by operations. Can also be reported in GHG intensity

Ozone depletion	LCA; IChemE; WAR (Azapagic et al., 2006; Ouattara et al., 2012)	
Photochemical Oxidation potential	LCA; IChemE; WAR (Azapagic et al., 2006; Diniz da Costa and Pagan, 2006; Ouattara et al., 2012)	
Acidification potential	LCA; IChemE; WAR (Azapagic et al., 2006; Diniz da Costa and Pagan, 2006; Ouattara et al., 2012)	
Eutrophication	LCA; IChemE; (Azapagic et al., 2006; Diniz da Costa and Pagan, 2006)	
Human toxicity	LCA; IChemE; WAR (Azapagic et al., 2006; Diniz da Costa and Pagan, 2006; Ouattara et al., 2012)	WAR splits this into human toxicity by inhalation and dermal exposure, and ingestion
Ecotoxicity	LCA (Azapagic et al., 2006)	Ecotoxicity
Aquatic ecotoxicity	LCA; IChemE; WAR (Ouattara et al., 2012)	
Aquatic oxygen demand	IChemE;	
Terrestrial ecotoxicity	LCA; WAR	
Mass of waste	GRI; (Azapagic and Perdan, 2000; Cano-Ruiz and McRae, 1998; Palaniappan et al., 2002)	Should be delineated by type and disposal method
Reduction of energy for products and services	GRI	Reduction in energy usage by a delivered product or service. I.e. reduction in energy usage by customer or client
Water reuse	GRI	How much water is reused. Can be
Energy indirect GHG emissions	GRI	Emissions of greenhouse gasses due to energy used in operations. Can also be reported in GHG intensity.
Other indirect GHG emissions	GRI	Emissions of greenhouse gasses due to operations (excluding energy-related GHG). Can also be reported in GHG intensity
Emissions of ozone-depleting substances	GRI	Emissions of ozone-depleting substances due to operations
Volume of water discharged	GRI	This measure includes measures of quality and destination of the water.
Environmental impact mitigation of products and services	GRI	How has environmental impact of products and services been reduced vs. some baseline (normally the previous reporting period)

Reclaimed products	GRI	How much of the products and packaging has been reclaimed/can be reclaimed?
Contribution to specific environmental problems	(Cano-Ruiz and McRae, 1998)	
Raw materials use	(Azapagic et al., 2006)	
Economic		
Value added	IChemE; GRI; (Azapagic et al., 2006; Azapagic and Perdan, 2000)	Profit per sales value or direct employee; return on capital
Taxes paid	IChemE (Azapagic et al., 2006)	Taxes paid as percentage of profit
Investment	IChemE (Azapagic et al., 2006)	Includes changes in capital employed
Process investments	(Azapagic et al., 2006)	Eg. Health and safety and decommissioning
Climate change risk/opportunities to operations	GRI	What risks are there for the organisation due to climate change?
Financial aid from government	GRI	What financial aid has been/could be received from government
Infrastructure development	GRI	What infrastructure had been developed and how
Indirect economic impact	GRI	Eg. Economic development in areas of high poverty P. 51
Proportion local suppliers	GRI	Local vs. global suppliers used.
Capital costs	(Azapagic et al., 2006)	
Operating costs	(Azapagic et al., 2006)	
Social		
Employee health and safety	(Azapagic et al., 2006; Chen and Shonnard, 2004; Palaniappan et al., 2002)	
Customer health and safety	(Azapagic et al., 2006)	
Citizen health and safety	(Azapagic et al., 2006)	
Employment	IMA (Azapagic et al., 2006)	Total number of people employed (by the process, company or sector)
Employee qualifications	IChemE	Level of qualification of the workforce, simplified by reporting the number or percentage of the workforce with a qualification at or above a certain level. (eg. Two years of post-school training)
R&D investment	IChemE; IMA	Total expenditure towards R&D or expenditure as percentage of profit or turnover
Accidents & illness	IChemE; IMA; GRI	Lost time accident frequency; also work-related illnesses.

Health and safety training	IChemE	expenditure on prevention of illness or accidents
Fatalities	IMA; GRI	Number of people who died in work-related accidents or illnesses
Society benefit	IChemE	Community benefit per value added
Odour nuisance	(Azapagic et al., 2006)	
Noise nuisance	(Azapagic et al., 2006)	
Visual impact nuisance	(Azapagic et al., 2006)	
Public acceptability of product	(Azapagic et al., 2006)	
Public acceptability of process	(Azapagic et al., 2006)	
High risk/incidence of illness	GRI	Are there workers with high risk or high incidence of work-related illness?
Local community engagement	GRI	Have proper community engagement and impact assessment been done and are there community development programs in place?
Community impact	GRI	Do some of the company's operations have significant actual or potential negative impacts on communities?
Societal impacts of supply chain	GRI	What are the negative impacts of the current supply chain? Which suppliers, what events?

C2.2 Method

Table A 3 and Table A 4 are useful for understanding the historical thinking around sustainability issues in organisations and processing plants. They are also a useful starting point for developing a fit-for-purpose set of criteria. A coherent and appropriate set of criteria must be thoughtfully constructed, however. The method below shows how a specific set of criteria is constructed to be useful for process selection.

C2.2.1 Requirements for set of criteria

A set of criteria must be evaluated for suitability before being used to inform decision making. There are several formulations of evaluation requirements (Belton and Stewart, 2002; Keeny and Raiffa, 1976; Von Winterfeldt and Edwards, 1986), all of which are similar, and those set out by Belton and Stewart (2002) are shown in Box A1 below.

Box A1 The requirements for a set of criteria. (Belton and Stewart, 2002)

- Value relevance
- Understandability
- Measurability
- Non-redundancy
- Judgmental independence
- Balancing completeness & conciseness
- Operationality
- Simplicity versus complexity

The requirement of *value relevance* stipulate that criteria need to be relevant to the decision-context. For example, when all the alternatives under consideration utilise technology that has been implemented successfully on a large scale, the criterion of ‘technical maturity’ will be superfluous. When the technologies have widely ranging maturities, however, this criterion will contribute an important perspective to the decision-making process. The criterion must also be of interest to decision-makers. Colour will, for instance, be unlikely to affect decision-makers’ preference for filtering equipment.

It should be clear to all decision-makers what the criterion means and measures. Belton and Stewart (2002) calls this *understandability*. If decision-makers are uncertain about the purpose of a criterion it is likely to lead to misunderstanding, poor analysis and possibly conflict.

The third requirement is that criteria should be *measurable*. This does not mean that it should of necessity be quantitative, but that one should be able to ascribe a value judgement to the criterion in a consistent way. The key is that it should be clear what is being measured and measurement should be possible. ‘Contribution to specific environmental problems’, for instance is difficult to measure. It raises the questions of what environmental problem is under consideration, what exactly warrants a contribution and whether different environmental problems will be considered at once.

Another requirement for a criterion set is that of *non-redundancy*. This means checking that no two criteria are measuring the same aspect. If, for instance, the analysis included both the criteria *emissions to water* and *total waste produced*, the *emissions to water* would be counted twice: once for *emissions to water* and another time for *total waste produced*.

Incorporated in that idea is the concept that two criteria should be *judgmentally independent*. This means that judgement on one criterion should not affect judgement on another or, similarly, that the scores of two criteria should not both be affected by a third consideration. In such cases it may be useful to combine criteria or consider what the truly important aspect to be considered is. It is also important to remember that criteria that appear to be environmental may have other connotations as well (Sikdar, 2003). For instance, the environmental criterion *eco-toxicity* will also have social and economic impacts.

The requirement for *balancing completeness and conciseness* means that all the criteria necessary for characterising the alternatives for the purpose of selection must be used, but no more. As discussed in section C2.2.2, the future project stakeholders should also be considered at this point, even though they will not be explicitly consulted at this point in the design cycle. The demands in terms of information requirement, etc. that the criterion list place on the decision-making process must be able to be satisfied within the available resource limits of the project. If one has only one day to make the decision, it makes sense to have criteria that would not require time-consuming data collection.

The next two requirements, *operationality and simplicity versus complexity*, are similar to *balancing completeness and conciseness*. *Operationality* refers to the requirement that the decision team be able to use the model within the time and resources to their disposal. For example, a model requiring lengthy laboratory test work will be inappropriate if the model outputs are expected within a week and the decision team has no laboratory available. *Simplicity versus complexity* dictates that a model should be as simple as possible without compromising the accuracy of its description of the decision problem.

C2.2.2 Stakeholders

The input of decision-makers is required when constructing a set of criteria (Belton and Stewart, 2002; Von Winterfeldt and Edwards, 1986). While this person or committee will dictate what criteria should be used, it is important to remember that other stakeholders will be of utmost importance in the future development of the project. These stakeholders should therefore be considered, if only conceptually, even at the early stage of a project (Azapagic et al., 2006). Table A 5 can be used to test a criterion for interest by different stakeholders. Due to the limited number of criteria that can successfully be judged by a person at a time (Basson, 2004; Belton and Stewart, 2002), it is necessary that all criteria should be in the 'very important' category for at least one decision-maker. In this study the completeness of the criteria set was tested by using the inputs from coal industry participants (see Chapter 4). It was considered beneficial to ensure that the criteria is as complete as possible, but methods for including non-industry stakeholder values must be explored. Corder (2015) suggested including institutional staff who are from affected communities to act as proxies, but in the absence of a fixed location or suitable staff, another solution must still be found.

Table A 5 Interest of potential stakeholders with regards to projects in the mining industry. Adapted from Azapagic (2004)**.**

Stakeholders	Economic	Environmental	Social	Technical
Employees	Yes	Some	Yes	Yes
Trade unions	Yes	No	Yes	No
Contractors	Yes	Some	Some/no	Yes
Suppliers	Yes	No	Some/no	Some
Customers	Yes	Some	Some	Some
Shareholders	Yes	Some	Some	Yes
Creditors	Yes	Some	Some	Yes
Insurers	Yes	Yes	Yes	Yes
Local communities	Yes	Yes	Yes	No
Local authorities	Yes	Yes	Yes	No
Governments	Yes	Yes	Yes	No
NGO's	some	Yes	yes	Some

Yes=strong interest; Some=some interest; No=no interest

C2.2.3. Constructing criteria

A set of criteria can be developed either top-down or bottom-up (Belton and Stewart, 2002; Von Winterfeldt and Edwards, 1986). Bottom-up development uses the properties, advantages, and disadvantages of the alternatives to begin constructing the criteria. Top-down criteria sets are developed by using experts' already-formulated values and, often, using them to construct value trees (Belton and Stewart, 2002; Von Winterfeldt and Edwards, 1986). Top-down criteria development is the approach suggested for the case of selecting technologies for the reuse of sulfide-enriched coal mine waste, since relatively little may be known about the properties of the technology alternatives. One can start by listing the decision-makers' general values and then delving into more detail with each of them. Or one can start by considering the individual characteristics that are important to the evaluation. An example of a simple value tree is the final set of criteria shown in Table A 6.

For the top-down approach, the general values that decision-makers may espouse are *technical viability*, *social sustainability*, *economic sustainability,* and *environmental sustainability*. These initial 'categories' are then fleshed out by more specific and operational sub-criteria (Von Winterfeldt and Edwards, 1986). The criterion *profit* may flesh out the category of *economic sustainability*, for instance. This will continue until a relatively complete, functional, and measurable list of criteria results. The decision analyst must beware of creating too many sub-divided criteria, however, as this can be complex and difficult to work with. The most disaggregated level of criteria is normally used for evaluating alternatives and these are refined with the process shown in Figure A 14.

Another way of identifying the list of criteria is by starting from the bottom and grouping your way up. It is helpful to start by asking the question "what features differentiate the alternatives?" and then create as comprehensive a list as possible (Von Winterfeldt and Edwards, 1986). Another way of answering the same question is by listing the good and the bad points of each alternative. That comprehensive list is then worked down to a manageable size by following the process depicted in Figure A 14.

The process of creating criteria is iterative and requires back-and-forth testing between phases. It is important to remember that the purpose of creating a list of criteria is to accurately reflect the factors of concern for the decision-makers and by extension the potential stakeholders to the final design. As such it is possible to add a criterion later in the process if it has been established that an important consideration has been omitted or to remove a criterion if it is less important than originally believed. The starting point is to brain-storm criteria or select a number of indicators from Table A 3 and Table A 4 that are pertinent to the design problem and its context, as shown in Figure A 14 below. Figure A 14 is self-explanatory and draws from section C2.2.

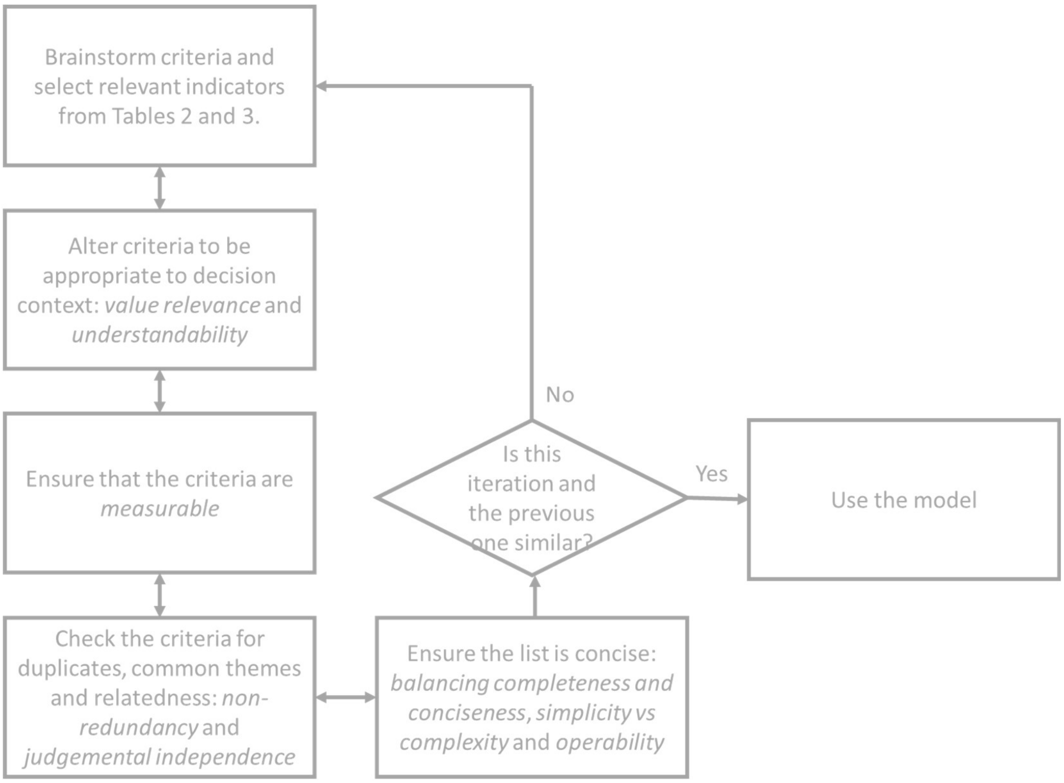


Figure A 14 The process for developing a list of criteria.

C2.3 Final criteria

The process in Figure A 14 was followed in the construction of a set of criteria appropriate for the case of South African sulfide-enriched coal waste reuse technologies. The final set is discussed next to illustrate the steps on checking for duplicates, ensuring that the criteria are measurable and that the list is concise.

The criteria were developed for an explicitly South African context, with alternatives for the reprocessing of sulfidic ultra-fine coal waste in mind. The South African context, especially around coal waste heaps, is one of high unemployment and water scarcity. South Africa also has problems with electricity supply. The poor living near waste deposits are often ill-equipped to deal with health and safety challenges posed by industries nearby. These considerations shaped the environmental, social, and economic criteria that were developed.

Table A 6 shows the final list of criteria that was chosen for evaluating early-stage process alternatives for producing a valuable product from waste. The list contains 15 criteria. After going through the process of refining the criteria, the list could not be shortened any further without reducing the accuracy of the decision-making model. A discussion on the criteria follows as well as the constructed scales used to measure a technology’s performance on them. Some of the constructed scales required explanatory panels to make their meaning clear and consistent. These are also reported here. The constructed scales were created to roughly follow linear value functions, so as to simplify weighting and aggregation, but in some cases these required adjusting and the correct value functions can be seen in (Stander et al., 2022a).

The interviews with industry participants showed that the industry is still focussed on techno-economic indicators for project success. The indicators *Technology maturity*, *Product market* and *Profitability* were identified as industry priorities. These were already included in the criteria and no additions were considered necessary.

Table A 6 The final value tree with criteria used in selecting the most promising options for down-stream processing of sulfide-rich coal tailings.

Technical	Simplicity of chemistry and process control	0.07
	System complexity	0.03
	Technical maturity	0.07
Social	Job creation	0.03
	Operating health and safety	0.07
	Community health and safety	0.1
	Skills development	0.03
Economic	Entrepreneurship	0.05
	Expected profitability	0.07
	Existing market	0.06
	South African deficit	0.1
	Scale of use	0.01
Environmental	Waste generation	0.11
	Mineral recovery	0.01
	Energy consumption	0.09
	Water consumption	0.09

C2.3.1 Technical

The technical aspect of process design is paramount, since it is the biggest deciding factor of whether a process will be implemented. Government and community stakeholders tend to not be interested in the finer workings of a process, providing it is functional. The stakeholders with the most interest in the technical side of the process will be the employees, contractors, shareholders, creditors and insurers. The employees and contractors must make it work, while the shareholders, creditors and insurers need to be able to do a risk assessment on the process.

A technical criterion that is not on the final list is *product/material match*, which considered the input vs product cost. It was eliminated due to its similarity with the criterion *profitability*.

Simplicity of chemistry and process control is a technical criterion that describes how easy or difficult it will be to operate the plant. This is included in the criterion list, since a more robust system that dependably produces output within broad systems parameters is preferable. Sensitivity to fluctuations in the process environment and composition of feed materials is how the performance of a process is measured against this criterion. This is distinct from the second criterion, system complexity, since a single reactor can be difficult to control, while a process of 15 cascading steps may be relatively easy to control and robust. This criterion is like the controllability indicator in Table A 3, but it is expanded to include the simplicity of the chemistry as well, since the two are closely related and both are important. An earlier version of this criterion was called *technical difficulty*.

0	1	2	3	4
The process will be difficult to control and be sensitive to fluctuations in the operating environment and feed compositions, but relatively low-level staff will be able to make adjustments under supervision/guidance from experts.	The process will be relatively difficult to control and be sensitive to fluctuations in the operating environment and feed compositions, but relatively low-level staff will be able to make adjustments with guidance of experts available from time to time.	The process will require adjustments to be made to account for differing operating conditions or inputs, but relatively low-level staff will be able to make the adjustments.	The process will require some adjustments to be made periodically, but not constantly, and low-level staff will be able to make the process adjustments.	Process control will be simple and the process will be relatively unaffected by changes in operating conditions or feed compositions.

System complexity is a measure of how many process steps, recycle streams and interacting operations a process alternative is likely to have. Fewer process steps and recycle streams are preferable. As discussed before, it is independent of *simplicity of chemistry and process control*, since many simple operations linked together may be simple to control, but still be complex to operate.

0	1	2	3	4
The process will be complex, incorporating many recycle streams and interacting unit operations, as well as employing technically advanced unit operations.	The process will be complex, incorporating many recycle streams and interacting unit operations or employing technically advanced unit operations.	The process will be moderately complex, incorporating some recycle streams and incorporating the use of moderately advanced technology.	The process will be moderately complex to simple, incorporating few recycle streams and employing simple technology.	The process will be simple, requiring no recycle streams and have low-tech unit operations.

Technical maturity is important since it is an indication of the research and development that still needs to be done to implement the technology successfully. With unknown and experimental technologies, the process unknowns and risks are still significant, so there might still be barriers to implementation or scale-up that are not yet known, whereas mature technologies can be bought off-the-shelf with minor changes to make it suitable for a specific context. This makes the ‘maturity of technology’ criterion especially important to shareholders, insurers, and creditors. Within the case study some of the alternatives were still novel, while others were mature, making this criterion relevant. This criterion is like the ‘number of new processes areas/steps’ and ‘technical maturity’ indicator in Table A 3 and is judgementally independent, since both simple and complex systems can be mature technologies.

0	1	2	3	4
The technology has never been implemented and is still being developed in the lab. Little development work has been done on this.	This technology has received a lot of R&D attention in the lab and has been implemented on a mini-plant scale.	The technology has been proven on a pilot or demonstration scale.	The technology has once or twice been successfully implemented on a commercial scale.	The technology is well-known and has been successfully implemented internationally for a number of years/commercially proven.

C2.3.2 Social

Social criteria tend to be of particular interest to employees, trade-unions, local communities, local authorities, governments, NGO's and insurers. Most of the stakeholders mentioned are directly impacted by the social performance of a process.

Direct job creation is an important aspect for stakeholders such as the community that the process will be located in and the local government looking after the wellbeing of that community. It is therefore important to consider upfront. A company that promises to employ many people may gain negotiating leverage with local governments, so the consideration would not only be of interest to future stakeholders, but to the decision-makers and shareholders as well. Job creation is measured on the total number of jobs generated if all the material generated in South Africa is processed by a single plant. Due to the relatively small stream size (20-600 ktpa)[38], a relatively small plant was envisioned.

0	1	2	3	4
5-10	11-20	21-45	46-60	61 or more

Skills development was considered as an additional social criterion, since it would be an important consideration for local communities, future employees and local government. This is measured by the percentage of highly skilled jobs likely to be created and hopefully filled by community members.

0	1	2	3	4
Majority of the jobs created will require unskilled labour (Gr. 9 or less).	Majority of the jobs created will require semi-skilled labour, with some unskilled.	The jobs created will require a mix of semi-skilled (majority), unskilled and highly skilled labour.	Majority of the jobs created will require highly skilled labour (eg. graduate diploma holders), with some semi-skilled labour.	Vast majority of the jobs created will require highly skilled labour (eg. graduate diploma holders).

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[38] For calculations see the data at Stander et al. (2022d) in the Agricultural statistics for South Africa spreadsheet in the Number of Farms tab.

Entrepreneurial activity development measures the extent to which the process lends itself to the development of entrepreneurs capable of running the process as their own business. A process that can be handed over to entrepreneurs from the community to operate as their own is therefore considered desirable for the community and local government stakeholders. Interestingly, this criterion has no counterpart in Table A 3. This is an example of a context-specific important criterion that was identified by the decision-makers. An early version of this criterion and *skills development* was called *promoting socio-economic development*. I was felt that this criterion needed disaggregating, however.

0	1	2	3	4
The products and production process does not lend themselves to being exploited by small/medium businesses or local entrepreneurs i.t.o. support-industries or further beneficiation of products, but only to large, established companies.	Some aspects of the products or process lend themselves to exploitation by small- or medium size business i.t.o. support industries and down-stream beneficiation or use, but only with the provision of significant support.	Some aspects of the products or process lend themselves to exploitation by small- or medium size business i.t.o. support industries and down-stream beneficiation or use.	The products and process lend themselves to exploitation by micro to small enterprises i.t.o. support industries, actual production and further downward beneficiation or use of the product. The enterprises will require support.	The products and process lend themselves to exploitation by micro to small enterprises i.t.o. support industries, actual production and further downward beneficiation or use of the product.

Explanatory panel 2: Indication of company category based on turnover, balance sheet and employment indicators

Company category	**Employees**	**Turnover**	**Balance sheet total**
Medium-sized	< 250	≤ € 50 m	≤ € 43 m
Small	< 50	≤ € 10 m	≤ € 10 m
Micro	< 10	≤ € 2 m	≤ € 2 m

http://ec.europa.eu/enterprise/policies/sme/facts-figures-analysis/sme-definition/

Operating environment health and safety is like the indicator Employee health and safety from Table A 4. In the mining industry, the concept of 'Zero harm' is an important operational imperative and it is essential to consider how processes might affect employees. This criterion integrates the consideration of risks associated with process chemicals as well as physical dangers. This criterion is distinct from *community health and safety* since the process chemicals and physical risks that employees interact with should not be relevant outside of a well-run facility. Likewise, employees should be protected from some of the factors affecting communities, such as dust and noise, by the provision of suitable personal protective equipment. The criterion is measured in the seriousness and regularity of worker exposure to hazards.

0	1	2	3	4

Workers will periodically be at risk of exposure to some hazardous (toxic, corrosive) and some moderately harmful materials, high temperature and pressures, as well as dangerous machinery and situations.	Workers will be at risk of exposure to moderately harmful materials with possible serious long-term side-effects, moderate temperatures and pressures and/or heavy duty machinery.	Workers will periodically be at risk of exposure to moderately harmful materials with possible serious long-term side-effects, moderate temperatures and pressures and/or heavy duty machinery.	Workers will be at risk of exposure to some corrosive or slightly toxic chemicals, machinery, etc.	Workers will be exposed to non-hazardous materials, ambient temperature and pressure.

Community health and safety measures the impact of the process on the community within which the plant is located. The plant can affect the community through noise pollution and/or contamination of the soil and drinking water with dust, for instance. A lower community health and safety risk is better. Although this criterion is closely linked to waste-related environmental criteria, it is still independent, because waste that is managed in a way that minimises release will have almost no impact on the surrounding community, regardless of whether it is toxic or not. Fugitive emissions and open processes are also likely to impact community health and safety, so this criterion is related to whether the process lends itself to uncontrolled spreading of waste and emissions.

0	1	2	3	4
The community living near to the production area will almost certainly experience negative health & life style effects, due to air, soil or water pollution, noise and dust creation. They may also be influenced by physical dangers, such as nearby tailings dumps.	The community living near to the production area will face risk of local contamination of land, water or air in case of accidental leakages or spills, in addition to dust and/or noise (Tailings dumps?).	The community living near to the production area will face some negative consequences from living near to the plant, such as noise and dust, but not chemical pollution-related issues.	The community living near to the production area will be at low risk, but may experience some physical disturbances.	The community living near to the production area will in no way be adversely affected by the nearby production processes.

C2.3.3 Economic

Almost all stakeholders are interested in the economics of a process. Economic indicators for process selection are well-developed and have been used in practice for many years.

Expected profitability is an important criterion, which speaks to the sustainability of the process as a business. It can be measured in expected internal rate of return (IRR) or the project's projected net present value (NPV) and a higher number for both indicates better profitability for the business. Payback time is another measures of a system's profitability. IRR was chosen, because it enables the comparison of projects of different sizes.

0	1	2	3	4
IRR <-10%	IRR -10%-0% (comparable to not implementing any process and discarding the waste in tailings impoundments)	IRR 0%-15%	IRR 15%-25%	IRR >25%

Explanatory panel 3: Typical South African IRRs

Bank loan	5
Government bond	8
Property	10
Shares	13
Projects	20

(Stander 2013)

The **existing market** criterion indicates whether an existing market for the product exists or whether a new market would have to be created. Creating a new market for a product, however useful, is a difficult and time-consuming process, whereas an existing market for a product would improve the likelihood of business success of the proposed process. It Is judgementally independent from *profitability* since a new, profitable, market may be created with much effort or an existing market can be unprofitable.

0	1	2	3	4
No known local market: Potential customers will have to be introduced to the product and convinced of its efficacy.	Limited & sporadic local market: The product is sold on the market, but only a few companies buy it from time to time.	Limited but consistent local market: The product is sold on the market, but only a few companies regularly buy it.	Moderate local market: The product is sold to a moderate number of customers and a few uses for the product exists.	Extensive local market: The product is sold to multiple different customers and multiple uses for the product exist. It is bought and sold freely.

If there is a **deficit of the product in South Africa** to the extent that it is currently imported, that would further increase the likelihood of business success, since the product can replace international imports and would not need to compete in a market that is already congested. This criterion can seem related to the product market criterion in that it measures aspects of the market. They are nevertheless separate in the sense that they measure different aspects of the market. A product that doesn't have an established market may still be very useful in a South African context, for example.

0	1	2	3	4
South African producers currently export the product or struggle to cover expenses due to oversupply in the country.	Imports or exports - supply and demand are relatively evenly matched.	Small volumes are imported (eg. 1000t-10,000t). South African producers are mosty able to supply the demand.	Medium volumes of the product is imported (eg. 10,000t-100,000t of imports).	Most of the product is imported due to severely limited supply in the country (eg. 10,000t-2,000,000t of imports).

Scale of use: Since the feed stream considered in the case study is mining waste, it is widely available in large volumes. A product that is bought and sold in large volumes is therefore favoured over products that trade in small volumes.

0	1	2	3	4
The product is typically bought in measures of kg.	The product is typically bought in measures of 10's of kg.	The product is typically bought in measures of 100's of kg.	The product is typically bought in measures of t.	The product is typically bought in measures of 10's of t or more.

Other indicators such as investments and capital and operating costs were not appropriate for adaption at this early stage of the design process.

C2.3.4 Environmental

Environmental criteria are of particular importance to insurers, local communities, local authorities, governments and NGO’s. Once again, these are the stakeholders that are more directly affected by environmental issues.

Environmental indicators are well-developed and there are many that can be adapted for early-stage process selection. The challenge with environmental indicators is to keep the number used within reasonable bounds so that the set of criteria is manageable, without sacrificing important indicators. For instance, *assuring sustainability of ecological system* was a criterion that formed part of one of the initial rounds, but was subsequently discarded. This problem was solved by choosing broad-ranging criteria that could effectively measure important aspects of environmental performance.

The criterion of ‘**waste generation**’ encompasses both the ideas that waste generation should be minimised on an absolute level and that waste should be as benign as possible. There are multiple criteria that can potentially be used to provide an indication of the waste produced and its impacts. Human toxicity, eco-toxicity and photochemical smog are examples of such. To minimise the number of criteria considered it was imperative to choose a criterion that would be roughly representative of many waste-related criteria. It is also helpful if such a criterion can be easily visualised and used. The criterion of waste generation was therefore used. It is judgementally independent from mineral recovery, since even if a small amount of the inherent mineral value is recovered as a high-value product/commodity, the rest of the material can still either be used or may be benign.

0	1	2	3	4
The process will produce medium to large volumes hazardous waste.	The process will produce small volumes of hazardous waste and/or large volumes of moderately hazardous waste.	The process will produce small volumes of moderately hazardous waste and large to moderate volumes of benign waste.	The process will produce small volumes of moderately hazardous waste or moderate volumes of benign waste.	The process will only produce small volumes of benign waste or no waste at all.

Explanatory panel 4: Classification of element toxicity

Group description	Estimated environmentally significant available concentration levels (mg/kg)	Elements	Classification
I: Potential for environmental risk if present at very low (trace) available concentration levels	< 10	Te < Hg < Ag < Cd , Re < Se < In < Pt < Tl < Sb < As < Au< Mo	Hazardous if present
II: Potential for environmental risk if present at low (minor) available concentration levels	10-100	Pb, Bi < Be << Ge < Ni, U < W	Hazardous if present
III: Potential for environmental risk if present at moderate available concentration levels	100-1000	Sn, I< Co< Ta< Mn, B, Cr < Cu < Hf < REE << Zn< Br < Ba < Ga < Zr < Nb < V	Moderately hazardous if present
IV: Potential for environmental risk only if present at relatively high available concentration levels	A: 1000-10 000	A: F < Sc < Li < Cl < Rb < Fe, Al < Ti < Sr < S < P	Moderately hazardous if present
	B: >10 000	B: Si < Mg < Na < K < Ca	Benign

(Broadhurst, 2007: 69)

Explanatory panel 5: Classification of waste volume

1-2Mt is considered to be large	10,000t-1000,000t is considered to be med	0t-10,000t is considered to be small

Mineral recovery: Mining waste inevitably still contain useful minerals. To increase resource efficiency, it is important to increase the extraction of minerals from the source material. The criterion of mineral recovery therefore speaks to increasing the reclamation of the value inherent in the waste. Increasing mineral recovery often needs to be balanced with other considerations, such as energy and water consumption. As such this is an example of a design trade-off that will need to be made.

0	1	2	3	4
Less than 10% of the inherent mineral value is recovered.	10%-40%	40%-60%	60%-90%	90%-100%

Explanatory panel 6: Indicatory composition of ultra-fine coal waste

Mineral	Fomula	% mineral in each phase
Quartz	SiO_2	34,9
Gypsum	$CaSO_4.2H_2O$	3,5
Epsomite	$MgSO_4.7H_2O$	<1.0
Kaolinite	$Al_2Si_2O_5(OH)_4$	59,4
Pyrite	FeS_2	1,6
Jarosite	$KFe^{3+}_3(OH)_6(SO_4)_2$	<1.0
Coal	$C_xH_xN_xO_xS_x$	n.a.
Total mineral phase		99,4
(Kotelo, 2011)		

Energy consumption is an important criterion to consider with process design due to the ecological and financial cost associated with securing energy. It is also related to fossil fuel depletion and greenhouse gas emissions if fossil fuel-based energy is used. In South Africa a very large proportion of the energy mix is still based on fossil fuels (Calitz et al., 2015), so in this context energy consumption also has a greenhouse gas implication. An indication of how much energy will be used in the process is therefore important to be able to compare the sustainability of alternatives. It is judgementally independent from *system complexity*, since energy use is more driven by energy intensive equipment, such as mills, than by the number of unit operations.

0	1	2	3	4
more than 100kWh/t processed	60-100kWh/t processed	30-60kWh/t processed	0-30kWh/t processed	0kWh/t processed - net energy production

Explanatory panel 7: theoretical electricity consumption of most energy-intensive option

Ferrous sulfate heptahydrate (worst case)	3	UV light tubes
	15	W/light tube
	120	hours
	1	kg processed
UV light energy usage:	5	kWh/kg processed
Additional plant energy usage		kWh/kg processed
Total energy usage	5	kWh/kg processed
(Viganico et al., 2011)		

Water consumption is also an important measure of the sustainability of alternatives, especially in a water-scarce country like South Africa. Since there are limited water resources to distribute between the different water consumers, it is important that the consumers limit the volume of water used and dirty water discharged to natural water ways. This will become more important as global warming changes weather patterns and makes certain areas drier. It is currently judgementally independent from *profitability* since the price of water is currently relatively low in comparison to other input costs (see for example the industrial water tariffs for the City of Johannesburg (2020)).

0	1	2	3	4
more than 4ℓ water/kg processed	2-4ℓ water/kg processed	1-2ℓ water/kg processed	0.5-1ℓ water/kg processed	0-0.5ℓ water/kg processed

Explanatory panel 8: theoretical water consumption of the various processes without consideration of purging, wash water or other water sinks				
Water for cement is 0.4-0.7 of dry cement mass (Sprung, 2008)	0,41	kg water/kg wet cement	0,7	kg water/kg dry cement
Water for pure sulfuric acid is 0.015 of total product (azeotrope is at 98.5% purity) + purge stream + washing water	0,02	kg water/kg conc sulfuric acid	0,01	kg water/kg pyrite excluding water for de-dusting.
Ferrous sulfate is input water, since the rest is evaporated to form crystals (liter/kg input? Is that reasonable in practice?)	7,87	kg water/kg ferrous sulfate hepta-hydrite	3	kg water/kg sulfide-rich tailings
Ferric sulfate is input water, since the product is used in dissolved form. (liter/kg input - is that reasonable in practice?)	0,83	kg water/kg ferric sulfate solution	1,2	kg water/kg sulfide-rich tailings
Cr(IV) reduction is zero, since it is going to be added to effluent	1	kg water/kg cleaned water		produces water, doesn't use water.
Soil amelioration is zero, since it is going to be added to soil	0	kg water/kg soil ameliorant (unless purification processes becomes important)		
Facilitating heap leaching is the purge water	0	kg water/kg product	0	
Cross reference with Mudd (2008)				

C.3 SWING weighting of criteria

The inputs to the weighting process are a set of criteria for evaluation of the alternatives and a set of observations of the alternatives' performance with regards to the criteria (Belton and Stewart, 2002; Von Winterfeldt and Edwards, 1986). With value function methods the performance observations are in the form of ratings on a natural or constructed scale (Belton and Stewart, 2002). Each value function is unique and therefore not directly comparable with the others in a specific decision-making problem. These value functions therefore need to be made comparable with each other to enable aggregation. This is the purpose of the weighting process.

The weighting process is in essence a process of constructing rescaling factors, so that the relative ranges and importance of the criteria can be meaningfully compared (Belton and Stewart, 2002). As such, some consider it to be the most important step in the decision-making process (Edwards and Barron, 1994). SWING weighting is a popular weighting method, since it implicitly considers the effect of both value range and importance and is therefore theoretically sound (Belton and Stewart, 2002). It is also a simple weighting method. It should be noted, however, that the weighting step's most important function is that of attaining insight into the problem and into decision-maker preferences, rather than on obtaining the exact numerical representation of the decision-makers preferences (Basson, 2004; Belton and Stewart, 2002).

This process for SWING weighting is based on Belton and Stewart (2002). In SWING weighting a hypothetical situation is posited in which an unhappy hypothetical alternative received the lowest score on each criterion. The decision-maker is then told that the possibility exists that the score on one criterion can be changed from the worst level to the best level and that he needs to choose the one. Then the decision-maker is informed that then they can choose another criterion to improve from the worst level to the best level. This process is repeated until only one is left at the worst position. The importance of considering the range-effect in the weighting exercise is often overlooked by those who are not well-acquainted with decision-making. It can be intuitively understood, however, when one considers the different weights a monetary criterion would receive if the price ranged between R 4950 and R 5000 versus if it ranged between R 50 and R 5000. The R 50 difference considered in the first instance may be unimportant to the decision-maker, where the R 4950 difference in the second instance may be significant. It is therefore imperative to consider the ranges as well as the intuitive importance of a criterion when assigning weights to criteria. The criterion that was first chosen should, naturally, be the one that is to receive the highest weight and so it is arbitrarily awarded a weight of one or 100. The decision-maker is then asked to assign weights to the other criteria with regards to the first criterion, considering a swing from the worst to the best possible value on that criterion.

The SWING weighting method is a method that uses ratio estimation (Mustajoki et al., 2005; Wang and Yang, 1998). Ratings given using this method can sometimes be inconsistent when different criteria are used as bases and this has been explained by the decision-maker's tendency to use multiples of 10 when rating, rather than using smaller denominations (Poyhonen, Volijk & Hamalainen, 2001 cited in (Mustajoki et al., 2005)) and the inconsistency which results from using the least important criterion as anchor. This underlines the importance of taking care when eliciting weights and eliciting more than the minimum number of weight ratios to ensure a valuable weighting process.

In this study, weighting was done by two senior academics in the Minerals to Metals Research Initiative, as the main decision-makers. They weighted the criteria in a single sitting and the results can be seen in Stander et al. (2022a) in the Collection 1 and Collection 2 Excel workbooks. It is interesting to note that the weighting for *Technology maturity* represented a point of conflict between the decision-makers and South African coal mine industry values. The academic decision-makers placed a much lower value on technology maturity, while for the conservative coal mine industry technical maturity is of utmost importance before implementation can take place. Due to the need for developing novel mine waste valorisation technologies, the academic perspective was used in weighting the *Technology maturity* criterion.

C.4 Aggregation

Following the weighting step, the function of aggregation is to combine the value function information and the weighting information so as to arrive at a single number (value index) representing each alternative. This representation is normally in the form of a number or a score, with the highest number representing the most preferred option. The robustness of the results is tested at this point using sensitivity analysis (Belton and Stewart, 2002).

While several aggregation methods exist, the additive model (Eq. 1) is simple and commonly used (Belton and Stewart, 2002).

$$Value\ index(a) = \sum_{i=1}^{m} w_i v_i(a) \tag{1}$$

Where *(a)* denotes the numbers for alternative *a*
w_i Is the weight of criterion *i*
$v_i(a)$ is the value score for alternative *a* on criterion *i*

For this to be an appropriate method of aggregation, however, the criterion requirement of judgemental independence must hold.

C.5 Conclusion

It is important to set it up a holistic set of criteria for early-stage process selection thoughtfully with stakeholder input. Every early-stage design criterion set may be slightly different, with location- and design context-specific issues being taken into consideration. Weighting of criteria is a cognitively taxing task that is made easier by using a theoretically sound method – in this case SWING weighting.

Appendix D Links to data files

While publishing the results of the study, data was collected, analysed, and stored in the UCT online data repository. These data files can be found in the reference list but are linked here for ease of reference.

- Stander, H.-M., Cohen, B., Harrison, S.T.L., Broadhurst, J.L., (2022a). Validity of using expert judgements to inform multicriteria decision support for selecting technologies for sustainable reuse of sulfide-enriched fine coal waste: Data and calculations. https://doi.org/10.25375/uct.21320601
- Stander, H.-M., Harrison, S.T.L., Broadhurst, J.L., (2022b). Expert input to inform multicriteria decision support for selecting technologies for sustainable reuse of sulfide-enriched fine coal waste: Interview transcripts. https://doi.org/10.25375/uct.21333576
- Stander, H.-M., Harrison, S.T.L., Broadhurst, J.L., (2022c). Characterisation of sulfide-enriched fine coal waste. https://doi.org/https://doi.org/10.25375/uct.14972463.v1
- Stander, H.-M., Harrison, S.T.L., Broadhurst, J.L., (2022d). Using sulfide-enriched fine coal waste as soil ameliorant for calcareous and alkaline soils. https://doi.org/https://doi.org/10.25375/uct.14973897.v1
- Stander, H.-M., Harrison, S.T.L., Broadhurst, J.L., (2023a). Report: Down-stream processing options for sulfide-enriched fine coal waste. https://doi.org/10.25375/uct.22361059.v1
- Stander, H.-M., Harrison, S.T.L., Broadhurst, J.L., (2023b). Distinguishability analysis for assessing larger groups of expert data: the case of larger groups of “average” experts. https://doi.org/10.25375/uct.22363069