

DEVELOPING A QUANTITATIVE FRAMEWORK FOR ASSESSING AND
REPORTING MINING'S CONTRIBUTIONS TO
SUSTAINABLE DEVELOPMENT

by
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ABSTRACT

With the establishment of the United Nations Sustainable Development Goals (SDGs) in 2015, the UN called on the private sector to further engage in responsible business practices to contribute to the achievement of sustainable development and acknowledged the mining industry as one of the leading industries to advance the SDGs. In the past three decades, the mining industry has been making efforts to adopt more sustainable and responsible practices and measure their outcomes in accordance with global and industry sustainability targets. However, evaluating a mining company's contribution to sustainable development across their operations is challenging because of the varied spatial and temporal scales at which they take place. At the temporal scale, there are significant operational differences between the phases of a mining operation. At the spatial scale, there is significant variation due to the adopted mining method, the size of the operation, the characteristics of the ore body, and the geological and geographical settings. Current sustainability assessment and reporting approaches of mining companies are unable to capture how their contributions to sustainable development change throughout the mining life cycle and across their operations. Thus, there is a disconnect between the reported contributions of mining companies to sustainable development at the corporate level, and the contributions at the site or operation levels.

Better assessment and reporting of the mining industry's contribution to sustainable development is essential for the mining industry to be able to manage the challenges related to contributions to the SDGs, social license to operate, stakeholder pressure, and becoming greener investments. To do this, sustainability assessment frameworks that capture the spatio-temporal scale of mining operations and that can be applied across different scales is necessary. In an attempt to meet these needs, this research develops an indicator-based quantitative framework for capturing mining's contributions to sustainable development at three different scales and aligns these contributions to the SDGs. This dissertation composes three research articles which seek to answer the following research questions:

1. What are the trends, strengths, and weaknesses in sustainability reporting of the mining industry? How does sustainability reporting in the mining industry compare to that in the oil and gas industry?
2. How can quantification be used to assess the mining industry's contributions to sustainable development at different spatial and temporal scales?
3. What indicators relate to the closure/post-closure phase of the mining life cycle? How do different stakeholders prioritize these indicators?
4. What indicators relate to the production phase of the mining life cycle, and specifically for low-carbon haulage technologies?

5. How does the contribution of mining to the SDGs compare for the closure/post-closure and production phases? How does the contribution of mining to the SDGs compare at the operation-, site-, and corporate-levels?

This dissertation informs these questions with three research activities:

An investigation of the baseline of what companies are reporting at the *corporate level*: This research examines the scope and consistency of sustainability indicators used in the sustainability reports of eight oil and gas and eight mining companies from 2012 to 2018. This research demonstrates that extractive industries' sustainability reporting practices are not consistent over time and that internal issues are better represented than external issues, in particular transportation and supply chain issues. It identifies the strengths and areas for improvement in sustainability reporting practices of the two industries and aligns the strengths and areas for improvement in terms of demonstrating their contributions to the related SDGs.

An analysis of mining's contributions to sustainable development at the *site level* for the *closure/post-closure* phase: This research uses stakeholder input to evaluate and compare three different repurposing alternatives for the tailings dam area of a mine that is approaching closure. With a primary focus on *people*, and more specifically the stakeholders, this research examines different stakeholder perspectives on sustainable development in the context of mine closure and repurposing based on environmental, social, and economic sustainability indicators. The research shows which alternative better reflects stakeholder preferences and provides the most sustainable outcome. It contends that integrating stakeholder views into mine closure design and repurposing can lead to more responsible and sustainable mine closure that is unique to a particular setting and stakeholder needs. Applying this methodology also highlights strengths for contributing to the SDGs.

An analysis of mining's contributions to sustainable development at the *operation level* for the *production* phase: Autonomous haulage trucks (AHT) are listed among the top low-carbon strategies by large iron ore companies. This research investigates AHT's potential for a lower carbon footprint for haulage by proposing an emission estimation methodology based on the Time Usage Model (TUM) and applying it to a surface iron ore mine in Australia. It finds that AHT result in higher overall emissions per ton of material moved compared to their conventional counterparts, while decreasing the emissions generated from non-productive activities, such as through standby or operating delay. It also finds that there is still very limited reporting of Scope 1 emissions at the site-level, and reporting is not transparent in terms of how it relates to specific processes like drilling or hauling. Although this research primarily focuses on *the environment*, and specifically emissions, it also discusses the broader socio-economic implications of AHT on workers and communities and identifies the related strengths and areas for improvement for the SDGs.

Collectively these studies identify very different focus areas, and hence very different strengths and areas for improvement for contributing to the SDGs for the corporate, site, and operation-levels. This indicates that the varied spatial and temporal scales of mining are complementary to each other in

contributing to sustainable development and the SDGs. In tracking and assessing their progress towards achieving the SDGs, mining companies should review the whole system (i.e., the corporate-level) together with its subsystems (i.e., site-level and operation-level). The findings of this dissertation inform a discussion of the usefulness of systems-based methodologies for tracking progress towards sustainable development. By approaching different scales with different assessment methods, this research was able to arrive at a more robust assessment of the mining industry's contributions to sustainable development.

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CHAPTER 1

INTRODUCTION

This chapter explains the background and motivation of the research and describes the scope, objectives, and contributions. The chapter is divided into subsections. The first subsection provides the background information about mining and sustainable development, and the importance of the topic. The second subsection reviews the relevant literature and identifies the remaining gaps. The third subsection describes the research goals and objectives and outlines the structure of the dissertation. The last subsection specifies the potential contributions to the mining and sustainable development literature, policy, and practice.

1.1. Mining and Sustainable Development

1.1.1. The Concepts of Sustainability and Sustainable Development

“Sustainability” and “sustainable development” are two terms that are often confused and used interchangeably (Salas-Zapata & Ortiz-Muñoz, 2019). Although both concepts emerged out of concerns that many industrial activities caused environmental degradation and social disruption, their roots are different. The term “sustainability” originated from ecology and refers to managing natural resources in a way that the desired level of environmental quality is maintained (Eggert, 2009; Ihlen & Roper, 2014). Sustainable development, on the other hand, shifts the focus to society (Ihlen & Roper, 2014) with the definition provided by the Brundtland Report (1987): “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987). This involves managing and utilizing the currently available resources by also considering future generations’ share in them, and with the least adverse environmental and social impacts possible.

One of the most well-known and applied concepts of sustainability is the life cycle analysis (LCA), which is used to assess and quantify mostly the environmental impacts associated with the entire life of a product. LCA is used by companies and product designers to better understand their products’ impacts and understand the ways in which the product can be improved (Michigan Tech, 2019). Sustainable development, on the other hand, is inherently multi-dimensional and refers to development that integrates and balances the environmental, social, and economic characteristics of an activity (Eggert, 2009). The United Nations Educational, Scientific and Cultural Organization (UNESCO) defines sustainability as a long-term goal, with sustainable development as one of the processes used to achieve this goal, including but not limited to production and consumption, good government, education, and training (UNESCO, 2005).

There have been attempts to define sustainable development in the corporate context (Siew, 2015). For example, the International Institute for Sustainable Development (IISD) defines sustainable development in the business context as: “adopting business strategies and activities that meet the needs of the enterprise and its stakeholders today while protecting, sustaining and enhancing the human and natural resources that will be needed in the future.” (IISD, 1992). Others define it as “the way in which the sector balances social, economic, and environmental interests” (Brueckner et al., 2013). Companies’ contributions to sustainable development are often embedded in their “sustainability reports” or “sustainability assessments” along with other metrics that relate to “sustainability”, such as those attained from an LCA. Although sustainability-related concepts are also critical, this research specifically focuses on the contributions of the mining industry to “sustainable development” which is distinguished from the sustainability concept and in a broader sense is linked to the United Nations Sustainable Development Goals (SDGs).

1.1.2. The Need for Better Assessment and Reporting of Contributions to Sustainable Development

In the late 1990s, the mining industry went through challenging times as the commodity prices had tumbled and mining operations started to lose the support of investors (ICMM, n.d.). In addition, companies’ social license to operate (SLO) was threatened by immense public scrutiny, growing community unrest, criticisms from civil society, and broader public opposition (Komnitsas, 2020). As a response, industry leaders acknowledged that the mining industry needed to change (ICMM, n.d.; IIED, n.d.). In 1998, a small group of mining company CEOs launched the Global Mining Initiative (GMI), which was led by the World Business Council for Sustainable Development (WBCSD) (ICMM, n.d.; IIED, n.d.). The GMI was intended to change the way the mining industry approached societal issues such as public scrutiny and poor public reputation (IIED, n.d.). Through the WBCSD, the GMI commissioned the International Institute of Environment and Development (IIED) to independently carry out a comprehensive consultation and research to examine the global challenge of sustainable development faced by the mining industry and to explore mining’s role in sustainable development (ICMM, n.d.; IIED, n.d.). These efforts of the IIED resulted in what became known as the Mining, Minerals and Sustainable Development (MMSD) project, which was a multi-stakeholder consultation and research process that took place between 2000 and 2002, and involved consultations with more than 5,000 individuals and organizations about mining’s role in contributing to sustainable development, and produced 175 research reports and papers (ICMM, n.d.; IIED, 2002). With the establishment of the United Nations Sustainable Development Goals¹ (SDGs) in 2015, the UN called on the private sector to further engage in responsible

¹ The SDGs are a set of 17 goals, which are adopted by the UN Member States in 2015 as part of the 2030 Agenda for Sustainable Development, are an urgent global call for action to end poverty, improve health and education, reduce inequality, and spur economic growth while tackling climate change and preserve the environment (United Nations, n.d.).

business practices to contribute to the achievement of sustainable development (The United Nations, n.d.). More importantly, the mining industry was acknowledged as one of the leading industries to advance the SDGs (UNDP, 2016; United Nations Africa Renewal, n.d.).

These milestones caused an awakening in the mining industry that their practices had a role to play in contributing to sustainable development. In the past three decades, the mining industry has been making efforts to adopt more sustainable and responsible practices and measure their outcomes in accordance with global and industry sustainability targets. These efforts are evidenced by company reports that use indicator-based methodologies to assess and communicate their contributions to sustainable development. Indicator-based methodologies gained popularity in sustainability assessments when Agenda 21 at the Rio Conference (1992) emphasized the need for the use of indicators to evaluate sustainability and guide the sustainable development process (Azapagic, 2004; Azapagic & Perdan, 2000; Boulanger, 2008).

Corporate sustainability reporting frameworks and guidelines include sets of indicators to guide corporations in assessing and communicating their sustainable development performance (Roca & Searcy, 2012). Companies use indicators as a tool to measure, monitor, and report on their sustainable development performance. However, there is a lack of consensus and standardization in corporate sustainability assessments in terms of the reporting style, content, methodology, and the indicators used (Jenkins & Yakovleva, 2006; Siew, 2015; Talbot et al., 2011). This precludes a clear and objective analysis of companies' sustainable development contributions, which is also critical in terms of demonstrating the industry's overall contributions to the SDGs (UNDP, 2016; United Nations Africa Renewal, n.d.).

What is even more challenging is evaluating a mining company's contribution to sustainable development across their operations because of the varied spatial and temporal scales at which they take place and the on-the-ground nuances of a particular mining development. At the temporal scale, there are significant operational differences between the phases of a mining operation (exploration, feasibility and planning, development and construction, production, closure, and post-closure). At the spatial scale, there is significant variation due to the physical footprint of a mining operation, which depends on the adopted mining method, the size of the operation, the characteristics of the ore body, and the geological and geographical settings. In addition, the spatial and temporal scales of mining operations are shaped by and influence the social, political, economic, and environmental settings in which they take place. Current sustainability assessment and reporting approaches of mining companies are unable to capture the ways in which their contributions to sustainable development change throughout the mining life cycle and across their operations. As a result, there is a disconnect between the reported contributions of mining companies to sustainable development at the corporate level and the contributions at the site or operation levels.

Mining companies are increasingly facing pressure from communities, investors, shareholders, the general public, and other stakeholders to address environmental, social, and governance (ESG) issues in

both their local operations and in corporate reporting. In addition, investors and financiers are increasingly seeking to invest in green and sustainable investments (Beith et al., 2013; PRI, n.d.). The mining industry needs to access such “green” and sustainability-linked financing as part of the transition to a lower carbon economy (Simmons & Simmons, 2019). This creates both a challenge and an opportunity for mining developments to evolve into greener investments by becoming more energy- and water-efficient, using more renewable energy sources, and adopting cleaner production strategies (Simmons & Simmons, 2019).

Better assessment and reporting of the mining industry’s contribution to sustainable development is essential for the mining industry to be able to manage the challenges related to SLO, stakeholder pressure, contributions to the SDGs, and becoming greener investments. To do this, research on sustainability assessment approaches that capture the spatio-temporal scale of mining operations and that can be applied across different scales is necessary. In an attempt to meet these needs, this research develops an indicator-based quantitative framework for capturing mining’s contributions to sustainable development at three different scales and aligns these contributions to the SDGs. The overall hypothesis that motivated this dissertation is that the development of such a framework would be useful for exploring and providing solutions for the disconnect between contributions to sustainable development at different spatial and temporal scales of mining and would improve mining’s roadmap toward the SDGs.

1.2. Assessing Mining’s Contributions to Sustainable Development

1.2.1. Indicator-Based Assessments

After the surge of interest in sustainability in the mining industry in the late 1990s, the MMSD emphasized the role of sustainability indicators in assessing, managing, monitoring, and reporting the mining industry’s contributions to achieving sustainable development goals (Warhurst, 2002). As a response, mining industry-led initiatives, as well as academics performed significant research on examining mining’s contribution to sustainable development using indicator-based assessments. Although these methods are becoming standard practice (Virgone et al., 2018), there is still not a consistent and agreed-upon approach to identifying indicators that assess mining’s contributions to sustainable development (Horsley et al., 2015).

Fonseca et al. (2013) compared five sustainability assessment and reporting frameworks that are used by or proposed specifically for the mining industry, namely, the Global Reporting Initiative (GRI), the Towards Sustainable Mining (TSM), Seven Questions to Sustainability (7QS), Innovation and Technology Driven Sustainability Performance Management Framework (ITSPM), and a framework proposed by Adisa Azapagic (Fonseca et al., 2013). Three of these five frameworks, Azapagic’s, 7QS, and ITSPM, have had limited use by mining companies. TSM and GRI, on the other hand, are two of the most adopted indicator-based frameworks in the mining industry (Fonseca et al., 2013).

7QS was an integrated and future-oriented framework that emerged as one of the major outcomes of the MMSD. It guides decision-makers to answer questions based on seven themes: 1. engagement; 2.

people; 3. environment; 4. economy; 5. traditional and non-market activities; 6. institutional arrangements and governance; and 7. synthesis and continuous learning (Fonseca et al., 2013). The 7QS requires decision-makers to provide answers to each of the seven questions, as well as specific indicators and metrics for those answers; however, its indicators and metrics are to be defined on a case-by-case basis (Fonseca et al., 2013).

Following the findings and recommendations of the MMSD, scholars have attempted to quantify the mining industry's contributions to sustainable development. Azapagic (2004) developed an indicator-based framework for mining companies that builds on the GRI framework and addresses the temporal dimensions of mining's contributions to sustainable development by focusing on the mining life cycle. She proposed a set of 24 economic, 45 social, and 63 environmental indicators for the metallic, construction, and industrial minerals sectors and integrated social, economic, and environmental indicators to provide a more holistic assessment (Azapagic, 2004). Even though Azapagic's study is one of the most comprehensive and constructive studies in this field of research, it has been criticized for its lack of spatial/geographical considerations and its organizationally centered indicators. In other words, the indicators were focused on the performance of the company itself and did not pay much attention to the settings and needs of the external components of mining sites or regions (Fonseca et al., 2013; Virgone et al., 2018).

ITSPM was a framework proposed by environmental scientists Arun Basu and Uday Kumar, with a rather conceptual orientation. The framework defined environmental, social, and economic dimensions of performance and more specific performance topics, such as technology and innovation to support sustainability goals but did not include specific indicators (Fonseca et al., 2013).

The Mining Association of Canada (MAC) developed an approach to measure the mining industries' contributions to sustainable development by establishing the "Towards Sustainable Mining (TSM)", which is a set of guiding principles and performance indicators. TSM focuses on the site-level and "internal" performance of companies and identifies eighteen indicators grouped into six categories (tailings management; energy use and GHG emissions management; aboriginal and community outreach; crisis management planning; biodiversity conservation management; and safety and health) (Fonseca et al., 2013). TSM has a narrow scope, as it focuses only on the site-level performance based on six categories, which has been regarded as a strength, as well as a weakness. It is valuable for producing more reliable and comparable results and more objective and quantifiable data that can be consistently aggregated into corporate-level reports (Fonseca et al., 2013). However, it is limited by its narrow scope, as it failed to be informative about the companies' performance and progress towards the general goals of sustainable development (Fonseca et al., 2013).

GRI is an independent international organization that was founded in 1997 (GRI, n.d.-b). In an attempt to standardize sustainability reporting practices of businesses, governments, and other organizations on various economic, environmental, and social impacts, GRI established the first version of the GRI reporting framework in 2000 (GRI, n.d.-b). The GRI Framework remains one of the most used

approaches to measuring and reporting the mining industry's contributions to sustainable development (Fonseca et al., 2014). However, the GRI framework has been critiqued for its insufficient consideration of spatial scales, in particular its lack of attention to how a company's performance varies across local, regional, national, and global scales (Fonseca et al., 2014; Virgone et al., 2018).

Due to the lack of a standard and agreed-upon approach, mining companies often use a combination of assessment frameworks, which fail to provide an overall picture of contributions to sustainable development, as well as fragmented information that may only be useful in specific contexts (Fonseca et al., 2013). Furthermore, none of these frameworks truly considers geographical scale variations, i.e., how performance varies across local, regional, national, and global scales (Fonseca et al., 2013). Frameworks that accurately measure progress and inform reporting in the mining sector must attempt to address the varied temporal and spatial scales at which mineral developments occur (Fonseca et al., 2013).

1.2.2. The Disconnect Between the Sustainability Assessment Across Different Levels

After mining companies started to use indicator-based assessment frameworks, the differences and disconnect between the sustainability assessment of mining companies at the local and company levels started to be addressed in the scientific literature. Fonseca et al. (2013, 2014) evaluated the current sustainability assessment and reporting frameworks used by the mining industry and emphasized the need for more systematic consideration of site-level performance for a more meaningful and accurate representation of sustainability performance at the corporate level (Fonseca et al., 2013, 2014). Yaylaci (2015) developed a sustainability assessment framework that compiled 347 sustainability indicators specific to the mining sector. This indicator set was then divided into "strategic-level" and "project-level" indicators to understand the impacts of proposed plans or programs at the macro scale (i.e., regional, national, or global), and the micro-scale (i.e., company- or local-level), respectively (Yaylaci, 2015; Yaylaci & Düzgün, 2016, 2017). Yaylaci and Duzgun (2017) demonstrated how the sustainability assessment outcomes might differ if the concerns and priorities are determined by the local stakeholders at the local level or by the mining companies or planning authorities at the regional/country level. Mancini and Sala (2018) examined the indicators used for the assessment of social impacts of the mining industry to understand the extent to which the indicators used at the global and country levels can capture and measure the social impacts at the local level. The authors confirmed the difference and disconnect between sustainability assessments at the local and company levels by showing that the indicators used in different contexts for sustainability assessment have different perspectives and scope, hence, they capture different aspects. They found that the local scale impacts (e.g., land use and demography) are less represented in the macro-scale frameworks and pointed out the need for the organization and harmonization of the indicators used at local-level impacts to be successfully used at the company level and other macro-scale assessments for evaluating the contribution of the sector to socio-economic development (Mancini & Sala, 2018). Talbot (2011) also underlined this disconnect and stated the need

to investigate ways to integrate project-level sustainability assessment into corporate sustainability reporting so that the same information could be used for multiple purposes (Talbot et al., 2011).

Sustainability assessments should be unique to the individual settings and circumstances of a mining operation as well as to the needs of various stakeholders (Gibson, 2006; Talbot et al., 2011). Moving from the local level (i.e., site-level) to the corporate level, changes the stakeholders that are relevant as well as the issues around sustainability. Approaches that aggregate indicators across geographical sites often disregard contextual issues. This leads to “irrelevant and even inaccurate” assessments of sustainability performance (Virgone et al., 2018: 2641). Therefore, both local and corporate level indicators are beneficial and essential for sustainability assessment. Leaving either one of these levels out might provide a slanted view of sustainability performance assessments. This is also confirmed by Azapagic (2004) through her emphasis on the importance of assessing the contribution to sustainable development of the mining industry at the sector, corporate, and local levels, since the sustainability issues are different at each of these levels, and they impact different stakeholders (Azapagic, 2004). Warhurst (2002) also stated that there are many and diverse drivers for indicator selection for sustainability assessment at the site level and larger levels (e.g., company level) with the common purpose of reporting to external stakeholders. She outlines the need for a sustainability assessment framework that can link site-level indicators with company, sector, and eventually global-level sustainability indicators (Warhurst, 2002).

Building on this literature and to capture the contextual aspects, this research assesses mining companies' contributions to sustainable development at the corporate, site, and operation levels with an attempt to identify the differences between the three levels and develop links between them.

1.2.3. Mapping Contributions onto the SDGs

With the establishment of the SDGs by the UN in 2015, efforts to quantify the contributions of the mining industry to sustainable development shifted gears toward mapping these contributions to the SDGs. The United Nations Development Programme (UNDP), together with the Columbia Center on Sustainable Investments, the Sustainable Development Solutions Network, and World Economic Forum (WEF), published the document, “Mapping Mining to the Sustainable Development Goals: An Atlas” to illustrate how the mining industry can contribute to the achievement of the SDGs (UNDP, 2016). The atlas encouraged and provided guidelines and recommendations to mining companies of all sizes to incorporate relevant SDGs into their business and operations, validate their current efforts, and highlight the SDGs where mining has the most impacts (UNDP, 2016). It is also emphasized that contributing to each SDG may take a different form depending on the mining phase. According to the Atlas, the mining industry has the opportunity and potential to positively contribute to all 17 SDGs; however, the aspects most relevant to a particular SDG might vary depending on the phase of mining, requiring different management approaches (UNDP, 2016).

Yakovleva et al. (2017) furthered the efforts of the Atlas by adding a region-specific dimension. Using the World Bank Development Indicators Databank, they proposed a set of indicators that could be used to

measure national progress toward sustainable development in sub-Saharan Africa (Yakovleva et al., 2017). Acknowledging the limitations for mining companies to achieve national-level changes since operations are locally fixed, they emphasized companies' potential to contribute to the SDGs through direct action at the local level (Yakovleva et al., 2017). They suggested a regional approach where mining companies develop sustainable development strategies by considering regional priorities and challenges in sub-Saharan Africa. Most importantly, they pointed to the need for developing indicators to measure industry progress towards the SDGs and link these to mining operations. They suggested that academics and practitioners extend the existing sustainability indicators to engage more directly with the SDGs and further explore how national-level SDGs can be translated into corporate-level indicators for mining companies (Yakovleva et al., 2017).

Ivic et al. (2021) analyzed, compared, and critically assessed the contributions of 10 European mining companies to the SDGs and identified the strengths and weaknesses of these companies in terms of contributing to the SDGs. However, their analysis was limited to the sustainability reports of the selected companies for the 2016–2018 period, and to the categories of broader issue areas instead of specific sustainability indicators (Ivic et al., 2021).

A handful of studies focused on conceptual or qualitative assessments of mining's contributions to the SDGs instead of quantitative approaches. Monteiro et al. (2019) discussed the best practices through which the mining industry can contribute to each SDG by conducting visits to three mining sites in Brazil; however, their study was limited to crushed stone mining. The authors qualitatively identified the current state of mining's contributions to the SDGs and proposed potential contributions that mining can provide to each SDG by comparing the actual activities at the visited mining sites to the recommendations provided in the scientific literature, including those provided in the Atlas (Monteiro et al., 2019). Sturman et al. (2020) discussed the potential contribution of both large-scale and artisanal and small-scale mining to the achievement of the SDGs in Africa by providing examples of how mining can improve livelihoods through job creation, provision of medical care, diversity and inclusion, and entrepreneurship. Although the study provided a guideline in terms of what needs to be done to improve contributions to the SDGs, it was limited to being conceptual instead of practical. The authors stressed that although outlining mining's contributions to the SDGs could be relatively simple; in practice, the implementation, scale-up, and measurement of the impacts is much more complex (Sturman et al., 2020). In an edited volume, Parra et al. (2020) systematically assessed how mining has contributed to the SDGs since the goals were established five years prior and they cast a vision of mining's long-term contributions to the SDGs beyond 2030. The book provided a comprehensive and global look at the lessons learned and pathways for increasing mining's positive contributions to each SDG but lacked a higher level of detail in terms of the spatial scale (Parra et al., 2020). Endl et al. (2021) investigated the extent to which current and future mining innovation trends that are employed, or that will be employed in the future in Europe, can contribute to achieving the SDGs. However, their assessment was exploratory and qualitative and was geographically limited to Europe (Endl et al., 2021). Finally, a few studies focused on mapping artisanal

and small-scale mining and their formalization to the SDGs and identifying opportunities (de Haan et al., 2020; Hilson & Maconachie, 2020; Laing & Moonsammy, 2021).

Identifying and mapping the mining industry's contributions to the SDGs is a recent area of research that is constantly evolving. The overall objective of this research is to add to this body of literature by discussing the links between mining companies' contributions to sustainable development and the progress made toward meeting the SDGs at the closure/post-closure and production phases as well as for the process, site, and corporate levels based on quantitative, indicator-based assessments.

1.3. Research Goals and Objectives

The overarching goal of this research is to develop a framework that captures mining's overall contributions to sustainable development across different spatial and temporal scales using the SDGs as an organizing (umbrella) framework. Mining spans several spatial and temporal scales which are all impacted by and influence external social, environmental, economic, or political settings. Mining companies often have multiple operations which are located in different countries and represent different phases of the mining life cycle. As such, mining's contributions to sustainable development can be considered as a three-dimensional complex structure of intertwined *scales*. The spatial scale consists of hierarchical spatial units ranging from continental or global scale (large-scale) through mine site (medium scale) to a single operation as a component of mining within a mine site (small scale). The temporal scale represents the phases in the mining life cycle from exploration to post-closure. The third dimension represents mining's interactions with its external settings based on the three main aspects of sustainable development (i.e., environmental, social, and economic).

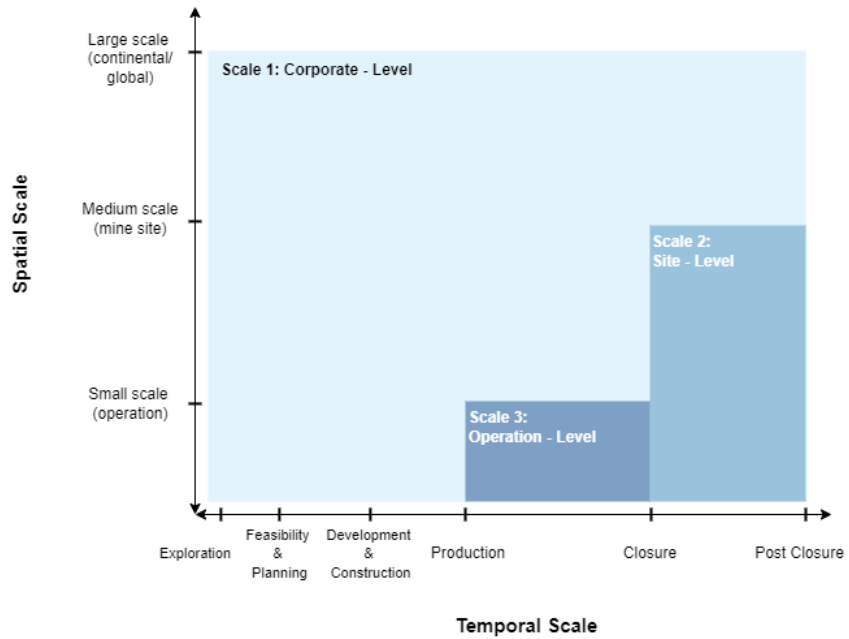
A single method is not suitable to evaluate mining's overall contribution to sustainable development since contributions differ across different spatial and temporal scales. Understanding mining's contributions to sustainable development via the SDGs requires considering the phenomena based on hierarchical scales, therefore this dissertation utilized *systems theory*, in particular, *hierarchical systems (hierarchy) theory*. Hierarchy theory is an offshoot of general systems theory and was developed to understand and simplify complexity by focusing on levels of organization and issues of scale (Allen, 2001; N. J. Smith & Sage, 1973; J. Wu, 2013). Systems are called complex if they have an internal structure of several qualitatively different processes, subsystems, interconnections, and interactions (Bossel, 1999), which applies to mining. Developed from an interdisciplinary perspective, the basic idea of hierarchy theory is to decompose a large system into smaller subsystems in a way that forms a hierarchical structure that can provide a greater level of understanding of the overall system (Joseph, 1999; N. J. Smith & Sage, 1973; J. Wu, 2013). Complex systems are often hierarchically structured in *levels* or *scales*, where higher levels tend to be larger and slower while lower levels tend to be smaller and faster (J. Wu, 2013). These hierarchical levels are inherently related to various temporal and spatial scales (Ewert et al., 2006; Giampietro & Mayumi, 1997; Hätönen, 2004; J. Wu, 2013; J. Wu et al., 2006) and therefore, the hierarchy theory requires *scaling* to bridge such scale gaps (J. Wu et al., 2006), which is

also applicable to mining. Scaling is the translation of information between and across temporal and spatial scales, or organizational layers, which significantly enhances the comprehensibility of the system (J. Wu, 2013).

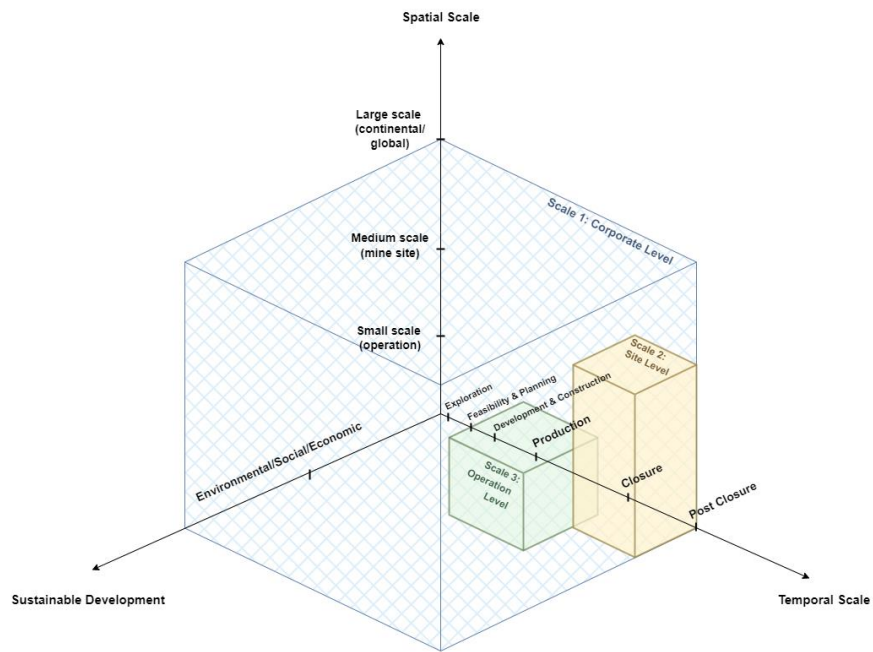
Hierarchy theory emerged in the early 1960s as an alternative and a complement to other existing approaches to complexity (Simon, 1962), with contributions from management sciences, economics, psychology, biology, and mathematics (J. Wu, 2013). Since the early 1980s, the theory has been further elaborated and expanded with a biological and ecological emphasis, but also influenced broad applications in other fields like geophysics, economics, and management services (J. Wu, 2013). The theory was also deemed appropriate to achieve a greater understanding of public and societal problems (N. J. Smith & Sage, 1973), as well as communities and ecosystems to analyze system sustainability (Ewert et al., 2006; Giampietro & Mayumi, 1997). In another study, the theory was applied for the conceptual analysis of sustainable development principles where the vertical hierarchical levels were adapted into a hypothetical “universe” that contains simultaneously operating systems within systems, ranging from the “individual universe” to “anthropocosmic universe” (J. S. Miller, 2009).

To assess mining’s contributions to sustainable development, we adopt a “systems within systems” hierarchy approach to examine interacting and simultaneously operating systems at different levels of complexity, rather than a vertical hierarchy that represents a chain of command (J. S. Miller, 2009). We employ three scales to understand mining’s contributions to sustainable development and propose different quantification methods for each scale (Figure 1.1(a)). The level of detail, the spatial and temporal scales, and the primary focus with respect to the three main pillars of sustainable development vary between the three scales in our study (Figure 1.1(b)). At the first scale, we have an overall look at the “baseline” of mining’s sustainability reporting practices at the *corporate level*. Corporate-level connotes a continental or global or continental spatial scale since it covers all operations of a mining company at the global scale. The second scale is a more granular scale where we investigate mining’s contributions to sustainable development at the closure/post-closure phase at the *site level* with a primary focus on *people*. With a primary focus on *the environment*, the third scale looks at the contributions to sustainable development and low-carbon strategies at the production phase and at the most detailed, *operation level* by focusing only on the haulage operation of mining. Operation-level connotes a small spatial scale as it delineates a sub-section in the mine site involving the movement of material (i.e., either the ore or the waste material) via haul trucks from one point to another. The first scale was selected since the corporate level is representative of all temporal and spatial scales. The second and third scales were selected by considering their importance in the mining life cycle, as well as the impacts they create. The production phase is the longest stage, and the most dynamic one in terms of the economic, environmental, and social impacts a mining operation faces and creates. The closure/post-closure stage is the stage where sustainable development planning is renewed for the repurposing of the mined land, which is a crucial step in ensuring successful environmental rehabilitation and reducing the socioeconomic risks related to the departure of the mining company. Therefore, the most significant differences in terms of contributions

to sustainable development are expected to be observed between these two phases. Our approach and methods inform the hierarchy theory and its application to mining and sustainable development. We use the SDGs as a tool to identify and compare the similarities and differences in mining's contributions to sustainable development at different scales, since the SDGs represent a universal, clearly defined, and integrated set of global goals for sustainable development (Endl et al., 2021).



(a)



(b)

Figure 1.1 (a) 2-D and (b) 3-D representation of the “systems within systems” hierarchy approach for assessing mining’s overall contributions to sustainable development

Structure of this Dissertation

This dissertation consists of three research activities that are each explored in their own standalone chapter, in which the relevant literature and methodologies used are discussed. Still, the chapters are complementary and build on one another to address the following research questions:

- What are the trends, strengths, and weaknesses in sustainability reporting of the mining industry? How does sustainability reporting in the mining industry compare to that in the oil and gas industry?
- How can quantification be used to assess the mining industry's contributions to sustainable development at different spatial and temporal scales?
- What indicators relate to the closure/post-closure phase of the mining life cycle? How do different stakeholders prioritize these indicators?
- What indicators relate to the production phase of the mining life cycle, and specifically for low-carbon haulage technologies?
- How does the contribution of mining to the SDGs compare for the closure/post-closure and production phases?
- How does the contribution of mining to the SDGs compare at the operation-, site-, and corporate levels?

Each research activity complements the other and informs the overall framework. Chapter 2 provides an overall look and essential baseline on what mining companies are reporting and examines the strengths and areas for improvement in terms of contributing to sustainable development at the corporate level. Chapter 3 focuses on a more specific, site-level scale and the closure/post-closure phase and identifies stakeholder perspectives on sustainable development in the context of mine closure and repurposing. Although stakeholders have different ideas about what constitutes sustainable development, with the proposed quantitative decision analysis approach, it is possible to identify to what extent different repurposing scenarios can address these perspectives. Such participatory closure and repurposing planning offer important opportunities for contributing to the SDGs. Finally, Chapter 4 focuses on the third and more detailed operation level for the production phase with two goals, one being investigating low-carbon haulage strategies, and the other being discussing broader social and economic implications of AHT. Strengths and areas for improvement regarding mining's contributions to the SDGs by utilizing AHT are discussed. More transparency, consistency, and granularity are required in emissions reporting at the mine site level, or preferably operation-level, to better support research, modeling, and policy making of low-carbon mining strategies.

Chapter 2: A Data-Driven Approach to Evaluation of Sustainability Reporting Practices in Extractive Industries

In this chapter, we investigate the baseline of what companies are reporting at the *corporate level*, which represents the first and largest scale addressed in our quantitative framework. We examine the scope and consistency of sustainability indicators used in the sustainability reports of eight oil and gas and eight mining companies from 2012 to 2018. The oil and gas industry, another major extractive industry under public scrutiny, has been publishing sustainability reports longer than the mining industry. Thus, mining's approach to sustainability reporting is analyzed and compared to that of oil and gas to provide insights into what mining can learn from a similar extractive industry with more experience and to determine the strengths and improvement areas in the sustainability reporting practices. Using content analysis and relevant statistical methods, we examine the ways in which companies reported on their contributions to sustainable development, with a focus on indicators used and trends over time both within each industry and between industries. The results demonstrate that extractive industries' sustainability reporting practices are not consistent over time and that internal issues are better represented than external issues, in particular transportation and supply chain issues. We identify the strengths and areas for improvement in sustainability reporting practices of the two industries and align those in terms of demonstrating their contributions to the related SDGs. This chapter is published in the journal, *Sustainability*.

Chapter 3: A Quantitative Sustainability Assessment for Mine Closure and Repurposing Alternatives in Colorado, USA

In this chapter, we analyze mining's contributions to sustainable development at the *site level* for the *closure/post-closure* phase, which represents the second and more granular scale in our framework. The closure/post-closure phase is of particular importance in the mining life cycle as the transition at mine closure poses major risks and opportunities for the local communities, the environment, and the SDGs in general. Often mine closure focuses on remediation and rehabilitation of mined lands, yet responsible mine closure and repurposing should consider stakeholder perspectives and the broader social and economic impacts of closure. Here, we use stakeholder input to evaluate and compare three different repurposing alternatives for the tailings dam area of a mine in Colorado, USA that is expected to close in the next twenty years. Having a primary focus on people, and more specifically the stakeholders, we build on the results and recommendations from the first research activity, specifically in terms of the need to address external sustainable development issues. We examined different stakeholder perspectives on what constitutes sustainable development in the context of mine closure and repurposing based on environmental, social, and economic sustainability indicators. The results show which alternative better reflects stakeholder preferences and is, therefore, the most economically, environmentally, and socially sustainable outcome. We contend that integrating stakeholder views into mine closure design and repurposing can lead to a more responsible and sustainable mine closure that is unique to a particular

setting and stakeholder needs. Applying this methodology also highlights opportunities for contributing to the SDGs. This chapter is published in the journal, *Resources*.

Chapter 4: Comparison of Autonomous and Conventional Haulage Trucks in terms of GHG Emissions and Contributions to the SDGs

In this chapter, we analyze mining's contributions to sustainable development at the *operation level* for the *production* phase with a sub-goal of investigating low-carbon haulage strategies. The research in this chapter represents the third and most detailed scale in our framework. The production phase is the longest phase and the most dynamic one in terms of the economic, environmental, and social impacts a mining operation faces and creates. Therefore, we focus on the *haulage* process in surface mining for simplification and scaling purposes. One of the most current topics in conversations about mining and sustainable development is the need to move toward a low-carbon future. Autonomous haulage trucks (AHT) are listed among the top low-carbon strategies by large iron ore companies. Autonomy provides a system change that improves the productivity of a mining operation by reducing the time trucks spend on non-productive activities. Yet, this system change might result in cascading effects on the workforce and communities. The research presented in this chapter investigates AHT's potential for a lower carbon footprint for haulage by proposing an emission estimation methodology based on the Time Usage Model (TUM) and applying it to a surface iron ore mine in Australia. We find that AHT result in higher overall emissions per ton of material moved compared to their conventional counterparts while decreasing the emissions generated from the time spent on non-productive (idling) time elements of the time usage model (TUM). Another finding is that there is still very limited reporting of Scope 1 emissions at the site level, and reporting on Scope 1 emissions is not transparent in terms of how it relates to specific processes like drilling or hauling. We suggest more transparent, consistent, and granular emissions reporting at the mine site level or preferably operation level. Although the primary focus in this chapter is on the environment, and specifically emissions, we also discuss the broader socio-economic implications of AHT on workers and communities and identify the related strengths and areas for improvement in terms of mining's contributions to the SDGs. This chapter will be submitted for publication.

Chapter 5: Conclusions and Recommendations for Future Work

The final chapter summarizes the results of each chapter and recommends potential future directions for assessing and reporting mining's contributions to sustainable development and the SDGs. It argues that by approaching different scales with different assessment methods, this dissertation was able to identify the differences between the three scales and develop links between them via the SDGs and arrive at a more robust assessment of the mining industry's contributions to sustainable development.

1.4. Contributions of This Dissertation

This research makes significant contributions to the mining and sustainable development literature, policy, and practice. Mining's contributions to sustainable development via the SDGs have never been examined at the corporate, site, and operation levels in an attempt to identify the differences between the three levels and develop links between them. The dissertation also contributes to the hierarchical systems (hierarchy) theory literature. This theory has very limited application in the context of mining and sustainable development. By adopting the "systems within systems" hierarchy approach, this dissertation significantly contributes to the application of hierarchy theory to mining and sustainable development. Overall, this research proposes a quantitative, indicator-based framework for assessing mining's contribution to sustainable development and meets the need for a framework that does the following:

1. captures the impacts of different spatial and temporal scales on mining's contribution to sustainable development
2. identifies the differences between sustainability assessment approaches and contributions to sustainable development at the corporate, site, and operation levels, and develops links between them
3. considers different stakeholders' perspectives
4. adds knowledge and insights about mining's contributions to SDGs.

The first research activity adds to our understanding of sustainability reporting in the mining and oil and gas industries with a data-driven approach by providing a temporal analysis of the reporting trends within and between each industry. The research investigates oil and gas and mining companies' approaches to sustainability reporting using a data-driven approach. Although the hypotheses of temporal variability in the reporting practices of extractive industries are common in the literature, testing these hypotheses with a data-driven approach that includes statistical tests has not been conducted. Therefore, the analysis of both industries' sustainability reporting practices addresses this gap by revealing the statistical significance of these temporal trends. Furthermore, this research contributes to the literature by identifying the strengths and areas for improvement in sustainability reporting indicates how sustainability reporting may be more representative of the different pillars of sustainable development and may align better with the SDGs.

The second research activity addresses a gap in the literature regarding participatory scenario analyses that support a priori decision-making for repurposing. It focuses on the ways in which different repurposing alternatives may contribute to sustainable development to determine which repurposing scenario would better reflect stakeholder preferences and result in the most economically, environmentally, and socially sustainable outcome. It emphasizes the fact that different stakeholder groups have different perspectives on sustainable development in general, and especially at the site level in the context of mine closure and repurposing. Finally, it provides a methodology that mining companies may consider using to understand stakeholder priorities and preferences.

The third research activity addresses the lack of understanding and quantification of the overall environmental impact of technological innovations like AHT, including in terms of GHG emissions. As far as we know, no study has been conducted on GHG estimations of specifically AHT in surface mining, and its comparison to the emissions from conventional trucks (CT). Given the limited amount of research and publicly available data on this subject, this study proposes a method that is a preliminary, initial attempt to estimate the carbon footprint of AHT and examines the opportunities and challenges of using AHT as a strategy to reduce emissions in mining operations.

Finally, this research might be useful for mining companies in assessing, reporting, and monitoring their contributions to sustainable development and aligning these contributions onto the SDGs at different phases of the mining life cycle and at process, site, and corporate levels. In addition, our methodology and findings have practical implications that may be of interest to non-governmental organizations (NGOs), policy-makers, investors, researchers, and other professionals in the sustainable development field.

CHAPTER 2

A DATA-DRIVEN APPROACH TO EVALUATION OF SUSTAINABILITY REPORTING PRACTICES IN EXTRACTIVE INDUSTRIES

An article published in the journal *Sustainability*²

Cansu PERDELI DEMIRKAN^{3,4,5}, Nicole M. Smith^{4,5}, H. Sebnem Duzgun⁴, and Aurora Waclawski⁶

2.1. Abstract

Sustainability reporting is one of the tools that contribute to incorporating sustainable development in the design of extractive operations (i.e., “Design for Sustainability”), and the demand for sustainability reports is increasing due to the increased focus on sustainable development and sustainable financing efforts. The extractive industries are believed to have unique strengths to contribute to achieving the Sustainable Development Goals. Nonetheless, companies are expected to be transparent and accountable not only to investors but to all stakeholders, including communities, suppliers, clients, employees, and governments. Therefore, extractive industries require effective sustainability accounting and reporting to transition and contribute to sustainable development. Through a data-driven approach, this paper examines the scope and consistency of sustainability indicators used in the sustainability reports of eight oil and gas and eight mining companies from 2012 to 2018. Through content analysis and relevant statistical methods, we analyze the ways in which companies reported on their contributions to sustainable development, with a focus on indicators used and trends over time both within each industry and between industries. We demonstrate that extractive industries’ sustainability reporting practices are not consistent over time and that internal issues are better represented than external issues, in particular transportation and supply chain issues. Furthermore, while there are similar trends across the industries in terms of social and environmental indicator reporting, there are significant differences in economic reporting. We conclude that although both industries have established sustainability reporting practices, there are trends that demonstrate what companies are focusing on more, as well as areas for

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improvement. We see this as an initial step for conceptualizing how these industries can more objectively, consistently, and effectively assess and contribute to sustainable development.

2.2. Introduction

Many environmental disasters and human rights incidents that have attracted public concern over the last five decades have taken place in the mining and oil and gas industries (Warhurst, 2001). Hence, both industries have been a focus of debates about environmental sustainability and social responsibility (Jenkins & Yakovleva, 2006), and companies belonging to the extractive industries generally have been subjected to more stakeholder pressure than others (Aggarwal & Singh, 2019; Szczepankiewicz & Mućko, 2016). As a result, many companies publish yearly sustainability reports to publicly broadcast their economic, environmental, and social impacts and their contributions to sustainable development (GRI, 2018; WBCSD, 2002).

Corporate sustainability reporting frameworks and guidelines include sets of indicators to guide corporations in assessing and communicating their sustainable development performance (Roca & Searcy, 2012). The need for indicators to evaluate sustainability and guide the sustainable development process was initially raised by Agenda 21 at the Rio Conference in 1992. After this, indicators started to be developed and widely used in sustainability assessments (Azapagic, 2004; Azapagic & Perdan, 2000; Boulanger, 2008). Companies often use the indicators provided in various guidelines/frameworks (i.e., Global Reporting Initiative (GRI), International Petroleum Industry Environmental Conservation Association (IPIECA), CDP-formerly known as “Carbon Disclosure Project”) to measure, monitor, and report their sustainable development performance. Oil and gas and mining companies constantly evolve their sustainability reporting schemes (Böhling & Murguía, 2014; Janus & Murphy, 2013), and these reports vary in terms of which indicators are used, the methodologies used to assess the indicators, the reporting styles, and the content (Jenkins & Yakovleva, 2006; Siew, 2015). The individual choices companies make about their approaches to sustainability reporting and which sustainability issues to disclose create subjectivity (Bernow et al., 2019; Büyüközkan & Karabulut, 2018; Calabrese et al., 2016) and temporal variability in sustainability reporting practices.

Previous analyses of the use of indicators in sustainability reporting suffer from being limited to one industry, one year, assessing only GRI indicators, one dimension of sustainability, or companies based in one country. This study adds to our understanding of sustainability reporting in the extractive industries by providing an analysis of the indicators that appeared in eight oil and gas and eight mining companies' corporate sustainability reports from 2012 to 2018. Through a comparison of the indicators that appeared in these reports with a comprehensive set of sustainable development indicators compiled from the literature, we reveal the scope and consistency of indicators used in these reports. Through a data-driven approach, we extracted data from the sustainability reports using content analysis and provided a temporal analysis of the appearance of indicators to identify and compare the reporting trends within and between each industry. We then conducted hypothesis testing with relevant statistical methods to assess

whether or not the temporal variabilities observed in reporting were statistically significant. This analysis demonstrates that extractive industries' sustainability reporting practices are not consistent over time and that internal issues (i.e., issues associated with companies' internal operating procedures or employees) are better represented than external issues (i.e., issues associated with companies' relations with communities and other stakeholders.), in particular transportation and supply chain issues. Similarly, direct environmental issues (i.e., issues that are directly related to the company and its operations and that do not involve any third parties) are reported on more than indirect environmental issues (i.e., issues involving third parties such as suppliers, contractors, and communities). Furthermore, while there are similar trends across the industries in terms of social and environmental indicator reporting, there are significant differences in economic reporting, in particular on *technology*. We conclude that although both industries have established sustainability reporting practices, there are trends that show what companies are focusing on more, as well as areas for improvement. We see this as an initial step for conceptualizing how these industries can more objectively, consistently, and effectively assess and contribute to sustainable development.

2.2.1. Sustainability Reporting in the Extractive Industries

Oil and gas companies' first efforts at sustainability reporting occurred in the 1980s, and mining companies followed suit in the 1990s (Jenkins & Yakovleva, 2006). Although the primary focus was on producing stand-alone environmental reports [12,17,18], both industries have since expanded their scope and become more invested in sustainability reporting than most other industries [3,7,19]. In the last decade, research on indicators used in sustainability reports of oil and gas and mining companies has primarily focused on a single industry (either oil and gas or mining); however, the research has varied in terms of scope. For example, some studies have focused on the indicators companies used in a single year (Alazzani & Wan-Hussin, 2013; Dilling, 2016; Guenther et al., 2006; K. H. Lee, 2017; Raufflet et al., 2014; Roca & Searcy, 2012; Yongvanich & Guthrie, 2005), and others have examined the trends in reporting practices over time (Aggarwal & Singh, 2019; Bhatia & Tuli, 2018; Hourneaux Junior et al., 2017; Jenkins & Yakovleva, 2006; Khan et al., 2019; Lodhia & Hess, 2014; Mahmood & Orazalin, 2017; Orazalin & Mahmood, 2018; Perez & Sanchez, 2009; Suska, 2021), but hypothesis testing to assess the statistical significance of the temporal trends in reporting has not been conducted. Likewise, some studies have focused on a single dimension of sustainability (e.g., only environmental indicators) (Alazzani & Wan-Hussin, 2013; Guenther et al., 2006; Khan et al., 2019; K. H. Lee, 2017), while others investigated more than one dimension (Aggarwal & Singh, 2019; Hourneaux Junior et al., 2017; Jenkins & Yakovleva, 2006; Lodhia & Hess, 2014; Mahmood & Orazalin, 2017; Orazalin & Mahmood, 2018; Perez & Sanchez, 2009; Raufflet et al., 2014; Roca & Searcy, 2012; Yongvanich & Guthrie, 2005). However, none of these studies simultaneously addressed both the oil and gas and mining industries and the three dimensions of sustainability.

Sustainability reporting provides several potential benefits for companies. It can increase companies' understanding of risks and opportunities, and it can provide them with the opportunity to increase transparency and therefore enhance their credibility and brand value in the eyes of customers, suppliers, and broader society (Heenetigala & Armstrong, 2019). It has also been viewed as a response to increased environmental and societal pressures and as a component of obtaining and maintaining a "social license to operate" (Böhling & Murguía, 2014; Guenther et al., 2006; Raufflet et al., 2014). It may increase competitiveness by allowing companies to benchmark and assess their sustainability performance with regard to legislation, standards, and voluntary initiatives, and it may motivate employees to learn more about and implement measures to contribute to companies' sustainability performance. "Development of sustainable development indicators and reporting and ongoing improvement against these indicators" is key for what has been referred to as "Design for Sustainability" in both the production and mineral processing stages of a mining operation (McLellan et al., 2009). Recording and reporting of sustainability risks and opportunities are also essential for better management of extractive operations, as they can be integrated into the project management system (Corder et al., 2012). Finally, it can encourage companies to streamline their processes and reduce costs by increasing efficiency (Fortanier et al., 2011; GRI, n.d.-a; R. Hahn & Kühnen, 2013; IPIECA et al., 2007; Orazalin & Mahmood, 2018).

Despite the benefits, criticisms have been lodged at the transparency, reliability, thoroughness, and utility of sustainability reports and the data presented within (Pennington & More, 2010). On its own, sustainability reporting has been criticized for its mostly voluntary nature, and companies have not appeared to prioritize sustainability reporting (Pennington & More, 2010). Companies have also been accused of "greenwashing" or presenting a favorable rather than a realistic view of their performance (Pennington & More, 2010; Siew, 2015), and exerting a significant level of higher management control over the reporting process without implementing any accountability or auditing mechanisms (Pennington & More, 2010). No less, sustainability reports are still the most institutionalized resource that discloses companies' activities related to sustainable development, and the demand for sustainability reports is increasing (Hourneaux Junior et al., 2017). Because large-scale extractive companies often operate multi-nationally, and in some cases are required to report on aspects of sustainability, while in other cases reporting is voluntary (Global Reporting Initiative & University of Stellenbosch Business School, 2020), there is a certain degree of subjectivity in sustainability reporting (Industry Today, 2020; Ioannou & Serafeim, 2011, 2017). This has potential political and managerial implications (Ioannou & Serafeim, 2011, 2017) and may contribute to the variation that occurs in these reports. However, among multinational corporations, traditional reporting topics and employment data have become more standardized as companies gain more experience reporting on these topics and their measurement is relatively more straightforward than other issues (Fortanier et al., 2011).

2.2.2. Oil and Gas Sustainability Reporting

Research on sustainability reporting practices of oil and gas companies has mostly focused on the ways in which companies are using the GRI indicators and the trends in reporting over time. Alazzani and Wan-Hussin (2013) evaluated the environmental reporting in 2009 of eight oil and gas companies against the GRI 2006 Sustainability Reporting Guidelines and revealed the least and most disclosed environmental indicators (Alazzani & Wan-Hussin, 2013). They concluded that companies made reasonable efforts to report their environmental performance in accordance with the GRI guidelines, that the voluntary adoption of GRI guidelines increased transparency, credibility, and comparability in sustainability reporting, and that the GRI guidelines should be adopted more widely among the industry (Alazzani & Wan-Hussin, 2013). Another study on environmental reporting by Khan et al. (2019) investigated the reporting of 30 environmental GRI indicators by 12 oil and gas companies in Pakistan for the years 2010–2014. They showed that overall, there was an increase in the presence of the indicators; however, the majority of the companies had relatively low coverage of these indicators, and the indicators were not consistently disclosed over the years (Khan et al., 2019). Orazalin and Mahmood (2018) evaluated the trends in sustainability reporting practices of the Russian oil and gas industry by manually collecting data from sustainability reports, annual reports, and audited financial statements of fifty companies from 2012 to 2016. The authors used the GRI-based environmental, social, and economic indicators for evaluation and analyzed the extent of disclosure in each pillar. They found a steady increase in the quantity of environmental and economic indicators disclosed across the survey years and detected an increasing trend in triple bottom line sustainability reporting, which measures a corporation's performance across the three main pillars of sustainability: economy, society, and the environment (Siew, 2015). They suggested that triple bottom line reporting resulted in more extensive sustainability disclosures (Orazalin & Mahmood, 2018).

Some studies have examined the relationship between the reporting practices of oil and gas companies and other parameters. Summerhays and De Villiers (2012) reported that the six largest oil and gas companies increased their environmental disclosures in response to the 2010 Gulf of Mexico oil spill, and Hourneaux et al. (2017) examined the association between companies' corporate strategies and their reporting on sustainability indicators. Through a comparative study of two large oil and gas companies using the GRI-G4 indicators, they identified the indicator categories that were and were not connected to each company's corporate strategy. Their results showed that the indicator categories that were strongly connected to strategy elements included *labor practices and decent work*, *environmental compliance*, and *indirect economic impacts*, while *transportation* had a very limited connection to company strategies. The authors also detected an imbalance in triple bottom line reporting, with a dominance of social aspects (Hourneaux Junior et al., 2017). In another study, Mahmood and Orazalin (2017) examined the relationships between corporate board characteristics and sustainability reporting practices of 30 Kazakhstan oil and gas companies between 2010 and 2013 by using GRI indicators and found that the

board's gender diversity and size had a positive impact on the scope and quality of environmental reporting. (Mahmood & Orazalin, 2017).

2.2.3. Mining and Sustainability Reporting

Research on sustainability reporting in the mining industry has primarily focused on understanding the trends and evolution of reporting practices in all sustainability pillars (social, environmental, and economic) and has emphasized the importance of integrated sustainability reporting. Yongvanich and Guthrie (2005) argued that reporting both financial and non-financial performance is essential. Their content analysis, based on 73 indicators that appeared in annual reports of 17 Australian mining companies for the financial year 2002, revealed the disclosure frequency of each indicator. They showed that although companies reported an average of 48% of all indicators, they disclosed only a small portion of environmental and social indicators (Yongvanich & Guthrie, 2005).

A number of studies have investigated the trends in reporting practices in the mining industry over the years. Jenkins and Yakovleva (2006) performed a temporal analysis of reporting of ten mining companies between 1999 and 2003. Although they found substantial variability in the reporting practices among these companies, there were increasing trends in social and environmental reporting, as well as in the incorporation of economic disclosures in the stand-alone Social and Environmental Reports. There was also a trend toward covering more complex issues related to sustainable development and corporate social responsibility (CSR). Similarly, Perez and Sanchez (2009) assessed the evolution of sustainability reporting in the mining sector between the years 2001 and 2006 by performing a content analysis of the sustainability reports of four mining companies. They compared these companies' reporting performance and adherence to best practices and scored them according to the most and least addressed topics. The social performance reporting score was the highest for all companies, and the economic performance score was the lowest. The environmental performance had the most variability in the reports. Furthermore, all of the companies showed an improvement in their sustainability reports in terms of structure and comprehensiveness. Lee (2017) investigated the relationship between the quality and quantity of environmental disclosures of 55 Australian mining companies based on their 2013 reports and the indicators in the GRI's Mining and Metals Sector Supplement. They found that the number of environmental disclosures of these companies was positively and significantly correlated with market capitalization and disclosure quality (i.e., the usefulness of information in understandability, relevance, reliability, and comparability) (K. H. Lee, 2017). Analyzing the literature on sustainability accounting and reporting practices in the mining industry from 2004 to 2013, Lodhia and Hess (2014) concluded that these practices were evolving slowly in the mining industry, and they identified the need for future studies that analyze the social, environmental, and economic aspects disclosed by companies and the extent to which they are integrated (Lodhia & Hess, 2014). Yaylaci and Duzgun (2016) compiled 347 sustainability indicators specific to the mining sector in their study that proposes an indicator-based sustainability assessment framework for the mining sector (Yaylaci & Düzgün, 2016).

2.2.4. Comparing Industries

Few studies have examined the sustainability reporting practices of both the oil and gas and mining industries. Raufflet et al. (2014) assessed the CSR practices in both industries through interviews with experts and practitioners in the extractive industries and through a content analysis of “regulatory scripts” in company reports in 2011, defined as shared practices among the sector in response to international frameworks and standards. They found that environmental topics (excluding transportation) and social, health, and safety issues were particularly well covered (Raufflet et al., 2014). Guenther et al. (2007) assessed the reporting practices of the two industries but limited the analysis to GRI environmental indicators over a one-year period. Their results revealed the three most commonly and comprehensively reported indicators as *total water use*, *compliance*, and *air emissions* and showed that only one-third of the GRI environmental indicators were reported. They also showed significant differences in environmental reporting between the two industries. Suska (2021) assessed the annual reports of the two industries for 2014–2019 and focused on the environmental and climate responsibility initiatives of three Polish companies. They showed that both industries were working toward reducing the environmental impact caused by wastewater discharge but that there were areas for improvement in reporting on carbon emissions and waste management (Suska, 2021). Dilling (2016) examined the financial and sustainability reports of the two industries and found that in 2012, Canadian companies minimally disclosed information related to long-term value creation (Dilling, 2016).

Building on the research outlined above, we investigated oil and gas and mining companies’ approaches to sustainability reporting using a data-driven approach. Considering the individual choices companies make in their reporting in terms of the indicators, reporting methodologies, styles, and content, we hypothesized (i) that the reporting practices of extractive industries show temporal variability and (ii) that there are differences between the reporting practices of oil and gas and mining companies. Although our hypotheses concur with the literature, testing these hypotheses with a data-driven approach that includes statistical tests has not been conducted. Therefore, our analysis of both industries’ sustainability reporting practices addresses this gap by revealing the statistical significance of these temporal trends. Here, we provide an analysis of eight oil and gas companies and eight mining companies’ reports over seven years to identify and compare the reporting trends both within and between industries. Using the triple bottom line approach to sustainable development and including environmental, social, and economic indicators in our analysis, we respond to a call from Lodhia and Hess (2014) to examine the integration of social, environmental, and economic aspects disclosed by companies (Lodhia & Hess, 2014). Our study also shows that external issues, in particular those related to supply chains, are relatively overlooked in the sustainability reports of extractive industries and that there is more thorough reporting on internal issues. Likewise, indirect environmental issues minimally appear in sustainability reports, while direct environmental issues are reported on more. Although the two industries share similar trends in terms of social and environmental reporting, there are significant differences in economic reporting, in particular reporting on *technology*. Identifying the strengths and areas for improvement in

sustainability reporting indicates how sustainability reporting may be more representative of the different pillars of sustainable development and may align better with common goals and efforts toward sustainable development.

We also contend that improvements in reporting based on particular optimization points can contribute to companies' ability to incorporate sustainable development concepts more effectively into the design of their operations and achieve more sustainable business models. Although design is a practical aspect of engineering, its main theoretical basis is optimization, which does not only include consideration of technical aspects but also includes the triple bottom line aspects of sustainable development (i.e., economics, society, and the environment). This also relates to the concept of a *sustainable business model* that builds on the triple bottom line approach (Bocken et al., 2014; Lemus-Aguilar et al., 2019) and is defined by Lüdeke-Freund (2010) as "a business model that creates competitive advantage through superior customer value and contributes to a sustainable development of the company and society" (Lüdeke-Freund, 2010). Organizational design for sustainable business models is another emerging concept that investigates the design considerations for creating new business models or changing the existing ones based on the triple bottom line approach (Lemus-Aguilar et al., 2019). This paper contributes to these theoretical foundations of engineering design by demonstrating how the design of extractive operations could be improved by considering explicit optimization points derived from sustainability indicators.

2.3. Methodology

A data-driven approach is an exploratory approach that derives scientifically interesting insights based on evidence coming from the analysis and interpretation of data (Maass et al., 2018), and it is widely adopted in sustainability research (Halkos et al., 2021; Lindgren et al., 2021; Lyu et al., 2019; K. J. Wu et al., 2021). In this study, we began with a comprehensive set of sustainability indicators (referred to hereafter as the "indicator set") and then collected data from the sustainability reports of selected oil and gas and mining companies from 2012 to 2018 to compare the indicators used in these reports with the indicator set (Figure 2.1). Through content analysis and relevant statistical methods, we analyzed the ways in which companies reported on their contributions to sustainable development, with a focus on indicators used and trends over time both within each industry and between industries.

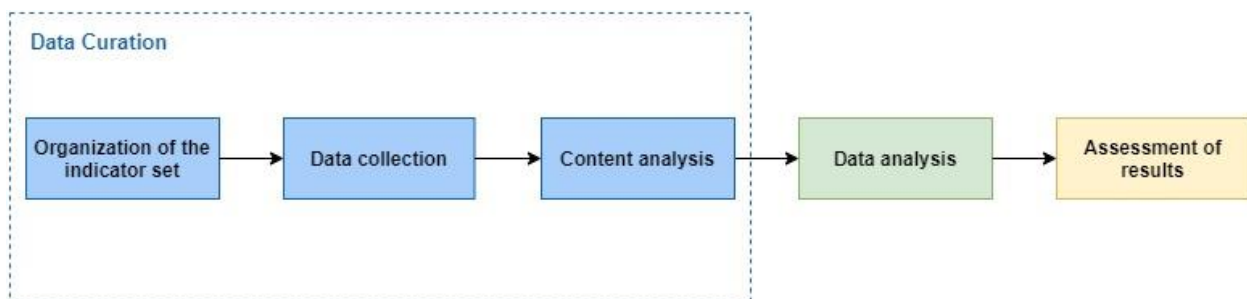


Figure 2.1 Research methodology flowchart

2.3.1. Organization of the Indicator Set

This study used an indicator set that was established as part of a larger study on sustainability assessment frameworks as decision support tools for the mining sector (Yaylaci, 2015; Yaylaci et al., 2017; Yaylaci & Düzgün, 2016, 2017). This indicator set was compiled by reviewing mining-related sustainability literature in scientific journals, and guideline documents produced by international organizations, including the GRI, the United Nations (UN), the World Bank (WB), the Organization for Economic Cooperation and Development (OECD), and the International Institute for Environment and Development (IIED), as well as publications by sectoral organizations such as the Mining Association of Canada and the International Council on Mining and Metals (ICMM). This indicator set was then divided into “strategic-level” indicators and “project-level” indicators (Yaylaci, 2015; Yaylaci & Düzgün, 2016). Strategic-level indicators were those used by decision-makers to understand the impacts of proposed plans or programs at the macro scale (i.e., regional, national, or global), and project-level indicators included the social, environmental, and economic impacts of specific projects or companies at the micro-scale (i.e., company- or local-level) (Yaylaci, 2015). We used the project-level indicator set since our focus was on the impacts of specific companies.

A comparison of our indicator set with the indicators used in oil and gas companies’ sustainability reports revealed that only 4% of the total indicators that appeared in the oil and gas reports were not covered by our indicator set. Therefore, for consistency, we used our original indicator set to analyze the sustainability reports of both industries. The indicator set included 225 indicators, which were classified as either social (105 indicators), environmental (87 indicators), or economic (33 indicators) (Yaylaci, 2015). Although there is a recent turn to Economic, Social, and Governance (ESG) reporting, we did not classify indicators according to “governance”, since the triple bottom line classification is still prevalent in the literature, and governance became a distinctive fourth pillar only recently (Tysiac, 2020). Even so, we did not ignore governance-related indicators, as they are mostly classified under “social” and “economic” indicators that cover business ethics, shareholders, employee relations, board diversity, audit mechanisms, transparency, and internal controls and policies against bribery and corruption. We then further grouped the indicators into categories based on how they were classified in the literature (e.g., human rights, emissions, economic performance) (see Appendix A).

We classified social indicators as “internal” or “external”. Internal indicators (e.g., business ethics or labor/management relations) signaled those that were related to the companies’ internal operating processes or business principles. External indicators (e.g., community engagement/impacts or human rights) included those mostly associated with companies’ external relations with communities, customers, suppliers, and other stakeholders outside of the companies’ employees. We also classified environmental indicators in the indicator set as “direct” and “indirect”. The majority of the environmental indicators were directly related to the company and its operations and did not involve any third parties. However, some of the indicators were “indirect”, as they involved third parties such as suppliers, contractors, and communities. The indirect indicators included all of the indicators under the *material use, transport and*

logistics, and *nuisance* categories; indicators related to indirect energy consumption in the *energy* category; indirect greenhouse gas emissions in the *emissions* category; and assessment of suppliers and contractors' quality and environmental performance in the *environmental management* category.

2.3.2. Data Collection

We selected the top ten largest oil and gas companies in 2018 based on their composite score of revenue, profits, assets, and market value (Forbes, 2018) and then checked the online availability of their sustainability reports for the period between 2012 and 2018. Three of the top ten oil and gas companies lacked sustainability reports for the full period under study; therefore, we added the eleventh-ranking company, for a total of eight oil and gas companies. For the selection of mining companies, we focused on the top 13 companies based on their market value as of 2017 (Els, 2017). We eliminated companies that had no formal sustainability reports in English for the period between 2012 and 2018. Five companies were eliminated, and eight mining companies were included in the sample, which represented the primary metal industries (gold, copper, and iron). The final sample included eight oil and gas and eight mining companies, for a total of 112 sustainability reports. We limited our sample to this number because we felt that this would provide us with a relatively thorough snapshot of reporting before and after the SDGs were announced in 2015 and to keep the dataset manageable without the use of machine learning tools. The report titles varied by company and year and included "Corporate Sustainability Report", "Corporate Social Responsibility Report", "Responsibility Report", "Corporate Responsibility Report", "Corporate Citizenship Report", "Working toward Sustainable Development Report", "Social and Environmental Performance Report", "Sustainable Development Report", "Sustainability Review", and "Registration Document". Some companies disclosed their economic performance in annual or financial reports instead of in sustainability reports, and such reports were rarely cross-referenced in the sustainability reports. The economic indicators that were accessible through the cross-references provided in sustainability reports were also considered "addressed".

2.3.3. Content Analysis

We compared our indicator set to the indicators used in companies' sustainability reports to examine the current approaches oil and gas and mining companies are using to measure their contributions to sustainable development.

We used the content analysis method, which is a favored technique in sustainability reporting research (Fuisz-Kehrbach, 2015; Hourneaux Junior et al., 2017; Lodhia & Hess, 2014; Papoutsi & Sodhi, 2020; Perez & Sanchez, 2009; Yongvanich & Guthrie, 2005). Content analysis systematically converts qualitative data into quantitative data by analyzing and quantifying the presence of certain words, concepts, or themes within textual material (e.g., reports and graphics) (Columbia University, n.d.; Krippendorff, 2004; University of Georgia, 2012). This method is useful as a data-driven approach for providing objective assessments and revealing trends in reporting (Yongvanich & Guthrie, 2005).

Following Papoutsi and Sodhi (2020), we employed the manual content analysis method, rather than using computer-aided text analysis tools, for two reasons: (i) companies do not always present data in text form but rather provide information via tables or figures, which would not be processed by computer-aided tools; and (ii) since the reporting styles and guidelines vary significantly among companies and industries, information specific to particular indicators could be included that may be missed when adhering to a set of pre-defined keywords (Papoutsi & Sodhi, 2020).

We identified and noted the presence or absence of indicators in texts covering corporate disclosures by searching for certain words and concepts that mapped onto the definitions of indicators in our indicator set. Accordingly, the presence of an indicator was given a score of “1”, while the absence of an indicator was given a “0”. In some cases, companies cross-referenced their indicators to the GRI index, which allowed us to directly link these to the indicator set.

It should be noted that the 2017 sustainability report of one of the mining companies was a summary report rather than a full report and included only about half of the indicators the company included in their other reports. Therefore, this company was omitted from the 2017 calculations so as not to distort the statistical results.

2.3.4. Data Analysis

We analyzed the data in terms of the extent to which the sustainability reports of oil and gas and mining companies included the indicators in the indicator set and the temporal variabilities in reporting. This analysis revealed the gaps and overlaps between the indicator set and company reporting on these indicators, the most and least emphasized indicator categories and the differences in oil and gas and mining companies’ sustainability reporting from 2012 to 2018. We used metrics of coverage ratio and reporting rate of indicators for the comparison and adopted statistical tests to assess the significance of the temporal variabilities observed in reporting.

2.3.4.1. Coverage Ratio

We determined the coverage ratio, or the ratio of the number of addressed indicators within an indicator subset to the total number of indicators in the corresponding indicator subset, for each year and each company. Equation 2.1 provides the calculation for the *coverage ratio*.

$$Coverage\ Ratio\ (\%) = \sum_{n=1}^7 \frac{disclosure_n}{number\ of\ indicators\ in\ the\ corresponding\ set} \times 100 \quad (2.1)$$

where, $disclosure_n$ = the total number of disclosed indicators by a company in n^{th} year within the seven-year period (2012–2018).

We calculated the coverage ratio for the entire indicator set and for the environmental, social, and economic indicator subsets to understand the extent to which the indicators in the literature were covered in companies' sustainability reports. We also examined the trends in coverage ratio over time to understand the trends in sustainability reporting from 2012 to 2018.

2.3.4.2. Reporting Rate of Indicators

We examined the average reporting rate of each indicator in a given number of years (i.e., the proportion of reports that disclose a particular indicator in n years). Equation 2.2 provides the method for calculating the *average reporting rate*.

$$\text{Average reporting rate in } n \text{ years} = \frac{\sum_{n=1}^7 \left(\frac{\text{disclosure}_n}{\text{total number of reports}} \right)}{n \text{ years}} \quad (2.2)$$

where, disclosure_n = the total number of reports that disclosed the indicator in n^{th} year within the seven-year period (2012–2018).

The average reporting rate of each individual indicator category revealed the most and least emphasized indicator categories in the reports.

2.3.4.3. Statistical Tests

We conducted statistical tests to assess whether or not the temporal variabilities observed in reporting were statistically significant. To do this, we used repeated measures ANOVA and supported it with Friedman's test, which is a nonparametric alternative to repeated measures ANOVA that does not require the data to meet the normality assumption. We used Friedman's test as a backup against a potential violation of ANOVA's normality assumption since not all of our tested datasets were normally distributed. After the Friedman's test, we also conducted a post hoc pairwise test (namely, a pairwise signed-rank test) that compared each year in pairs to determine where exactly the differences lay. All statistical tests and post hoc tests were conducted at a 95% confidence level using the Real Statistics Resource Pack software (Release 7.6; Copyright 2013–2021) (Zaiontz, 2020). The set p -value for this confidence level was $p = 0.05$, with all of the p -values below this threshold value providing statistically significant results. These tests allowed for a more in-depth analysis of temporal variations and signaled the areas that were most and least consistently reported. See statistical test results in Appendix B.

2.3.4.4. Study Limitation

We recognize that this study is limited by our analysis of the sustainability reports only, and it was not triangulated with more information from the companies. Future studies might consider internally and externally validating the analysis of results by also investigating industry papers, reports, or other

documents that could enrich the analysis, as well as by conducting interviews with experts, employees, and managers of these companies.

2.4. Results

2.4.1. Coverage of the Indicator Subsets

Over the seven-year period, mining companies included a larger proportion (52%) of the total indicator set in their reports than oil and gas companies (45%) (Table 2.1). Both industries reported a higher proportion of social indicators than the other indicator subsets, but mining companies reported more social and environmental indicators than oil and gas companies, which reported on environmental indicators at a relatively low rate (37%). Both industries reported on the economic indicators to the same extent (45%).

Table 2.1. Coverage of indicator subsets in sustainability reports.

Indicator Subsets	Indicator Set	Oil and Gas Companies		Mining Companies	
	Total Number of Indicators	Number of Indicators Covered	Coverage Ratio	Number of Indicators Covered	Coverage Ratio
Social	105	53	50%	61	58%
Environmental	87	32	37%	41	47%
Economic	33	15	45%	15	45%
Total	225	100	45%	117	52%

2.4.2. Reporting Rates by Indicator Categories

To understand the extent to which company sustainability reports disclosed specific indicators over time, we analyzed the reporting rates of indicators grouped into thematic categories within each subset for each year, as well as over the study period (Tables 2.2–2.7). In Tables 2.2–2.7, the means represent the proportion of reports that disclosed an indicator category in a given year, or over the seven years, and the standard deviations (SD) represent how spread-out the data values were around the mean. For both industries, yearly reporting rates were calculated for eight reports, and the seven-year average reporting rates represented 56 reports in total for each industry. The high SD values demonstrate the high level of variation that lies within the nature of the collected data, and more specifically, the differences in reporting practices between different companies, as well as the differences observed in a single company's reports over seven years.

2.4.2.1. Temporal Variabilities in Reporting of Social Indicators

Overall, the two industries showed similar trends in disclosing social indicators in their reports (Tables 2.2 and 2.3). However, mining showed higher temporal variability than oil and gas in reporting most social indicator categories. There were also some overlaps in the reporting of both industries' most and least

reported topics over the study period (Tables 2.2 and 2.3). *Social performance management* and *business ethics* appeared in the top five most frequently disclosed indicator categories for both industries, and *customer health and safety*, *product/materials stewardship*, *suppliers and contractors*, and *child labor* appeared in the five least reported categories for both industries.

Table 2.2. Means and standard deviations (Mean ± SD) of reporting rates of social indicator categories by oil and gas.

Social Indicator Categories	2012	2013	2014	2015	2016	2017	2018	7-Year Average
External Indicator Categories								
Product/Materials Stewardship	0.30 ± 0.46	0.33 ± 0.47	0.29 ± 0.46	0.23 ± 0.42	0.28 ± 0.45	0.24 ± 0.43	0.21 ± 0.41	0.27 ± 0.44
Suppliers and Contractors	0.13 ± 0.34	0.19 ± 0.40	0.31 ± 0.48	0.31 ± 0.48	0.31 ± 0.48	0.31 ± 0.48	0.31 ± 0.48	0.27 ± 0.44
Customer Health and Safety	0.30 ± 0.46	0.40 ± 0.50	0.43 ± 0.50	0.35 ± 0.48	0.30 ± 0.46	0.30 ± 0.46	0.23 ± 0.42	0.33 ± 0.47
Child Labor	0.38 ± 0.49	0.42 ± 0.50	0.33 ± 0.48	0.38 ± 0.49	0.33 ± 0.48	0.33 ± 0.48	0.33 ± 0.48	0.36 ± 0.48
Indigenous Peoples	0.42 ± 0.50	0.46 ± 0.51	0.38 ± 0.49	0.38 ± 0.49	0.42 ± 0.50	0.33 ± 0.48	0.33 ± 0.48	0.39 ± 0.49
Forced or Compulsory Labor	0.31 ± 0.48	0.44 ± 0.51	0.38 ± 0.50	0.38 ± 0.50	0.50 ± 0.52	0.38 ± 0.50	0.44 ± 0.51	0.40 ± 0.49
Community Engagement/Impacts	0.41 ± 0.49	0.43 ± 0.50	0.44 ± 0.50	0.39 ± 0.49	0.40 ± 0.49	0.38 ± 0.49	0.40 ± 0.49	0.41 ± 0.49
Human Rights	0.59 ± 0.50	0.63 ± 0.49	0.70 ± 0.46	0.68 ± 0.47	0.66 ± 0.48	0.63 ± 0.49	0.70 ± 0.46	0.65 ± 0.48
Internal Indicator Categories								
Labor/Management Relations	0.38 ± 0.49	0.42 ± 0.50	0.40 ± 0.49	0.48 ± 0.50	0.46 ± 0.50	0.40 ± 0.49	0.40 ± 0.49	0.42 ± 0.49
Employment Practices	0.58 ± 0.50	0.54 ± 0.50	0.56 ± 0.50	0.54 ± 0.50	0.54 ± 0.50	0.48 ± 0.50	0.54 ± 0.50	0.54 ± 0.50
Diversity and Equal Opportunity	0.58 ± 0.50	0.48 ± 0.50	0.56 ± 0.50	0.56 ± 0.50	0.58 ± 0.50	0.58 ± 0.50	0.59 ± 0.50	0.56 ± 0.50
Occupational Health and Safety	0.59 ± 0.49	0.58 ± 0.50	0.60 ± 0.49	0.61 ± 0.49	0.58 ± 0.49	0.53 ± 0.50	0.52 ± 0.50	0.57 ± 0.49
Training and Education	0.58 ± 0.50	0.60 ± 0.50	0.65 ± 0.48	0.60 ± 0.50	0.58 ± 0.50	0.60 ± 0.50	0.55 ± 0.50	0.59 ± 0.49
Business Ethics	0.54 ± 0.50	0.57 ± 0.50	0.61 ± 0.49	0.60 ± 0.49	0.63 ± 0.48	0.63 ± 0.49	0.62 ± 0.49	0.60 ± 0.49
Social Performance Management	0.68 ± 0.47	0.73 ± 0.45	0.77 ± 0.43	0.75 ± 0.44	0.75 ± 0.44	0.73 ± 0.45	0.73 ± 0.45	0.73 ± 0.44

Table 2.3. Means and standard deviations (Mean \pm SD) of reporting rates of social indicator categories by mining.

Social Indicator Categories	2012	2013	2014	2015	2016	2017	2018	7-Year Average
External Indicator Categories								
Customer Health and Safety	0.38 \pm 0.49	0.33 \pm 0.47	0.28 \pm 0.45	0.18 \pm 0.38	0.20 \pm 0.41	0.20 \pm 0.41	0.20 \pm 0.41	0.25 \pm 0.43
Product/Materials Stewardship	0.50 \pm 0.50	0.39 \pm 0.49	0.39 \pm 0.49	0.16 \pm 0.37	0.16 \pm 0.37	0.19 \pm 0.39	0.19 \pm 0.39	0.28 \pm 0.45
Suppliers and Contractors	0.25 \pm 0.45	0.31 \pm 0.48	0.31 \pm 0.48	0.31 \pm 0.48	0.38 \pm 0.50	0.29 \pm 0.47	0.25 \pm 0.45	0.30 \pm 0.46
Forced or Compulsory Labor	0.56 \pm 0.51	0.50 \pm 0.52	0.44 \pm 0.51	0.56 \pm 0.51	0.50 \pm 0.52	0.50 \pm 0.52	0.44 \pm 0.51	0.50 \pm 0.50
Child Labor	0.54 \pm 0.51	0.58 \pm 0.50	0.54 \pm 0.51	0.58 \pm 0.50	0.54 \pm 0.51	0.38 \pm 0.50	0.42 \pm 0.50	0.51 \pm 0.50
Human Rights	0.63 \pm 0.49	0.66 \pm 0.48	0.61 \pm 0.49	0.63 \pm 0.49	0.70 \pm 0.46	0.61 \pm 0.49	0.66 \pm 0.48	0.64 \pm 0.48
Indigenous Peoples	0.58 \pm 0.50	0.71 \pm 0.46	0.67 \pm 0.48	0.54 \pm 0.51	0.71 \pm 0.46	0.67 \pm 0.48	0.71 \pm 0.46	0.65 \pm 0.48
Community Engagement/ Impacts	0.63 \pm 0.49	0.67 \pm 0.47	0.66 \pm 0.47	0.63 \pm 0.48	0.69 \pm 0.46	0.64 \pm 0.48	0.67 \pm 0.47	0.66 \pm 0.47
Internal Indicator Categories								
Occupational Health and Safety	0.57 \pm 0.50	0.53 \pm 0.50	0.51 \pm 0.50	0.49 \pm 0.50	0.52 \pm 0.50	0.48 \pm 0.50	0.57 \pm 0.50	0.52 \pm 0.50
Training and Education	0.60 \pm 0.50	0.63 \pm 0.49	0.60 \pm 0.50	0.63 \pm 0.49	0.58 \pm 0.50	0.57 \pm 0.50	0.53 \pm 0.51	0.59 \pm 0.49
Diversity and Equal Opportunity	0.66 \pm 0.48	0.64 \pm 0.48	0.63 \pm 0.49	0.69 \pm 0.47	0.72 \pm 0.45	0.68 \pm 0.47	0.64 \pm 0.48	0.66 \pm 0.47
Business Ethics	0.67 \pm 0.47	0.70 \pm 0.46	0.68 \pm 0.47	0.67 \pm 0.47	0.67 \pm 0.47	0.62 \pm 0.49	0.68 \pm 0.47	0.67 \pm 0.47
Labor/Management Relations	0.65 \pm 0.48	0.69 \pm 0.47	0.63 \pm 0.49	0.69 \pm 0.47	0.73 \pm 0.45	0.67 \pm 0.48	0.67 \pm 0.48	0.67 \pm 0.47
Social Performance Management	0.73 \pm 0.45	0.73 \pm 0.45	0.75 \pm 0.44	0.73 \pm 0.45	0.73 \pm 0.45	0.71 \pm 0.46	0.75 \pm 0.44	0.73 \pm 0.44
Employment Practices	0.75 \pm 0.44	0.75 \pm 0.44	0.73 \pm 0.45	0.81 \pm 0.39	0.77 \pm 0.42	0.79 \pm 0.42	0.71 \pm 0.46	0.76 \pm 0.43

The ranges in reporting rates (i.e., the difference between the maximum and the minimum proportion of disclosing reports over the seven-year period) (Figure 2.2) and the results of statistical tests applied at a 95% confidence level (Appendix B, Tables B.1, and B.2) revealed the most significant temporal variabilities. Oil and gas companies reported on *customer health and safety*, *suppliers and contractors*, and *forced or compulsory labor* with the highest ranges, meaning that there was significant variability in the presence (or absence) of these indicators in the reports over the study period. There was also significant variability in the reporting of *customer health and safety* ($p = 0.036$), *diversity and equal opportunity* ($p = 0.037$), and *occupational health and safety* ($p = 0.019$) (Table B.1).

For mining companies, *product/materials stewardship*, *child labor*, and *customer health and safety* showed the highest ranges in reporting over the study period, with a general decrease in reporting over time (Table 2.3). The reporting of *product/materials stewardship* ($p = 2.2 \times 10^{-18}$), *customer health and safety* ($p = 0.002$), and *business ethics* ($p = 0.006$) showed significant variation over time (Table B.2). However, mining's reporting on *product/materials stewardship* and *customer health and safety* seems to have stabilized in recent years, as the reporting rates between 2015 and 2018 do not show significant variation, despite their difference from earlier years (2012–2014) (Table B.2). The reporting rate of *business ethics* did not change much over the years, except dropping to its lowest in 2017 (Table 2.3), which was significantly different compared with all other years (Table B.2).

There were some categories where the results of neither ANOVA nor Friedman's test showed statistically significant differences over the years for the lump dataset, but the post hoc test detected differences between some years. For one category in mining (*social performance management*), the opposite was observed, where the result of Friedman's test showed a statistical difference for the lump dataset, but the post hoc test did not detect any difference between years (Tables B.1 and B.2).

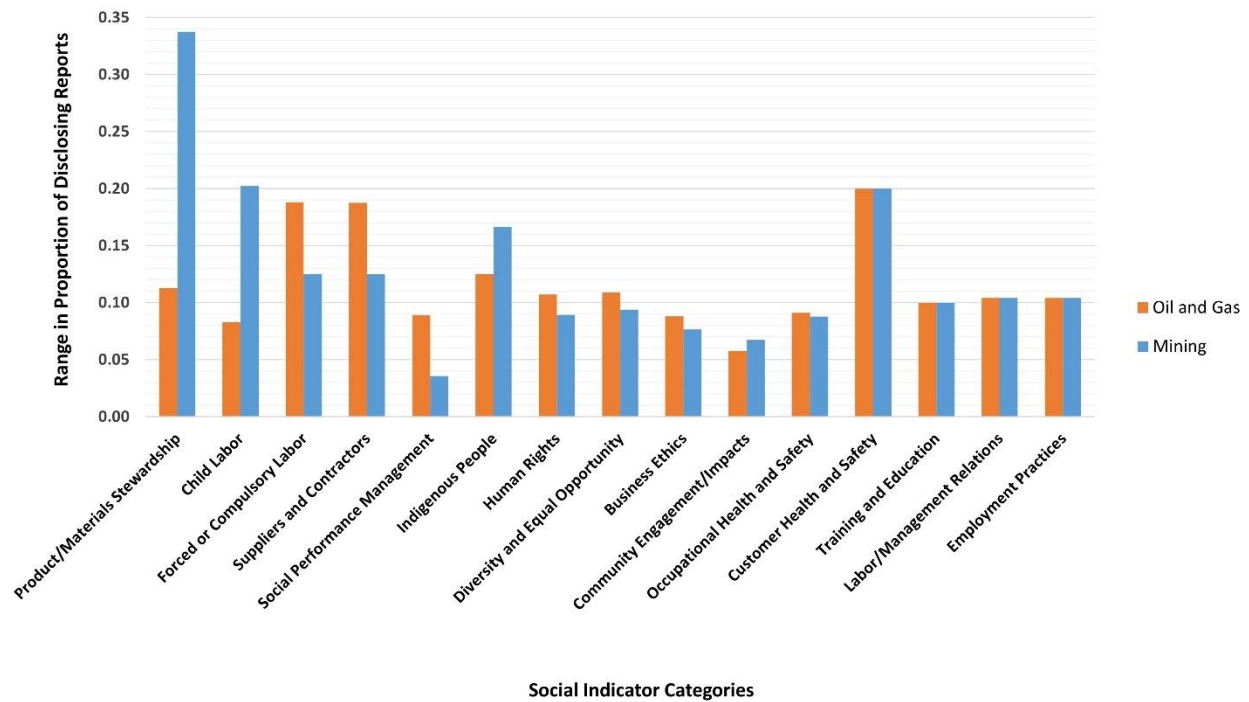


Figure 2.2. Range in reporting rates of social indicator categories, representing the extent of change in their appearance in reports over seven years (2012–2018).

2.4.2.2. Reporting on Internal vs. External Indicators

A deeper dive into the reporting of indicators themselves revealed trends that potentially demonstrate places where companies were focusing more or less. In both industries, internal indicators (i.e., *business principles* or *employee management*) were generally reported on more and showed lower temporal variability than external indicators (i.e., relations with communities, customers, suppliers, and other stakeholders).

In most categories, indicators that can be narratively disclosed (e.g., indicators directly related to company policies or programs) appeared in more reports, while indicators requiring quantitative data or demonstrable proof (e.g., information regarding the number of incidents, complaints, fines, and legal actions for noncompliance with laws) were reported in a limited number of reports. Similarly, reporting was limited on indicators that were related to actual incidents of violation or the identification of risks regarding external issues, such as child labor, forced labor, and indigenous peoples.

In addition, social indicators were reported on less, as the required level of detail increased. For example, in the *employment practices* category, both industries reported on the number of direct employees on their payroll in almost every report, but reporting decreased for indicators that required more detailed employment information and statistics, such as the number of indirect employees, employee turnover, and benefits provided to full-time employees. Similarly, in the *diversity and equal opportunity* category, quantitative indicators related to gender diversity were reported at higher rates,

while the reporting on the percentage of ethnic minorities in executive and management ranks was limited. Additionally, in the occupational health and safety category, fatalities and lost-time accidents were quantitatively disclosed by both industries in almost every report; however, the number of compensated occupational diseases was among the least reported indicators.

2.4.2.3. Reporting on Direct vs. Indirect Environmental Issues

Both industries reported more on their direct environmental impacts, especially *water consumption* (Tables 2.4 and 2.5). *Environmental investments and activities, water consumption, environmental management, and polluting incidents* were among the most reported categories by both industries. Although indirect environmental indicators appeared more in mining reports than oil and gas reports, both industries minimally reported on the environmental impacts resulting from their interactions with third parties. Furthermore, the environmental impacts of activities conducted at the lower ends of the supply chain, such as material use and transport and logistics, were among the least disclosed categories by both industries (Tables 2.4 and 2.5).

An important difference between the environmental reporting of the two industries was discovered for the *energy* category. In mining reports, the water-energy nexus was well-covered, as *energy* and *water consumption* were the top two disclosed categories. However, in oil and gas reports, *energy* was reported much less than *water consumption*.

Table 2.4. Means and standard deviations (Mean \pm SD) of reporting rates of environmental indicator categories by oil and gas.

Environmental Indicator Categories	2012	2013	2014	2015	2016	2017	2018	7-Year Average
Material Use	0.13 \pm 0.33	0.15 \pm 0.36	0.08 \pm 0.28	0.08 \pm 0.28	0.06 \pm 0.24	0.10 \pm 0.31	0.04 \pm 0.20	0.09 \pm 0.29
Nuisance	0.13 \pm 0.34	0.13 \pm 0.34	0.13 \pm 0.34	0.13 \pm 0.34	0.17 \pm 0.38	0.17 \pm 0.38	0.21 \pm 0.41	0.15 \pm 0.36
Transport and Logistics	0.28 \pm 0.46	0.31 \pm 0.47	0.25 \pm 0.44	0.22 \pm 0.42	0.25 \pm 0.44	0.19 \pm 0.40	0.22 \pm 0.42	0.25 \pm 0.43
Liquid Effluents	0.23 \pm 0.42	0.27 \pm 0.45	0.29 \pm 0.46	0.29 \pm 0.46	0.31 \pm 0.47	0.29 \pm 0.46	0.29 \pm 0.46	0.28 \pm 0.45
Closure and Rehabilitation	0.30 \pm 0.46	0.38 \pm 0.49	0.30 \pm 0.46	0.30 \pm 0.46	0.28 \pm 0.45	0.23 \pm 0.42	0.23 \pm 0.42	0.29 \pm 0.45
Emissions	0.26 \pm 0.44	0.26 \pm 0.44	0.32 \pm 0.47	0.33 \pm 0.47	0.32 \pm 0.47	0.33 \pm 0.47	0.35 \pm 0.48	0.31 \pm 0.46
Biodiversity	0.41 \pm 0.50	0.38 \pm 0.49	0.41 \pm 0.50	0.44 \pm 0.50	0.41 \pm 0.50	0.41 \pm 0.50	0.41 \pm 0.50	0.41 \pm 0.49
Energy	0.36 \pm 0.48	0.36 \pm 0.48	0.44 \pm 0.50	0.44 \pm 0.50	0.43 \pm 0.50	0.43 \pm 0.50	0.41 \pm 0.50	0.41 \pm 0.49
Solid Waste	0.42 \pm 0.50	0.42 \pm 0.50	0.44 \pm 0.50	0.44 \pm 0.50	0.42 \pm 0.50	0.40 \pm 0.49	0.42 \pm 0.50	0.42 \pm 0.49
Mineral Resources	0.44 \pm 0.51	0.44 \pm 0.51	0.44 \pm 0.51	0.44 \pm 0.51	0.44 \pm 0.51	0.44 \pm 0.51	0.44 \pm 0.51	0.44 \pm 0.50
Polluting Incidents	0.49 \pm 0.50	0.47 \pm 0.50	0.49 \pm 0.50	0.47 \pm 0.50	0.47 \pm 0.50	0.47 \pm 0.50	0.46 \pm 0.50	0.47 \pm 0.50
Environmental Management	0.48 \pm 0.50	0.52 \pm 0.50	0.52 \pm 0.50	0.56 \pm 0.50	0.58 \pm 0.50	0.60 \pm 0.49	0.50 \pm 0.51	0.54 \pm 0.50
Water Consumption	0.50 \pm 0.51	0.53 \pm 0.51	0.73 \pm 0.45	0.68 \pm 0.47	0.50 \pm 0.51	0.60 \pm 0.50	0.63 \pm 0.49	0.59 \pm 0.49
Environmental Investments and Activities	0.94 \pm 0.25	0.94 \pm 0.25	0.94 \pm 0.25	0.88 \pm 0.34	0.88 \pm 0.34	0.88 \pm 0.34	0.94 \pm 0.25	0.91 \pm 0.29

Table 2.5. Means and standard deviations (Mean \pm SD) of reporting rates of environmental indicator categories by mining.

Environmental Indicator Categories	2012	2013	2014	2015	2016	2017	2018	7-Year Average
Transport and Logistics	0.09 \pm 0.29	0.13 \pm 0.34	0.13 \pm 0.34	0.09 \pm 0.29	0.16 \pm 0.37	0.14 \pm 0.36	0.19 \pm 0.40	0.13 \pm 0.34
Material Use	0.27 \pm 0.45	0.25 \pm 0.44	0.15 \pm 0.36	0.13 \pm 0.33	0.13 \pm 0.33	0.10 \pm 0.30	0.10 \pm 0.31	0.16 \pm 0.37
Emissions	0.33 \pm 0.47	0.31 \pm 0.46	0.28 \pm 0.45	0.29 \pm 0.46	0.32 \pm 0.47	0.33 \pm 0.47	0.33 \pm 0.47	0.31 \pm 0.46
Mineral Resources	0.38 \pm 0.50	0.38 \pm 0.50	0.38 \pm 0.50	0.38 \pm 0.50	0.38 \pm 0.50	0.36 \pm 0.50	0.38 \pm 0.50	0.37 \pm 0.48
Solid Waste	0.48 \pm 0.50	0.48 \pm 0.50	0.38 \pm 0.49	0.38 \pm 0.49	0.44 \pm 0.50	0.33 \pm 0.48	0.50 \pm 0.51	0.43 \pm 0.49
Biodiversity	0.44 \pm 0.50	0.50 \pm 0.51	0.47 \pm 0.51	0.53 \pm 0.51	0.47 \pm 0.51	0.43 \pm 0.50	0.41 \pm 0.50	0.46 \pm 0.50
Closure and Rehabilitation	0.45 \pm 0.50	0.50 \pm 0.51	0.55 \pm 0.50	0.53 \pm 0.51	0.65 \pm 0.48	0.40 \pm 0.50	0.43 \pm 0.50	0.50 \pm 0.50
Nuisance	0.42 \pm 0.50	0.50 \pm 0.51	0.50 \pm 0.51	0.46 \pm 0.51	0.67 \pm 0.48	0.48 \pm 0.51	0.58 \pm 0.50	0.51 \pm 0.50
Liquid Effluents	0.54 \pm 0.50	0.54 \pm 0.50	0.48 \pm 0.50	0.50 \pm 0.51	0.54 \pm 0.50	0.48 \pm 0.51	0.52 \pm 0.50	0.51 \pm 0.50
Polluting Incidents	0.50 \pm 0.50	0.51 \pm 0.50	0.51 \pm 0.50	0.50 \pm 0.50	0.58 \pm 0.50	0.49 \pm 0.50	0.60 \pm 0.49	0.53 \pm 0.50
Environmental Management	0.56 \pm 0.50	0.54 \pm 0.50	0.52 \pm 0.50	0.58 \pm 0.50	0.60 \pm 0.49	0.55 \pm 0.50	0.56 \pm 0.50	0.56 \pm 0.50
Environmental Investments and Activities	0.69 \pm 0.48	0.69 \pm 0.48	0.75 \pm 0.45	0.75 \pm 0.45	0.81 \pm 0.40	0.79 \pm 0.43	0.75 \pm 0.45	0.75 \pm 0.44
Water Consumption	0.70 \pm 0.46	0.65 \pm 0.48	0.65 \pm 0.48	0.78 \pm 0.42	0.83 \pm 0.38	0.83 \pm 0.38	0.85 \pm 0.36	0.75 \pm 0.43
Energy	0.79 \pm 0.41	0.78 \pm 0.42	0.79 \pm 0.41	0.79 \pm 0.41	0.75 \pm 0.44	0.71 \pm 0.46	0.75 \pm 0.44	0.76 \pm 0.42

2.4.2.4. Temporal Variabilities in Reporting of Environmental Indicators

The yearly reporting rates in Tables 2.4 and 2.5 show the variation in reporting of environmental issues from year to year. Oil and gas reported on *water consumption*, *closure and rehabilitation*, *environmental management*, and *transport and logistics* with the highest ranges (Figure 2.3). Statistical tests revealed a significant difference in the reporting of all of these categories over the years, except *transport and logistics* (Table B.3). The temporal variability observed in the reporting of *emissions* was also significant ($p < 0.0001$) (Table B.3). For oil and gas' reporting on *energy*, neither ANOVA nor Friedman's test showed significant difference over the years for the lump dataset, but the post hoc test detected differences between some years (Table B.3). Oil and gas' reporting on *water consumption* fluctuated over the years by peaking in 2014 and significantly decreasing in 2016 (Table 2.4), as demonstrated by the significant difference when comparing 2012 and 2014, 2013 and 2014, 2014 and 2016, and 2015 and 2016 (Table B.3). Oil and gas reported on *closure and rehabilitation* with a general decreasing trend after 2013, significantly decreasing in 2017 to its minimum, and remaining the same in 2018, as demonstrated by the statistically significant difference when comparing 2013 and 2017 as well as 2013 and 2018 (Table B.3). The reporting of *environmental management* made its peak in 2017 (Table 2.4) and significantly decreased in 2018 (Table B.3). There was a significant increase in the reporting of *emissions* when comparing the earlier years (2012 and 2013) with more recent years (after 2014) (Table B.3).

For mining companies, the highest ranges occurred in the reporting rates of *closure and rehabilitation*, *nuisance*, and *water consumption* categories. Statistical tests revealed a significant difference in the reporting of all of these categories over the years, except for *nuisance* (Table B.4). The ranges that occurred in the reporting rates of closure and rehabilitation could be due to a lack of relevant data (i.e., no sites reached closure that year). Reporting on *water consumption* had an increasing trend after 2013 and peaked in 2018 (Table 2.5). Mining's reporting on *water consumption* seems to have stabilized after 2015 since no significant difference was observed when comparing the more recent years with each other, but the reporting in recent years significantly differed from earlier years (2012–2014) (Table B.4). The temporal variability in reporting of *polluting incidents* ($p = 0.032$), *material use* ($p = 0.0001$), and *solid waste* ($p = 0.0048$) was also significant. Mining's reporting on *polluting incidents* was almost stable between 2012 and 2015 but fluctuated significantly after 2015 (Tables 2.5 and B.4). Reporting on *material use* decreased after 2013 and stabilized after 2014, and the reporting in more recent years (2014 to 2018) significantly differed from that in earlier years (2012 and 2013) (Table B.4). Mining's reporting on *solid waste* fluctuated over the years, dropping to its minimum in 2017 and peaking in 2018 (Tables 2.5 and B.4).

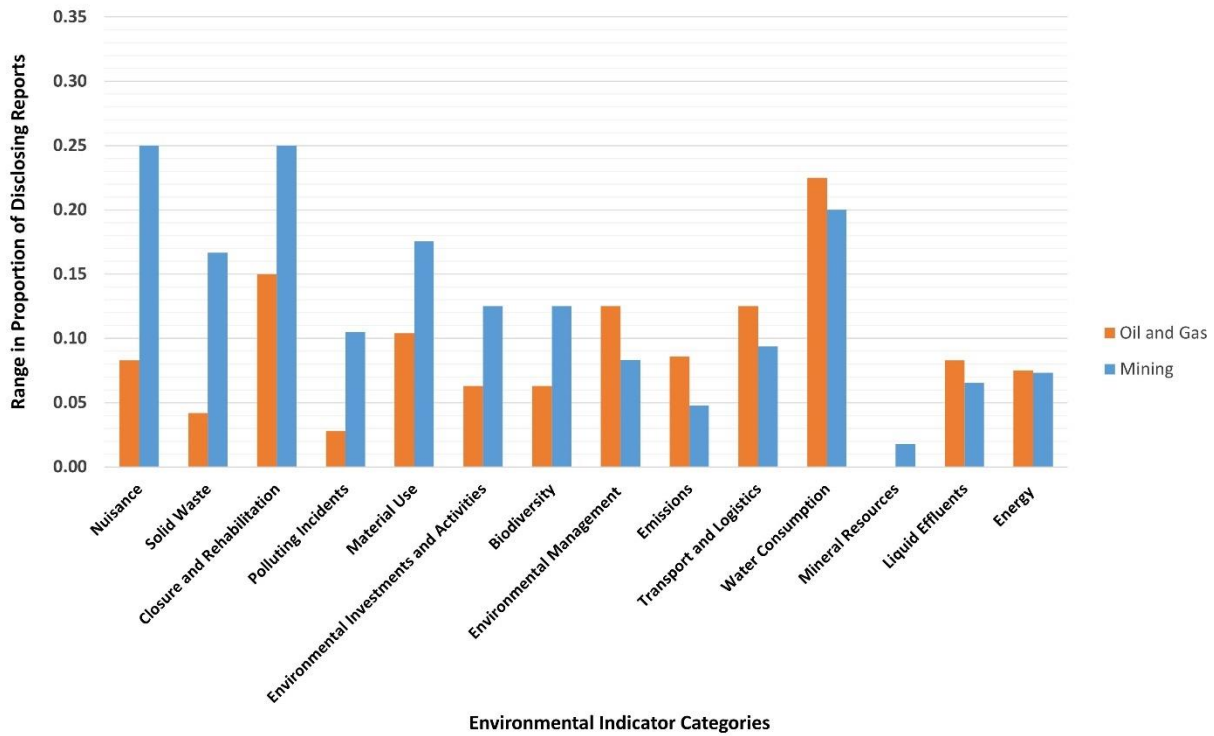


Figure 2.3. Range in reporting rates of environmental indicator categories, representing the extent of change in their appearance in reports over seven years (2012–2018).

2.4.2.5. Differences Emerging in the Reporting of Economic Indicators of the Two Industries

Overall, the coverage of the economic indicator subset was the same for both industries (Table 2.1). However, the economic indicator categories were generally disclosed at a higher rate in mining than in oil and gas (Tables 2.6 and 2.7). There were some overlaps in both industries' most and least reported topics. *Indirect economic impacts* and *products* were the two most frequently disclosed categories, while *customers* and *resource intensity* were reported the least by both industries. Despite these commonalities, the details of reporting revealed significant differences between the two industries.

Table 2.6. Means and standard deviations (Mean ± SD) of reporting rates of economic indicator categories by oil and gas.

Economic Indicator Categories	2012	2013	2014	2015	2016	2017	2018	7-Year Average
Customers	0.25 ± 0.45	0.25 ± 0.45	0.25 ± 0.45	0.25 ± 0.45	0.19 ± 0.40	0.19 ± 0.40	0.31 ± 0.48	0.24 ± 0.43
Resource Intensity	0.28 ± 0.46	0.28 ± 0.46	0.34 ± 0.48	0.28 ± 0.46	0.31 ± 0.47	0.28 ± 0.46	0.28 ± 0.46	0.29 ± 0.46
Employees	0.35 ± 0.48	0.35 ± 0.48	0.35 ± 0.48	0.35 ± 0.48	0.33 ± 0.47	0.38 ± 0.49	0.38 ± 0.49	0.35 ± 0.48
Procurement Practices	0.29 ± 0.46	0.38 ± 0.49	0.42 ± 0.50	0.38 ± 0.49	0.42 ± 0.50	0.50 ± 0.51	0.58 ± 0.50	0.42 ± 0.49
Market Presence	0.46 ± 0.51	0.46 ± 0.51	0.50 ± 0.51	0.42 ± 0.50	0.38 ± 0.49	0.42 ± 0.50	0.42 ± 0.50	0.43 ± 0.50
Technology	0.38 ± 0.50	0.38 ± 0.50	0.50 ± 0.52	0.56 ± 0.51	0.44 ± 0.51	0.56 ± 0.51	0.63 ± 0.50	0.49 ± 0.50
Compliance and Public Sector	0.41 ± 0.50	0.38 ± 0.49	0.50 ± 0.51	0.50 ± 0.51	0.53 ± 0.51	0.56 ± 0.50	0.63 ± 0.49	0.50 ± 0.50
Providers of Capital	0.50 ± 0.51	0.50 ± 0.51	0.50 ± 0.51	0.50 ± 0.51	0.53 ± 0.51	0.56 ± 0.50	0.50 ± 0.51	0.51 ± 0.50
Economic Performance	0.56 ± 0.50	0.53 ± 0.51	0.56 ± 0.50	0.56 ± 0.50	0.56 ± 0.50	0.63 ± 0.49	0.59 ± 0.50	0.57 ± 0.49
Products	0.88 ± 0.35	0.88 ± 0.35	0.88 ± 0.35	0.88 ± 0.35	0.75 ± 0.46	0.75 ± 0.46	0.75 ± 0.46	0.82 ± 0.38
Indirect Economic Impacts	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00

Table 2.7. Means and standard deviations (Mean ± SD) of reporting rates of economic indicator categories by mining.

Economic Indicator Categories	2012	2013	2014	2015	2016	2017	2018	7-Year Average
Customers	0.06 ± 0.25	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.06 ± 0.25	0.00 ± 0.00	0.00 ± 0.00	0.02 ± 0.13
Technology	0.13 ± 0.34	0.06 ± 0.25	0.13 ± 0.34	0.19 ± 0.40	0.06 ± 0.25	0.14 ± 0.36	0.19 ± 0.40	0.13 ± 0.33
Resource Intensity	0.03 ± 0.18	0.06 ± 0.25	0.13 ± 0.34	0.16 ± 0.37	0.16 ± 0.37	0.14 ± 0.36	0.25 ± 0.44	0.13 ± 0.34
Employees	0.28 ± 0.45	0.28 ± 0.45	0.33 ± 0.47	0.30 ± 0.46	0.33 ± 0.47	0.31 ± 0.47	0.30 ± 0.46	0.30 ± 0.46
Providers of Capital	0.47 ± 0.51	0.47 ± 0.51	0.53 ± 0.51	0.53 ± 0.51	0.59 ± 0.50	0.57 ± 0.50	0.53 ± 0.51	0.53 ± 0.50
Economic Performance	0.59 ± 0.50	0.53 ± 0.51	0.53 ± 0.51	0.50 ± 0.51	0.63 ± 0.49	0.61 ± 0.50	0.56 ± 0.50	0.56 ± 0.50
Compliance and Public Sector	0.53 ± 0.51	0.56 ± 0.50	0.63 ± 0.49	0.59 ± 0.50	0.59 ± 0.50	0.64 ± 0.49	0.66 ± 0.48	0.60 ± 0.49
Procurement Practices	0.54 ± 0.51	0.54 ± 0.51	0.63 ± 0.49	0.67 ± 0.48	0.71 ± 0.46	0.67 ± 0.48	0.71 ± 0.46	0.64 ± 0.48
Market Presence	0.58 ± 0.50	0.63 ± 0.49	0.67 ± 0.48	0.71 ± 0.46	0.79 ± 0.41	0.81 ± 0.40	0.67 ± 0.48	0.69 ± 0.46
Products	0.88 ± 0.35	0.88 ± 0.35	1.00 ± 0.00	0.88 ± 0.35	1.00 ± 0.00	0.86 ± 0.38	1.00 ± 0.00	0.93 ± 0.26
Indirect Economic Impacts	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	0.86 ± 0.38	1.00 ± 0.00	0.98 ± 0.13

Both industries reported the most on the same two categories, both of which had only one indicator. The indicator under *indirect economic impacts* is “understanding and describing significant indirect economic impacts, including the extent of impacts”, and it was disclosed as a broad range of contributions by the companies, including the number of jobs supported in the supply or distribution chain, enhanced skills and knowledge in a community or in a geographic location, stimulating foreign direct investment, and other contributions such as wages and tax revenues. Most companies disclosed it both narratively and quantitatively in their reports, under “broader socio-economic contributions” or “local development” titles, and mentioned the distributed economic benefits, as well as training and grants provided to local communities. The *products* category included a “breakdown by product type” indicator, which was disclosed either as the types and diversity of products, or the total amount of individual products sold. Oil and gas companies, in general, quantitatively disclosed this indicator through their production amounts. Some mining companies did the same, but some also provided descriptions and locations of their assets or product groups instead of providing quantitative information.

Customers was among the least reported categories by both industries. This category had two quantitative indicators disclosing the geographic breakdown of markets to which the companies sell, with (i) their national market shares and (ii) contribution to GDP. These indicators assess the significance of market presence and the contribution to the economies (and wealth) of the countries in which the companies have their markets (Azapagic, 2004). Although *customers* were reported the least by both industries, oil and gas had a much higher reporting rate (0.24) than mining (0.02). Similarly, *resource intensity* was another category that was least reported by both industries, but oil and gas had a much higher reporting rate (0.29) than mining (0.13). This category included indicators looking at the amount of produced goods or services per material, land, and energy inputs, as well as another indicator related to transport intensity. Mining companies disclosed “produced goods or services per material input” the most in this category, but in a limited number of reports (0.28), while oil and gas companies disclosed “produced good per energy input” the most (0.57). “Produced goods per land input” was the least disclosed indicator in this category by both industries (0.02 of mining reports and none of oil and gas reports).

Procurement practices included indicators related to the supply chain (i.e., percentage of local suppliers, cost of goods and materials purchased, and “equity”, as in equitable contracting and procurement practices). Both industries reported the most on the “cost of goods, materials, and services purchased”. Mining reported more than oil and gas on “percentage of purchasing from local suppliers to out of region”, which is in line with the findings of the social reporting results, where oil and gas reported less than mining on the percentage of their local suppliers to total suppliers. The indicator that was least reported by both industries in this category was “equitable contracting and procurement practices”.

The most significant difference between the economic reporting of the two industries was in *technology*. This category had two indicators, one specific to innovation and R&D investment and the other specific to wastewater treatment efficiency. Both industries reported on their technology

investments considerably more than their wastewater treatment efficiency. Oil and gas companies reported (a 0.49 reporting rate) and potentially invested more in *technology*, which has the potential for great contributions to sustainable development, while mining companies' reporting on this topic was quite minimal (0.13).

2.4.2.6. Temporal Variabilities in Reporting of Economic Indicators

Oil and gas reported on *procurement practices, compliance and public sector, and technology* with the highest ranges (Figure 2.4). Statistical tests revealed a significant difference in the reporting of all of these categories over the years, except for *technology* (Table B.5).

For mining companies, the highest ranges were observed in the reporting rates of *market presence, resource intensity, and procurement practices* categories. The reporting of *resource intensity* showed a significant variation ($p = 0.020$) (Table B.6). For mining's reporting on *market presence*, neither ANOVA nor Friedman's test showed a significant difference for the lump dataset, but the post hoc test detected differences between some years. For *providers of capital*, the opposite was observed, where the result of Friedman's test showed a difference for the lump dataset, but the post hoc test did not detect any difference between years (Tables B.5 and B.6).

The economic topics that were reported with the highest ranges showed an overall increasing trend in both industries' reports. *Compliance and public sector* and *technology* categories had fluctuating reporting rates over the years but an overall increasing trend in oil and gas reports (Table 2.6). Mining's reporting of *resource intensity* had an overall increasing trend over the years (Table 2.7), with a significant increase from 2012 and 2013 to 2018 (Table B.6). *Market presence* had a steady increase in mining reports from 2012 to 2017 (Table 2.7), although this steady increase was broken in 2018. The reporting of *procurement practices* had a steady increase in both oil and gas and mining reports (Tables 2.6 and 2.7). These results suggest that the focus of both industries on these issues increased over the years.

In general, mining's reporting showed higher temporal variability than oil and gas for most of the economic indicator categories (Figure 2.4). This was confirmed by the results of post hoc pairwise tests (Tables B.5 and B.6). Oil and gas showed no variability at all in reporting indicators related to their *indirect economic impacts* (Figure 2.4).

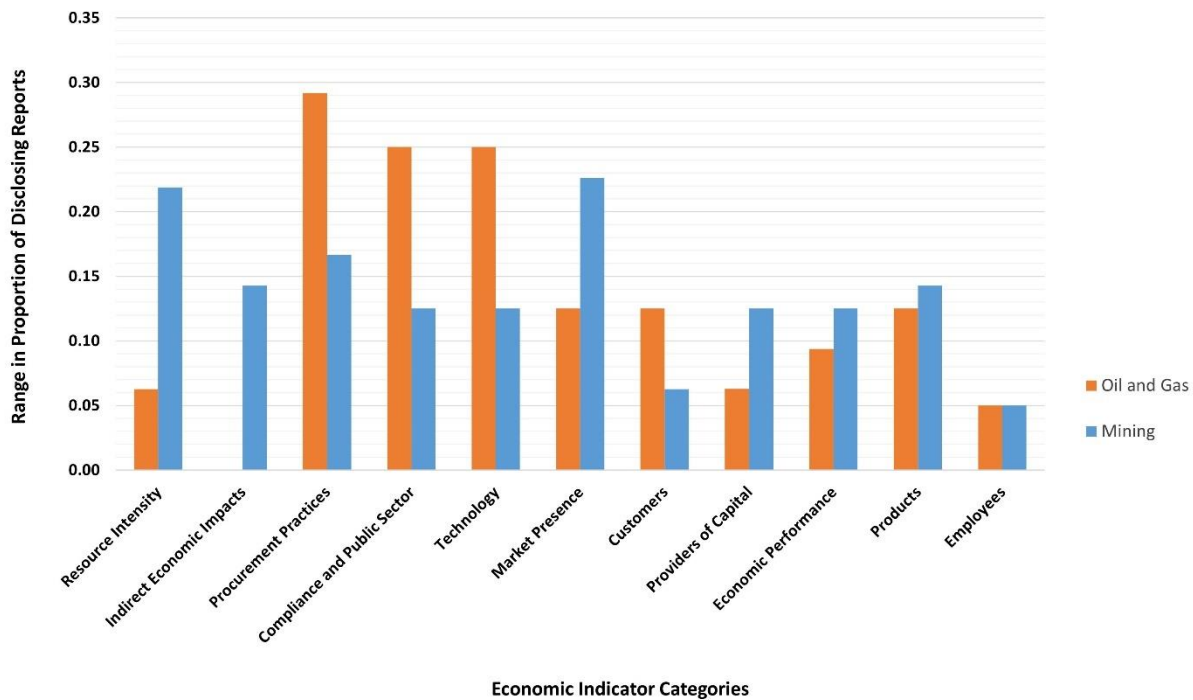


Figure 2.4 Range in reporting rates of economic indicator categories, representing the extent of change in their appearance in reports over seven years (2012–2018).

2.5. Discussion

The analysis of the indicator subsets used in oil and gas and mining companies' sustainability reports revealed that both industries reported a higher proportion of social indicators than the other indicator subsets (Table 2.1), which might be expected given the close association between CSR and sustainability reporting in the industries (Hamann, 2003; Jenkins & Yakovleva, 2006). Notably, mining reported more social and environmental indicators than oil and gas companies. Although we do not know the exact reasons behind this difference, it may be indicative of the larger spatial and temporal scales at which mining developments take place or the varied resources and commodities represented by the mining industry. These factors result in relatively unique designs for each mine, with particular social and environmental constraints. Hence, reporting more of these indicators may be inherent to the nature of mining operations. It is also important to note that both industries primarily report social and environmental data at the corporate rather than site level. For example, one oil and gas company stated that they manage and report on water-related issues at the local level to comply with local environmental regulations and do not include this information in their corporate level sustainability reports. This aggregation may contribute to a lack of transparency in reporting, where site-specific issues are masked. Both industries might consider expanding their reporting on social and environmental indicators to include both corporate and site-level data or providing links to site-level reporting.

Both industries reported on less than half of the economic indicators. This could reflect a general pattern of reporting only baseline economic data in sustainability reports and disclosing more specific economic data in annual or financial reports. For both industries, it might be beneficial to report on more economic indicators in their sustainability reports or to at least provide cross-references to their annual or financial reports. This could align more with triple bottom line reporting and allow companies to gain a better understanding of the interdependence of their social, economic, and environmental performance (Heenetigala & Armstrong, 2019).

Our results prove our two overarching hypotheses. We demonstrated that the reporting practices of extractive industries show temporal variabilities (i.e., inconsistencies) and revealed the statistical significance of these inconsistencies. We also revealed the significant differences between the two industries, specifically in economic reporting. In addition to proving our hypotheses with the discrepancies we identified, we revealed more nuanced findings that we believe are equally as important. We discuss these findings in more detail in the remainder of this section.

2.5.1. The Need for Greater Attention to External Issues

Diving deeper into the topics covered within the indicator subsets, in both industries, internal indicators (related to the companies' internal operating processes, business principles, or employee management) were generally reported on more and showed lower temporal variability than external indicators (related to a companies' relations with communities, customers, suppliers, and other stakeholders). Although both industries covered a relatively higher proportion of indicators in the social pillar (Table 2.1), both industries placed more emphasis on their internal operations by reporting on *social performance management*, *business ethics*, and other internal indicators more than the external indicators (Tables 2.2 and 2.3). The high reporting rate of internal indicators by both industries may reflect the straightforward nature of reporting on corporate policies and management structures rather than more complex issues "outside of the fence".

As previous research suggests, the indicators reported in sustainability reports should address external sustainability issues as well as internal ones to provide information that is more "representative" of the impacts on sustainable development (Azapagic, 2004). This is also critical in terms of designing more sustainable business models and corporate strategies, as it requires the consideration of all stakeholders, including customers, suppliers, and shareholders (Lemus-Aguilar et al., 2019). Furthermore, reporting external indicators can encourage companies to take a systems engineering perspective, wherein their design and planning incorporate both downstream and upstream processes and actors. Therefore, there is still room for improvement in terms of addressing externally focused contributions to sustainable development (N. M. Smith et al., 2020). We recommend that both industries adopt a systems engineering approach while identifying external indicators, and report on these least emphasized external indicators more explicitly.

Social indicators that are directly related to company policies or programs and that can be narratively disclosed were reported more, while reporting of indicators requiring quantitative data or demonstrable proof was limited. Similarly, reporting was limited on actual incidents of violation or the identification of risks regarding external issues, such as child labor, forced labor, and indigenous peoples. In addition, social indicators were reported on less as the required level of detail increased. These results might suggest that there is room for improvement in terms of transparency and accountability. There is a need for continuous monitoring and evaluation and greater attention to such external issues. If extractive industries pay more attention to this, they might also avoid the risk of being critiqued for “greenwashing”. These might point out the need for more detailed and robust data collection in both industries.

2.5.1.1. Supply Chain Traceability

In both industries, *customer health and safety*, *product/materials stewardship*, *suppliers and contractors*, and *child labor* appeared in the five least reported categories. At formal oil and gas and mining operations, child labor is highly unlikely, explaining its low levels of reporting. However, the low reporting on the other indicators suggests that the further down the supply chain from the company to which an indicator refers, or the more “external” the issue is to the company, the less it is reported. This may be due to the difficulties in collecting and monitoring data at the corporate level related to downstream suppliers and contractors, as most extractive companies work with a large number of these providers across their global operations. Nonetheless, this contributes to the critique that both sectors lack supply chain traceability (J. Lee & Bazilian, 2020; Mubarik & Zuraidah, 2019; Upson & Clarke, 2015). Incorporating sustainable development in the design of extractive operations requires a holistic approach based on life cycle thinking and a systems engineering perspective, and sustainability reporting should involve all activities in the supply chain (Azapagic, 2004; Lemus-Aguilar et al., 2019). For this reason, supply chain aspects of the design should be taken into account as a set of design constraints. Researchers in the field of organizational design for sustainable business models also suggest that linkages to external partners such as distributors and outsourcers should be established (Kaplan & Norton, 2001) to enrich the final output of a value chain (Lages, 2016; Lemus-Aguilar et al., 2019). Other researchers have suggested that sustainable value chains are not possible unless issues concerning a company’s relationship with suppliers are addressed (Nidumolu et al., 2009). Furthermore, given the increased global attention to supply chain issues among investors, consumers, and governments, companies are under pressure to have more responsible and sustainable supply chains (Gurzawska, 2020; Lambrechts, 2020; van den Brink et al., 2019). Therefore, we suggest that these lesser reported aspects of the supply chain need to be more represented in sustainability reports.

2.5.2. The Need for Greater Attention to Environmental Issues Involving Third Parties

The environmental indicators that were among the most reported by both industries included *environmental investments and activities*, *water consumption*, *environmental management*, and *polluting*

incidents. This reflects other studies that found that environmental topics were generally well covered in extractive industries' sustainability reporting (Jenkins & Yakovleva, 2006; Orazalin & Mahmood, 2018; Raufflet et al., 2014) and suggests that reporting of such environmental topics is an "older" and "more institutionalized" issue (Raufflet et al., 2014). Furthermore, we found that oil and gas companies reported on their *environmental investments and activities* at a relatively high rate, which might be related to efforts to shift the public perception of the oil and gas industry after incidents such as the 2010 Gulf of Mexico oil spill.

The most reported environmental categories by both industries reflected their direct environmental impacts. Both industries minimally reported on the environmental impacts resulting from their interactions with third parties and on activities conducted at the upper and lower ends of the supply chain, such as *material use* and *transport and logistics* (Tables 2.4 and 2.5). However, *material use* and *transportation* are among the topics that investors look for in companies' sustainability disclosures (ATHEX, 2019; BM&F Bovespa, 2016; Borsa Istanbul, 2020; Botswana Stock Exchange, 2018; Bursa Malaysia, 2018; HNX, 2016; KASE, 2018). This relates to the traceability issue in the supply chain, and similar to social reporting, we suggest an increased focus on these more external issues.

An important difference between the environmental reporting of the two industries was discovered for the *energy* category. In mining reports, the water-energy nexus was well covered, as they were the top two disclosed categories. However, in oil and gas reports, energy was reported much less than *water consumption*. The global demand for water and energy is increasing as a result of the growing population, urbanization, and economic growth, while the resources are becoming scarce. Hence, the water-energy nexus is central to sustainable development, and governmental and non-governmental organizations are keeping track of the consumption of these resources (UN Water, n.d.). Furthermore, energy consumption is frequently listed among the topics that investors would like to see in companies' sustainability disclosures (ATHEX, 2019; Bahrain Bourse, 2020; BM&F Bovespa, 2016; BNV, 2018; Borsa Istanbul, 2020; BSE, 2018; Bursa Malaysia, 2018; DFM, 2019; FSC & ACSI, 2015; HNX, 2016; KASE, 2018; Nasdaq, 2019; Santiago Exchange, 2017; TMX, 2020). Hence, it would serve oil and gas better to report more on energy issues to deliver a more integrated and representative reporting on issues related to sustainable development and investment.

2.5.3. Inconsistency in Reporting Over Time

Both industries demonstrated similar temporal variabilities in their reporting over time, although overall, mining companies showed more inconsistency than oil and gas companies in reporting most of the environmental, social, and economic indicator categories. Hypothesis testing with statistical tests showed that most of the temporal variabilities observed in reporting were statistically significant.

These temporal variabilities reflect companies' divergent approaches to sustainability reporting and introduce a level of subjectivity that obscures a robust assessment of the extractive industries' collective contributions to sustainable development. Although variability in reporting is to a certain extent inevitable,

in the long run, it would be beneficial for companies in the oil and gas and mining industries to learn from each other and attempt to coalesce around similar reporting structures. This will allow professionals in the extractive industries to gauge the progress and challenges of companies and the industry in general in contributing to the Sustainable Development Goals.

In both industries, the reporting of external indicators (e.g., *customer health and safety*, *product/materials stewardship*) showed higher temporal variability than internal indicators. In addition, *water consumption* and *closure and rehabilitation* were among the categories that were reported with the highest variability by both industries over time. However, these are important topics that affect a large number of stakeholders; hence, we suggest more consistent reporting on such issues.

2.5.4. Differences Observed in Economic Reporting

The details of economic reporting revealed significant differences between the two industries. Although customers were reported the least by both industries, oil and gas had a much higher reporting rate (0.24) than mining (0.02) (Tables 2.6 and 2.7). This may make sense given the oil and gas' direct access to their customers, unlike mining. Since mining produces raw materials instead of final products, mining companies usually do not have direct access to their customers. However, it might be more beneficial for mining companies to better address customer-related indicators in their reports since more customers are placing more importance on sustainability reports and companies' contributions to sustainable development.

Similarly, resource intensity was less reported by both industries, but oil and gas had a much higher reporting rate (0.29) than mining (0.13). Topics related to resource intensity may appear less in the reporting of both industries because these topics are generally part of production data and may be more explicitly reported in financial reports. Indicators referring to the amount of produced goods or services per material, land, and energy inputs should be reported more by both industries, considering the importance of resource efficiency for international financial institutions (Rentschler & Flachenecker, 2019). The indicator that was least reported by both industries was "equitable contracting and procurement practices" in the procurement practices category. This indicator can indicate to what extent underrepresented entrepreneurs have access to business opportunities and can also reflect aspects of diversity and inclusion.

The most significant difference between the economic reporting of the two industries was in technology. Oil and gas reported more on technology (0.49), while mining's reporting on this topic was quite minimal (0.13). Roca and Searcy (2012) similarly found in their study that indicators related to technology were reported by oil and gas and not reported at all by mining (Roca & Searcy, 2012). This might suggest that mining companies' investments in technology are limited. In fact, mining's lower investment in innovation and R&D relative to other industries has been emphasized in the literature (Bartos, 2007; Bryant, 2015; Sánchez & Hartlieb, 2020a; Theron & Volk, 2015). According to Ernst & Young, innovation is among the top 10 business risks and opportunities facing mining, and significant

productivity gains can be achieved by fostering innovation (Mitchell, 2019). Although oil and gas companies reported more on technology, their reporting in this category did not appear to be well-established due to its high reporting range and fluctuations over the years (Table 2.6 and Figure 2.4). With the current efforts to transition to a low-carbon economy, companies may benefit from communicating their investments in innovation and R&D more proactively and consistently to attract investors (London Stock Exchange Group, 2017).

2.5.5. Implications for Mining's Contributions to the SDGs

The identified strengths and areas of improvement in mining companies' sustainability reporting practices bring in areas for improvement and strengths for contributing to some of the SDGs. A detailed overview of identified strengths and areas for improvement for contributing to the SDGs at the corporate level are provided in Appendix D, together with the site and operation levels.

SDG 1 (No Poverty)

Mining companies were able to demonstrate their contributions to SDG 1 by reporting well on:

- *employment practices* and *labor/management relations*, by declaring the number of direct and indirect jobs they provide and demonstrating their inclusive employment practices by reporting their workforce breakdown by gender, and
- *indirect economic impacts* and *local procurement of goods and services*, enabling mining companies to track their progress for leveraging local procurement (UNDP, 2016).

Mining companies could have demonstrated their contributions to SDG 1 by reporting more on the economic aspects of *employment*, such as the benefits and pensions provided to employees. If such issues are included more in sustainability reports, it would help mining companies demonstrate the social protection they provide to employees (United Nations, n.d.).

SDG 3 (Good Health and Well-being)

Mining companies could demonstrate their contributions to SDG 3 by reporting more on *occupational health and safety (OHS)*. This might serve mining companies better in demonstrating their commitment to and progress in promoting workplace health (UNDP, 2016).

SDG 5 (Gender Equality)

By reporting well on their workforce breakdown by gender, mining companies were able to track their progress in recruiting more women and demonstrate their commitment to enabling equal access to jobs (UNDP, 2016).

SDG 6 (Clean Water and Sanitation)

Water consumption was one of the most reported topics by mining companies, which allowed them to demonstrate their contributions to SDG 6 by incorporating water reporting and tracking their progress in reducing water consumption and increasing water recycling (UNDP, 2016).

SDG 7 (Affordable and Clean Energy)

Energy was one of the most reported topics by mining companies, showing their contributions to SDG 7 by incorporating energy reporting and tracking their progress on improving energy efficiency, reducing energy demand on site, incorporating renewable energy, and investing in clean energy (UNDP, 2016). On the other hand, their contribution to SDG 7 was minimal with lower reporting rates on *resource intensity*, in particular the energy efficiency of produced goods and services.

SDG 8 (Decent Work and Economic Growth)

Mining companies were able to demonstrate their contributions to SDG 8 by reporting well on:

- *employment practices* and *labor/management relations*, by declaring their commitment to protecting labor rights and creating decent jobs, and
- *indirect economic impacts* and *local procurement of goods and services*, enabling mining companies to track their progress for driving economic growth with local procurement, working with local suppliers, and catalyzing indirect employment.

Mining companies could demonstrate their contributions to SDG 8 by reporting more on *forced labor* and *child labor* (UNDP, 2016).

SDG 9 (Industry, Innovation, and Infrastructure)

Mining companies were able to show their contributions to SDG 9 by reporting well on *indirect economic impacts* and *local procurement of goods and services*. Mining companies could demonstrate their contributions to SDG 9 by reporting more on *technology*, including their R&D investment. This might help mining companies show their commitment to promoting R&D initiatives (UNDP, 2016).

SDG 11 (Sustainable Cities and Communities)

Mining companies could demonstrate their contributions to SDG 11 by reporting more on *solid waste*. Reporting more on solid waste management and disposal might serve mining companies better in demonstrating their commitment to reducing adverse environmental impacts via proper waste management (UNDP, 2016).

SDG 12 (Responsible Consumption and Production)

The supply chain traceability issue detected in mining companies' sustainability reporting practices together with some of the other less reported topics impeded their reported contributions to SDG 12 as follows:

- lower reporting rates for *customers, customer H&S, product stewardship, suppliers and contractors, material use, transport and logistics, emissions, solid waste, and biodiversity* impeded mining companies' demonstration of incorporating life cycle thinking in analyzing mineral and chemical products, extending responsible sourcing to suppliers, and engaging with consumers, and reducing waste generation through recycling and reuse, and
- lower reporting rates for *resource intensity* impeded mining companies' demonstration of their progress in monitoring resource efficiency in produced goods and services.

On the other hand, mining companies' higher reporting on *environmental investments and activities, environmental management, and polluting incidents*, allowed them to track their progress towards minimizing waste and effluents and mitigating polluting incidents (UNDP, 2016)

SDG 13 (Climate Action)

Mining companies could demonstrate their contributions to SDG 13 by reporting more on *emissions*. This might serve mining companies better in demonstrating their commitment to reducing, measuring and reporting emissions, improving capacity for climate change mitigation, and aligning with the intended nationally determined contributions (INDCs) of the countries they operate in (UNDP, 2016).

SDG 14 (Life Below Water)

Mining companies were able to show their contributions to SDG 14 by reporting well on *environmental investments and activities, environmental management, and polluting incidents*, allowing them to track their progress in minimizing waste and effluents, and mitigating polluting incidents. On the other hand, they could demonstrate their contributions to SDG 14 by reporting more on *solid waste*, including hazardous waste. This might help mining companies show their commitment to properly disposing of their waste, including tailings (UNDP, 2016).

SDG 15 (Life on Land)

Mining companies could demonstrate their contributions to SDG 15 by reporting more on *biodiversity*. This might serve mining companies better in demonstrating their commitment to preserving ecosystem services and biodiversity, avoiding impacts on critical habitats, and mitigating biodiversity impacts (UNDP, 2016).

SDG 17 (Partnership for the Goals)

Mining companies could demonstrate their contributions to SDG 17 by reporting more on social indicators requiring quantitative data or demonstrable proof, and by minimizing the statistically significant temporal variability observed in their reporting practices. By building more detailed and robust data collection practices and reporting capacity, and improving shared knowledge, mining companies might better demonstrate their commitment to SDG 17 (UNDP, 2016).

2.6. Conclusions

We analyzed the current use of sustainable development indicators by the two major extractive industries with a data-driven approach and identified the strengths in sustainability reporting practices of the two industries, while also providing insights into areas for improvement. The supply chain traceability issue is a particular area that can improve in reporting, and we may anticipate seeing an uptick in this because of the growing attention being given to more responsible and ethical supply chains. The concept of design for sustainability encompasses the life cycle of projects and products and requires seeking ways to reduce the impacts of operations along and between production and recycling chains (McLellan et al., 2009). Therefore, we propose that the extractive industries focus on resolving the supply chain traceability issue to better incorporate sustainable development considerations into the design and management of their operations. This is also a part of responsible investment efforts, as investors pay increasing attention to companies' disclosures on topics related to their suppliers, supply chain, responsibility to customers, product stewardship, and child labor (ATHEX, 2019; Bahrain Bourse, 2020; BM&F Bovespa, 2016; BNV, 2018; Borsa Istanbul, 2020; Botswana Stock Exchange, 2018; Bursa Malaysia, 2018; DFM, 2019; KASE, 2018; Nasdaq, 2019; SET, 2012). From the investors' perspective, these topics are "material investment risks", and the lack of accurate and meaningful disclosure might make it more challenging for companies to assess their own risks and create value and impede investors' interpretation and incorporation of such information into their decision making (Deloitte, 2016).

Ernst & Young recently cited "social license to operate" as the number one risk for the mining industry for the second year in a row, as social responsibility, stakeholder demands, and scrutiny from end consumers increase (Mitchell, 2019). We see this risk reflected in the less frequent reporting of external indicators in sustainability reporting of the extractive industries. We believe that improving the sustainability reporting of both oil and gas and mining in terms of the representativeness of external sustainable development issues would have a significant impact on addressing some of these risks, as it would allow companies to identify blind spots and areas for improvement. In addition, the United Nations' most recent policy brief provides recommendations to "transform the extractives sector into an engine for sustainable development" by including civil society, vulnerable groups, local communities, and other stakeholders in the design, implementation, and monitoring of extractive operations (The United Nations, 2021). Thus, increasing the focus on reporting external issues would help extractive industries better incorporate sustainable development considerations into the design and management of their operations.

This is also critical for capturing the interactions and synergies between different institutions that play important roles in achieving common Sustainable Development Goals, including industry, communities, governments, academia, and the media, or the “Penta-Helix” (Caraka et al., 2021; Opoku, 2016; Upe et al., 2021). Additionally, reporting practices with reduced temporal uncertainty would aid extractive industries in more successfully monitoring their own performance and contribute to more transparent, ethical supply chains and a lower carbon footprint (Mitchell, 2019).

A recent report produced by the Responsible Mining Initiative (RMI 2020) cautioned about “SDG-washing” (Responsible Mining Foundation, 2020). Accordingly, although mining companies are increasingly aligning their sustainability reporting with the SDGs, their reporting is selective, and they generally omit the negative impacts potentially hindering the achievement of the SDGs. This points to the need for an honest picture of the challenges the mining sector faces in its support of the SDGs (Responsible Mining Foundation, 2020), which is also valid for the oil and gas industry. We believe that sustainability reporting practices with increased temporal stability and representativeness could aid both extractive industries in addressing the critique of “SDG-washing” and may provide a profound method for mapping the contributions of extractive industries’ practices to SDGs. For example, if the external issues that are currently being overlooked, such as indicators related to product stewardship and supply chain, are included more in sustainability reports, it would help the extractive industries demonstrate their contributions to SDG 8 (decent work and economic growth), and SDG 12 (responsible consumption and production), as well as areas where they can improve. Similarly, if the mining industry reports more on technology and innovation, it would serve them better in demonstrating their contributions to SDG 9 (industry, innovation, and infrastructure). Therefore, we suggest that more representativeness of sustainable development issues would be beneficial for the extractive industries.

Although the two industries have been reporting for several years and they cover a large number of indicators in their reports, there are still areas for improvement in terms of the representativeness of the issues and goals related to sustainable development that appear in their reports. This suggests that the number of reported indicators does not really matter in the sustainability reporting of extractive industries; what matters is the reported indicators’ content and their connections to sustainable development. Future research could investigate the real reasons behind the trends and temporal variabilities in companies’ reporting practices through primary data (e.g., interviews with companies). Moreover, research might be conducted on more companies over a longer time to obtain more precise statistical results and to better identify potential correlations of the reporting trends with other parameters. Finally, we advocate for a framework or a decision-making tool that allows for more objective sustainability assessments yet attends to the temporal and spatial variability that occurs across extractive industries’ operations.

CHAPTER 3

A QUANTITATIVE SUSTAINABILITY ASSESSMENT FOR MINE CLOSURE AND REPURPOSING ALTERNATIVES IN COLORADO, USA

An article published in the journal *Resources* ⁷

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3.1. Abstract

Responsible mine closure and repurposing are key to contributing to sustainable development by ensuring successful environmental rehabilitation and reducing socioeconomic risks. However, mine closure has primarily focused on remediation and rehabilitation of mined lands with limited consideration of stakeholder perspectives and the broader social, economic, and cultural impacts of closure. In this paper, we use stakeholder input to evaluate and compare three different repurposing alternatives for the tailings dam area of a mine in the state of Colorado, USA, that is expected to close in the next twenty years. By using multi-attribute utility theory (MAUT), we determine which alternative better reflects stakeholder preferences and results in the most economically, environmentally, and socially sustainable outcome. Our results show that although stakeholder groups have different ideas about what constitutes sustainable development in the context of mine closure and repurposing, it is possible to identify to what extent different scenarios can address these perspectives. We argue that integrating stakeholder views into mine closure design and repurposing can lead to more responsible and sustainable mine closure that is unique to a particular setting and stakeholder needs, and we provide a methodology that mining companies may use to understand stakeholder priorities and preferences. Applying this methodology also highlights opportunities for contributing to the SDGs.

3.2. Introduction

Although mining is a heavy industry that causes environmental degradation and disrupts communities (Hilson, 2002; Muller et al., 2020), it can also lead to positive socio-economic outcomes. When a mine begins operation, it may bring welfare by generating jobs, building skills and infrastructure, and enhancing

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the local economy (i.e., “boom”) (Boerchers et al., 2018; Marimuthu et al., 2021). However, mineral resources are not renewable, and the operational stage comes to an end when the ore has been depleted or when mining is no longer economically or socially feasible. In many cases, the departure of a mining company may have adverse impacts on local economies through employment losses, declines in local cash flow and tax revenues, an inability to maintain infrastructure, and a decline in services (i.e., “bust”) (Boerchers et al., 2018; Monosky & Keeling, 2021). Poorly managed closure may worsen these impacts, and stakeholders increasingly expect mining companies to proactively manage the impacts of closure (Bainton & Holcombe, 2018).

Mine closure must be planned so that the value of the impacted area is equal to or better than its original value, and the welfare created by the company is sustained and improved. To better manage the boom-and-bust cycle and obtain a broader acceptance of closure outcomes, a more comprehensive and stakeholder-inclusive approach to closure planning is needed (Erzurumlu & Erzurumlu, 2015; IIED & WBCSD, 2002b). Reconceptualizing mine closure is vital for enhancing mining’s contribution to sustainable development by ensuring successful rehabilitation of disturbed land, mitigating negative socio-economic impacts brought by the company’s departure, and building capacity in local communities (Holcombe & Keenan, 2020; ICMM, 2019; Keenan & Holcombe, 2021; Stacey et al., 2010).

Although the name connotes “end-of-mine”, closure planning should start from the earliest stages of mine planning and should be guided by sustainable development principles (Yaylacı & Düzgün, 2017). Defining a closure vision early, integrating it into planning, and regularly updating the plan may result in more closure options and the ability to evaluate the feasibility of alternatives. Moreover, community participation and input in closure planning may lead to better post-closure outcomes for communities, the company, and other stakeholders (Finucane, 2008; Hattingh et al., 2019; ICMM, 2019). Historically, however, this has not always been the case, and delaying closure planning to later in the project cycle and even to ‘when the mine is about to close’ has been a common practice (Lamb & Coakes, 2012; McCullough, 2016) with relatively little input from communities and other stakeholders (Bainton & Holcombe, 2018; McAllister et al., 2014). This has limited repurposing options and stood as a barrier to environmental, social, and economic sustainability after the life of the mine (Finucane, 2008; IIED & WBCSD, 2002b).

In this paper, we use stakeholder input to investigate the potential contributions that post-closure scenarios could make to sustainable development. We do this by evaluating and comparing three different repurposing alternatives for the tailings dam area of a mine in the state of Colorado, USA that is expected to close in the next twenty years. We evaluate these alternatives with a decision support tool that considers stakeholder perspectives and priorities. This tool is derived from a quantitative, multi-attribute decision analysis (MADA) approach, namely, multi-attribute utility theory (MAUT), and we populated the MAUT by creating an indicator-based sustainability survey to solicit the preferences and priorities of different stakeholders in terms of environmental, social, and economic aspects of repurposing. Our results show that stakeholder groups have different ideas about what constitutes

sustainable development in the context of mine closure and repurposing and that even within the same stakeholder group, there are divergent perspectives. Although this variation is a major challenge, we argue that integrating stakeholder views into mine closure design and repurposing can lead to more responsible and sustainable mine closure that is unique to the particular settings and needs of various stakeholders, and we provide a methodology that mining companies may consider using to understand stakeholder priorities and preferences.

3.2.1. Case Study Background

The Henderson Mine is a large underground molybdenum mine located in Clear Creek County, Colorado, USA (Figure 3.1). The orebody was discovered in 1964 and shaft sinking began in 1968. The mine has been in operation since 1976 and is expected to close in the next 20 years. It is the largest primary producer of molybdenum in the world with a yearly production capacity of 8.2 million kilograms. The mine delivers ore via a 15.3-kilometer-long conveyor tunnel and a 7.9-kilometer-long overland conveyor to the mill, where processing takes place. The mill is in Grand County, Colorado, along the Williams Fork River between approximately 2,682 and 2,805 meters above sea level. The Henderson operation currently provides more than 350 jobs and contributed approximately \$22.5 million in 2017 and \$18.3 million in 2018 to the local tax base. This is expected to decrease to \$3 - \$8 million per year over the next seven years, which will be a significant change and could be potentially devastating for local communities. The Henderson Mine was grandfathered into current reclamation rules and regulations that stipulate the preparation of detailed reclamation plans that establish post-mining land uses (Colorado Division of Reclamation, n.d.-b, n.d.-a), and mine closure guidelines that specify that closure planning should start from the earliest phases of exploration and feasibility (ANZMEC & MCA, 2000; Government of Western Australia, 2015; ICMM, 2019; IIED & WBCSD, 2002a, 2002b), hence has only recently begun to consider repurposing alternatives. There are other mines in the US that are in a similar situation, so this paper attempts to provide an example of how to better manage the process.

The mining company has been establishing challenges for students at the Colorado School of Mines to solicit ideas for repurposing the site. The first Henderson Sustainable Development and Entrepreneurial Challenge was launched in 2018, and student teams were tasked with developing a concept for repurposing the mine's surface facilities and land holdings. The second and most recent challenge took place in 2019. Student teams were asked to develop a concept for sustainable repurposing of the mill site, which is where the mineral processing occurs, and the tailings are deposited. Approximately 567 hectares are covered by tailings at the mill site. Several student teams competed, and a panel of judges chose three winners based on the potential impact of the concept, its creativity, and the groups' presentations. These three scenarios, in the actual order of awarded place in the challenge, were glass manufacturing of tailings ("*tailings*"), organic shrimp farming ("*shrimp*"), and CBD and hemp production ("*hemp*"). In this paper, we focus on these three winning projects and examine to what extent they contribute to sustainable development according to stakeholder priorities and preferences.

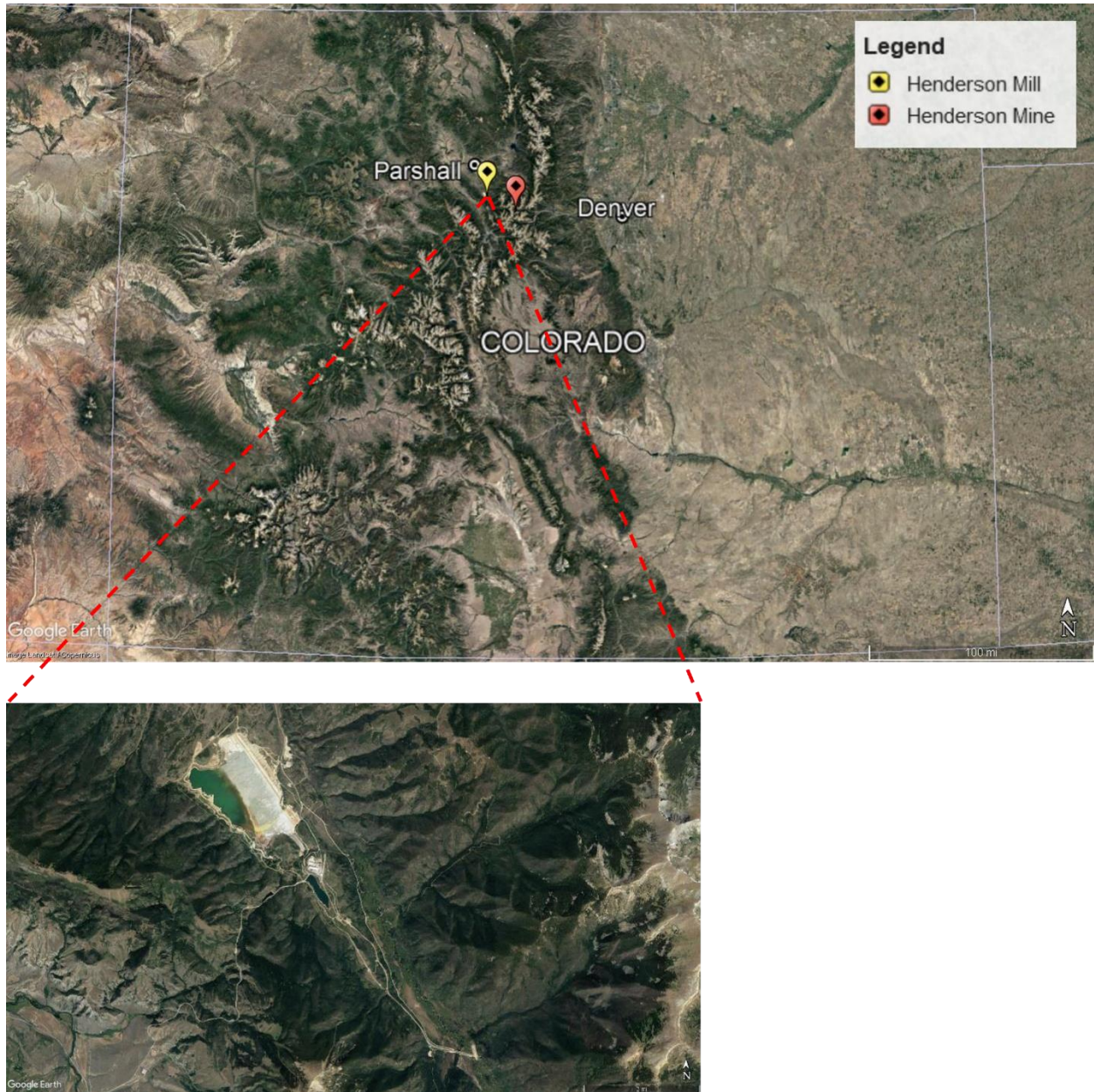


Figure 3.1. The locations of the Henderson Mill and Mine. The total land footprint of the mine and mill is 5,180 hectares. (Source: Google Earth)

3.3. Mine Closure Planning and Sustainable Development

The mining industry has the potential to significantly contribute to sustainable development and has been making efforts to engage in more responsible practices (Marimuthu et al., 2021; Perdeli Demirkan et al., 2021). Mine closure is rated among mining's top operating risks (Vivoda et al., 2019), and its importance has been increasingly acknowledged in best-practice guidelines and more stringent mine closure regulations that have been put in place since the 1990s (Monosky & Keeling, 2021). Mine closure

can cause negative impacts, including losses of employment, tax revenues, infrastructure, and services, as well as a decrease in the demand for local goods and services (Everingham et al., 2020; Monosky & Keeling, 2021). The development opportunities that mines can offer to the local community during operation must continue after closure (Limpitlaw, 2004). If managed properly, the transition at mine closure may offer significant opportunities that can be aligned with the Sustainable Development Goals (SDGs), such as repurposing the land and infrastructure for innovative uses that support the transition to a low-carbon future and creating alternative economies for local communities (Everingham et al., 2020; Vivoda et al., 2019).

To achieve these goals, an early definition of the closure vision (i.e., “closure planning”) is crucial (Asr et al., 2019; Monosky & Keeling, 2021; Morteza & Mahdi, 2014). According to the recent guide by the International Council for Mining and Metals (ICMM) on integrated mine closure, a closure vision should be informed by the mine’s area of influence, the socioeconomic and environmental context, stakeholder input, country-specific requirements, and the SDGs (ICMM, 2019). The primary objective of closure planning should be to ensure the successful decommissioning and reclamation of a site (Asr et al., 2019; Australian Government, 2016; Kabir et al., 2015) and maximize sustainable development in the area (ANZMEC & MCA, 2000; Australian Government, 2016; Finucane, 2008; ICMM, 2019; IIED & WBCSD, 2002b; Kabir et al., 2015; Limpitlaw, 2004; Monosky & Keeling, 2021).

Closure planning should start from the earliest phases of exploration and feasibility (ANZMEC & MCA, 2000; Asr et al., 2019; Everingham et al., 2020; Finucane, 2008; Government of Western Australia, 2015; ICMM, 2019; IIED & WBCSD, 2002a, 2002b; Stacey et al., 2010; The Mining Association of Canada, 2008), and can help minimize the negative impacts and financial burden of closure and maximize the post-mining benefits (ANZMEC & MCA, 2000; Stacey et al., 2010). If closure planning starts too late in the mine life cycle, the closure may fail in terms of ensuring environmental and socioeconomic sustainability (Finucane, 2008; IIED & WBCSD, 2002b).

Legislative requirements define the process of closure and the release of responsibilities and ownership rights after closure. Countries vary considerably in terms of these requirements. Some countries have well-established and detailed mine closure regulations while others have limited or no valid legislation (ICMM, 2019; IIED & WBCSD, 2002b)[33]. In general, mine closure regulations mainly focus on the environmental and physical aspects of mine closure, specifically reclamation and rehabilitation, and pay limited attention to the social aspects (Clark & Clark, 2005; Monosky & Keeling, 2021; Vivoda et al., 2019). Only a few countries and individual provinces or states have enacted and executed actual mine closure laws or regulations (e.g., the United Kingdom, Chile, Peru, Manitoba, and Ontario–Canada, and the state of Nevada, United States), and most countries cover mine closure requirements either within the mining law or within broader environmental legislation that is applicable to mining (Clark & Clark, 2005; IIED & WBCSD, 2002a; Vivoda et al., 2019). The modern approach to closure is to adhere to the legislative requirements as a minimum and exceed these whenever possible (ANZMEC & MCA, 2000).

In recent years, international best-practice guidelines have encouraged mining companies to commit to principles of sustainable development in planning closure (Asr et al., 2019). Industry bodies and international development organizations have established guidelines and standards around mine closure. Some key themes in these guidelines and standards include integrated closure planning that considers the environmental, financial, physical, and socio-economic contexts of a particular site, incorporates stakeholder perspectives including community objectives and aspects of social well-being, and includes best practice-based environmental management and protection, and uses for land and infrastructure (Bainton & Holcombe, 2018; ICMM, 2019; IIED & WBCSD, 2002b).

Several studies have emphasized the importance and positive consequences of incorporating stakeholders in decision-making for post-mining lands (Akbar et al., 2020; Doley & Audet, 2013; Lechner et al., 2017; Worrall et al., 2009). These include reaching a broader consensus about future land use options, identifying priorities and decision-making factors for land use (Akbar et al., 2020), and greater community acceptance and reduced conflict regarding the outcomes (Lechner et al., 2017). However, stakeholder input being only solicited as part of the official public comment period after developing a closure plan is not uncommon (IIED & WBCSD, 2002b). There is a need for more stakeholder involvement in closure planning (IIED & WBCSD, 2002b), but the variation in stakeholder groups' post-mining interests, values, and expectations is a major challenge (Akbar et al., 2020; Antwi et al., 2017; Bainton & Holcombe, 2018; Eshun et al., 2018; Mert, 2019; Nell, 2015; Owen & Kemp, 2013; Pimentel et al., 2016; Rixen & Blangy, 2016; Stacey et al., 2010). "Sustainability" has different meanings to different people and must be defined according to the needs and values of the affected stakeholders (Morrison-Saunders et al., 2014; Yaylaci, 2015). Similarly, stakeholder theory recognizes that value is created when the interests of different stakeholders are considered and addressed (Nell, 2015; Parmar et al., 2010). This may be accomplished through effective stakeholder engagement for a realistic and transparent sustainability assessment and decision-making process (Everingham et al., 2020; Yaylaci & Düzgün, 2017). Fortunately, the importance of stakeholder involvement in mining project lifecycle management has been increasingly recognized in the last two decades (Falck & Spangenberg, 2014; IAEA, 2006). In addition, the environmental, social, and governance (ESG) goals are commonly included in resource assessment and analysis tools, leading to investors' increased commitment to projects that meet these goals (*Home - Sustainability*, n.d.; PRI, n.d.). These developments might help make societal aspects more mainstream in mine closure planning.

Post-mining planning has often been limited to landscape restoration (Antwi et al., 2017), but repurposing entails finding a new use for the site that utilizes the existing mine site elements and infrastructure to deliver a productive economic activity or other beneficial land use after closure (Holcombe & Keenan, 2020; ICMM, 2019). Historically, repurposing of closed mine sites has been rare, but there is increasing pressure for the mining industry to go beyond rehabilitation, and repurposing mines is now starting to become more common (Holcombe & Keenan, 2020; ICMM, 2019). Some novel and successful repurposing projects have included tourism attractions, educational and sports facilities,

and industrial uses (Akbar et al., 2020). Though not possible for all sites, the ICMM suggests identifying and assessing repurposing options by using a Multi-Criteria Decision Making (MCDM) approach, which is incorporated into the mine closure plan after engaging with stakeholders (ICMM, 2019). Such an approach is more likely to enable positive post-mining land-use transitions (Holcombe & Keenan, 2020; Morteza & Mahdi, 2014).

3.3.1. Previous Studies and Gaps

Previous studies on mine closure and post-mining land use have primarily focused on remediation and rehabilitation of mined lands with limited consideration of stakeholder perspectives and the broader social, economic, and cultural impacts of closure (Asr et al., 2019; Bascetin, 2007; Bielecka & Król-Korcak, 2010; Cao, 2007; Cooke & Johnson, 2002; Kuter, 2013; Lei et al., 2016; McHaina, 2001; Mukhopadhyay et al., 2014; Neri & Sánchez, 2010; Pavloudakis et al., 2009; Sklenicka et al., 2004; C. M. S. Smith et al., 2016; Srivastava et al., 2014; Unger et al., 2015; Vickers et al., 2012; Wang et al., 2011; X. Q. Wu et al., 2011). Research on sustainable development and mine closure has focused on risks (Amirshenava & Osanloo, 2018; Krzemień et al., 2016; Laurence, 2006, 2011) and costs (Hutchison & Dettore, 2011; Paricheh & Osanloo, 2017) associated with mine closure, as well as policies related to closure (Cao, 2017; Srikanth & Nathan, 2017). A couple of studies have focused on community wellbeing in the context of mine closure. For example, Odell et al. (2011) developed a framework of socio-environmental indicators by interviewing nearby communities to assess and improve social wellbeing and sustainability through mine closure (Odell et al., 2011). In another study, post-mining scenarios were presented to communities three years before the anticipated closure of a gold mine, and through this exercise, it was determined that closure would impact family life, food security, and health (Rixen & Blangy, 2016).

Several studies have used MCDM techniques to evaluate different options in mining, including alternatives for current and future mining developments (Mihai et al., 2015; Yaylacı & Düzgün, 2017), community investments (Esteves, 2008), locations for mine waste storage (Straka et al., 2014), mining methods (Gelvez & Aldana, 2014; Gupta & Kumar, 2012), and mining equipment (Bascetin, 2013; Bascetin et al., 2006; Kursunoglu & Onder, 2015). Only a few studies have focused on identifying and ranking post-mining land uses. Amirshenava and Osanloo (2018) assessed mine closure risks by following an MCDM approach for an iron ore mine in Iran and ranked the post-mining land use alternatives based on the opinions of an expert team and not stakeholders (Amirshenava & Osanloo, 2018). Bangian et al. (2012) used fuzzy multi-attribute decision making (MADM) to estimate the closure and reclamation costs of 17 post-mining land use alternatives for the pit area of a copper mine in Iran but did not incorporate real stakeholders in the decision-making process (Bangian et al., 2012). Soltanmohammadi et al. (2008, 2009, 2010) used three different MADM techniques in separate studies to rank potential post-mining land uses of a hypothetical mined land to demonstrate to what extent the MADM method influenced the selection of optimal land use (Soltanmohammadi et al., 2008, 2009, 2010).

Eshun et al. (2018) used a MADM technique to determine the optimum mine closure alternative for a mine in Ghana based on the opinions of five experts and with respect to 40 criteria attributes (Eshun et al., 2018). Masoumi et al. (2014) focused on selecting the optimal post-mining land use alternative using fuzzy MADM for a surface coal mine using 28 attributes based on three experts' judgments (Masoumi et al., 2014).

Most existing mine closure plans do not align with the closure guidelines by ICMM, The Mining Association of Canada (MAC), and others that encourage early engagement with stakeholders (Monosky & Keeling, 2021). Managing the socio-economic impacts of mine closure is a noted gap in research, policy, and practice (Antwi et al., 2017; Finucane, 2008; Hattingh et al., 2019; IIED & WBCSD, 2002b; Kabir et al., 2015; Limpitlaw, 2004), which hinders sustainable post-mining land use opportunities (Holcombe & Keenan, 2020). Mine closure and post-closure land use involve more than decommissioning and rehabilitation (Bainton & Holcombe, 2018; Monosky & Keeling, 2021). Long-term development is possible with an integrated mine closure approach and innovative repurposing solutions. However, participatory scenario analyses or case studies that support decision-making for repurposing have been insufficiently explored. Mert (2019) examined the benefits of repurposing a former sand quarry in Turkey as a solar power plant and interviewed engineers, residents, and local government officials to understand their satisfaction with the power plant. They found that all stakeholders were satisfied with the transformation (Mert, 2019). However, this study examined stakeholder perspectives after the repurposing took place, interviewed few stakeholder groups, and did not provide or compare any repurposing alternatives.

Our analysis addresses a gap in the literature regarding participatory scenario analyses that support a priori decision-making for repurposing. We focus on the ways in which different repurposing alternatives may contribute to sustainable development by using multi-attribute utility theory (MAUT) to determine which repurposing scenario would better reflect stakeholder preferences and result in the most economically, environmentally, and socially sustainable outcome. We also demonstrate the robustness of our sustainability assessment method through sensitivity and scenario analyses.

3.4. Methodology

Our methodology consisted of five major steps which we outline in the sections below (Figure 3.2). We first identified the relevant indicators to be used for the sustainability assessment of the three different repurposing scenarios. We then collected data through two channels, one being the data related to the identified indicators through the student projects and the current mine, and the other being a survey methodology to examine the preferences of diverse stakeholders and obtain the weights assigned to different aspects of sustainability. In the first data collection step, we refined the identified indicators if there was not enough data, and once we had the required data, we moved on to the survey with our final set of indicators. We integrated the collected data into our sustainability assessment by following Multi-Attribute Decision Analysis (MADA). Here, we employed the multi-attribute utility approach, which allows

for a comparison between diverse attributes. The attributes in this study were the environmental, social, and economic indicators. We then obtained the ranking of alternatives for the combined decision of all stakeholders, as well as for different stakeholder groups, and evaluated the outcomes. Finally, we performed sensitivity and scenario analysis.

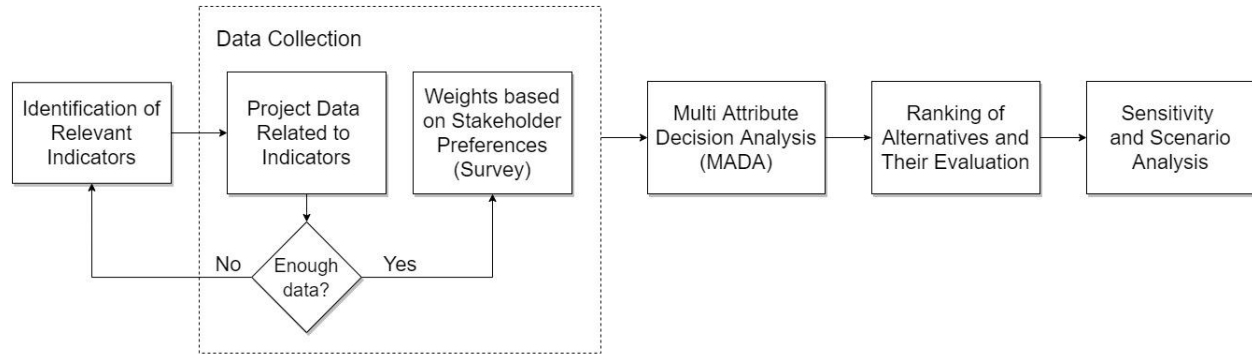


Figure 3.2. Research methodology flowchart

3.4.1. Identification of Relevant Indicators

To determine the indicators used in this study, we drew from a comprehensive indicator set that was established as part of a larger study on sustainability assessment frameworks as decision support tools for the mining sector (Yaylaci, 2015). From this set, we identified an initial set of 31 indicators (9 social, 14 environmental, and 8 economic) that were most suitable for the repurposing phase of the mining life cycle and this case study. We categorized the indicators according to the three dimensions of sustainability (environmental, economic, and social), as recommended in the literature for sustainability assessment (Iacovidou & Voulvoulis, 2018; Kumar et al., 2015; Lindfors, 2021; Matthews et al., 2019; Nicoletti Junior et al., 2018). Because of the availability and quality of data, it was necessary to eliminate some of the indicators and add some new indicators that were relevant for this case. The elimination of some indicators was also required to decrease the cognitive load of the survey participants and to optimize the time they spent on completing the survey. This was a necessary step to ensure that our indicator set reduces complexity, is easily understandable, and resonates with the survey participants (Falck & Spangenberg, 2014). After refining the indicator set, the final set included 17 indicators (attributes) in total, broken down into five economic, five social, and seven environmental indicators (Table 3.1). The verbiage of indicators was modified to simplify the survey. The indicators were coded in the order of their appearance in the survey questions.

Table 3.1. Indicator set used in this study

Code	Indicator	The verbiage used in the survey
ECONOMIC INDICATORS		
Ec1	Corporate income taxes and royalties paid at full capacity	The new facility's income tax payments
Ec2	Extent of community and infrastructure investments	New facility's investments in public services for the community (<i>e.g., road maintenance, housing assistance</i>)
Ec3	Number of years it will take to reach the full capacity from the day the production begins	The time it will take for the new facility to reach its maximum production amount
Ec4	Annual production capacity at full capacity	The maximum number of products that the new facility can produce
Ec5	Annual revenue at full capacity	The amount of money the new facility makes from the sales of their goods and services
SOCIAL INDICATORS		
S1	Potential nuisance and more significant risks that may affect local communities.	Nuisances (<i>e.g., odor</i>) or hazards (<i>e.g., fire</i>) that may arise from the new facility and could impact the nearby communities
S2	Road use and traffic load compared to the baseline	The potential traffic volume around the project site
S3	Average annual salary of full-time workers	Annual salary offered for employees by the new facility
S4	Number of full-time and hourly-based employees at full capacity	Number of employees that can work in the new facility
S5	Number of different job types offered on site	Number of different job types offered by the new facility
ENVIRONMENTAL INDICATORS		
En1	Expense of anticipated energy consumption	The new facility's energy use
En2	Proportion of heating energy that the new facility can potentially supply by renewables on-site	The amount of energy that the new facility gets from renewable energy resources such as solar roof panels
En3	Potential percentage of recycled input materials	The amount of recycled materials used by the new facility to produce their products
En4	Total amount of untreated tailings in 15 years	The amount of unremoved mine waste remaining in the new project area after 15 years
En5	Waste production potential	The amount of waste to be produced by the new facility
En6	Estimated total air emissions	Air Pollution (<i>The amount of gases released to the air by the new facility</i>)
En7	Area used for production	Total land area used by the new facility

We understand and acknowledge the links between some of the indicators. For example, while *investments in public services (Ec2)* falls under economic aspects in our categorization, it is also a key component of social aspects of sustainable development. We grouped the indicators into categories based on how they are commonly classified in the literature.

3.4.2. Data Collection

We performed data collection in two parts: i) collection of data about the current mine and proposed student projects, and ii) examination of stakeholder preferences to obtain weights to be used in Multi-Attribute Decision Analysis (MADA). In the first part, data related to the current mine operation, its footprint, and its impacts on the community and the environment were collected through publicly available data (e.g., company reports, company website, and government documents). These data allowed us to understand and define the “baseline” in the tailings dam area before considering the post-closure period. Then, we collected data related to the proposed repurposing scenarios from the student reports. Almost all the indicators in our final set could be informed by the data in the student reports. Only one indicator, *emissions (En6)*, was estimated based on similar industries’ public data.

Following the “contribution to sustainability” model (Morrison-Saunders et al., 2014; Yaylaci, 2015), and stakeholder theory (Nell, 2015; Parmar et al., 2010), which recognize the different needs and values of affected stakeholders, we also considered what aspects of “sustainability” were the most important to various stakeholders. The second part of the data collection examined the preferences of stakeholder groups with the goal of integrating them into the sustainability assessment of repurposing alternatives. To do this, we first identified the stakeholders that were relevant and interested in the repurposing of the tailings dam area through a brainstorming activity based on our knowledge of the region. We then mapped the identified stakeholder groups based on their power over and interest in the repurposing projects, and we prioritized them for involvement in the decision-making process. After obtaining our final stakeholder list, we utilized an online survey method where the stakeholders were asked to perform pairwise comparisons among all sub-goals (level 2), criteria (level 3), and attributes (level 4) by using the Saaty Scale (Saaty, 1977). This examination of stakeholder preferences was necessary to obtain the weights to be used in the multi-attribute utility function. We continued our survey to the point where we achieved relatively equal representation from all the stakeholder groups. In the end, we collected responses from 41 individuals from seven different stakeholder groups (Figure 3.3). We used the term, “government agencies” to refer to state and federal agency representatives and “local governments” to refer to mayors, city councils, and county commissioners. Industry advisors included industry professionals who provided guidance to the students during the challenge. Similarly, a group of faculty members served as mentors to the student groups during the challenge.



Figure 3.3. Number of respondents by stakeholder group

The survey included 27 questions, divided into i) four questions related to demographic information; ii) five questions about financial contributions and economic performance; iii) five questions about community impacts and employment; iv) ten questions about waste, emissions, resource consumption, and land use; and v) three questions about general aspects of sustainability (see Appendix C for the complete survey).

3.4.3. Multi-Attribute Decision Analysis (MADA)

We performed the sustainability assessment for the three repurposing scenarios by using MADA, which is a subdiscipline of Multi-Criteria Decision Making (MCDM) for making preference decisions, such as prioritization, evaluation, and selection over different alternatives (Karunathilake et al., 2020). We achieved MADA based on the multi-attribute utility theory (MAUT), which is a technique in the broader field of MCDM (Shanmuganathan et al., 2018). MAUT is an analytical approach for making logical decisions and for converging toward a preferred solution where there are multiple objectives or attributes (Erzurumlu & Erzurumlu, 2015; Merkhofer & Anderson, 1997). It is frequently used in decision-making processes involving sustainability issues since these issues are more complex and require more than a cost/profit assessment (Bangian et al., 2012; Eshun et al., 2018; W. J. Hahn et al., 2012; Iacovidou & Voulvoulis, 2018; Lechner et al., 2017; Lindfors, 2021; Morteza & Mahdi, 2014; Narrei & Osanloo, 2011; Padur & Purre, 2021). Furthermore, optimizing project selection through balancing economic,

environmental, and social goals creates an opportunity for developing decision-support tools for mining companies, and MAUT is a well-suited technique to support the prioritization of conflicting goals (Pimentel et al., 2016).

MAUT has three basic steps:

1. Construction of a goals hierarchy to define the attributes by which the decision objectives will be measured
2. Formulation of single-measure utility functions for each attribute to normalize the measurement or scale of all attributes across all alternatives, and
3. Weighting of the preferences between attributes (W. J. Hahn et al., 2012).

As the first step in decision analysis, we constructed a goals hierarchy (Figure 3.4) comprised of four levels. From the bottom to the top, the levels represent the following:

- Level 4 consists of the attributes, in other words, the sustainability indicators selected for this assessment (refer to Table 3.1 to see which indicators the codes stand for)
- Level 3 represents criteria that classify the attributes based on broader issue areas
- Level 2 includes the economic, social, and environmental sub-goals that form the overall goal
- Level 1 is the overall goal of “sustainable repurposing” of the tailings dam area.

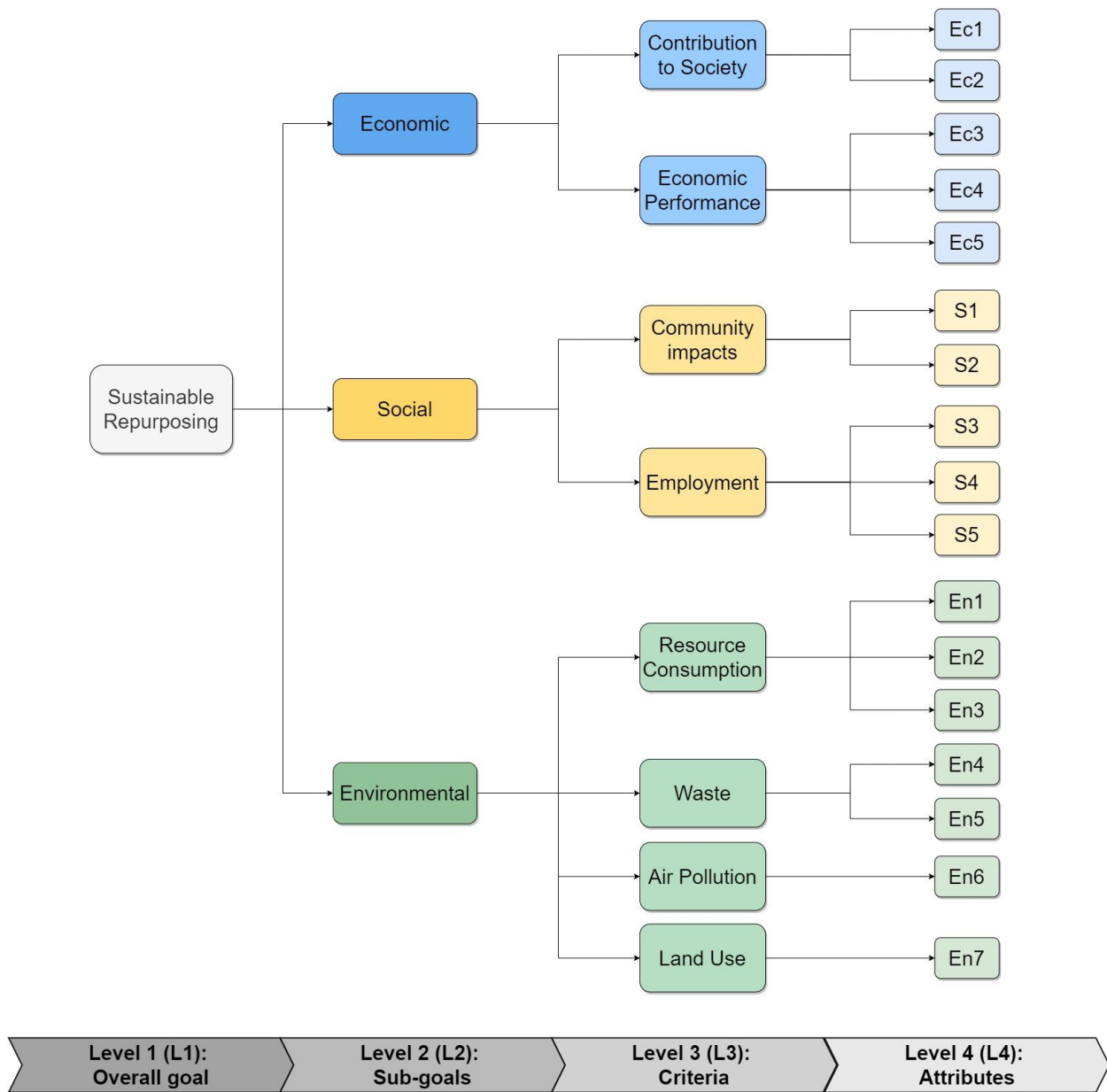


Figure 3.4. The goals hierarchy constructed for MADA

In the second step of MADA, we formulated single-measure utility functions for 17 different attributes ($U_1(a_1)$, $U_2(a_2)$, ..., $U_{17}(a_{17})$) for 17 different attributes from a_1 to a_{17}) to mathematically transform monetary or other values into utility values on a standardized scale, in this case, from 0 to 1. The Logical Decisions Software (v 8.0) was used to formulate the utility functions (G. Smith, 1991). Although single-measure utility functions can be in any shape (i.e., linear and non-linear), utility functions of all attributes were assumed to be linear in this study for practical reasons and because it is widely stated in the literature that attribute weights (Pöyhönen & Hamalainen, 2001) and ranking of alternatives (Chelst & Canbolat, 2011; Mateo, 2012) do not really depend on the shape of the value function. In addition, in

most sustainability evaluation studies (Gomez-Limon et al., 2003; Karatas & El-rayes, 2014), experimental studies, and in practical applications, the utility functions are often assumed to be linear (Pöyhönen & Hamalainen, 2001; Zietsman et al., 2006). Lastly, the construction of non-linear utility functions is time-consuming and complex as it requires long interviews with decision makers with comprehensive knowledge of the problem area (Keeney, 1977), which was unfeasible for our study, especially with the prevalence of the COVID-19 pandemic at the time of the study.

In the last step of MADA, we used the Analytical Hierarchy Process (AHP) method to calculate the relative importance weight of each subgoal, criteria, and attribute. We selected AHP as it is a well-established, reliable, and popular technique for decision-making (Brunelli, 2018; Forman & Peniwati, 1998; Karatas & El-rayes, 2014; Yaylacı & Düzgün, 2017), especially for handling multiple decision makers (Rao, 2007). It is also considered to be easier for stakeholders to perform when compared to other weighting methods (Lindfors, 2021). Following the AHP approach, we used the stakeholder responses in the online survey, checked for consistency, and calculated the weights assigned to each subgoal, criteria, and attribute by each respondent. As AHP examines the relative importance of parameters, the parameter with the higher weight is deemed to be given higher importance than the other parameters in the same comparison set (Yaylacı & Düzgün, 2017).

We aggregated preferences at the stakeholder group level as well as the combined group level (i.e., the combined decision of all 41 participants). We obtained the weights assigned by each individual stakeholder group by using the Aggregation of Individual Judgments (AIJ) technique, and the weights assigned by the combined group decision were obtained by using the Aggregation of Individual Priorities (AIP). We decided to use both techniques as they were complementary to each other in our case study. AIJ is used when individuals act in concert and pool their judgments in such a way that the group becomes a new 'individual' and behaves like one (i.e., if the group is a synergistic unit) (Abel et al., 2015; Forman & Peniwati, 1998; Ossadnik et al., 2016; Schmidt et al., 2016). In our case, we first considered the stakeholder groups as synergistic units with members that may have similar ways of thinking about sustainability aspects. AIP, on the other hand, is used when individuals express different value systems (Abel et al., 2015; Forman & Peniwati, 1998; Ossadnik et al., 2016; Schmidt et al., 2016) It is suggested for groups larger than five people and shows great potential to support decisions with diverging or conflicting goals (Ossadnik et al., 2016), which fit our case study. Hence, we used AIP to achieve the weights that reflect the whole group's decision.

We calculated both the geometric average of the judgments (AIJ), and the arithmetic average of priorities (AIP) with Equations 3.1 and 3.2 respectively, by assuming that the individual respondents were of equal importance in contributing to the decision, which is the most common assumption (Adamcsek, 2008; Forman & Peniwati, 1998).

$$J_g(k, l) = \prod_{i=1}^n J_i(k, l)^{w_i} \quad (3.1)$$

where,

$J_g(k, l)$ is the group's judgment for the relative importance of parameters k and l in pairwise comparisons,

$J_i(k, l)$ is the individual respondent i 's judgment for the relative importance of parameters k and l in pairwise comparisons,

w_i is the importance of individual respondent i ; $\sum_{i=1}^n w_i = 1$, and n is the number of respondents.

$$P_g(A_j) = \sum_{i=1}^n w_i P_i(A_j) \quad (3.2)$$

where,

$P_g(A_j)$ is the group's priority weight for the parameter j , obtained through pairwise comparisons,

$P_i(A_j)$ is the individual respondent i 's priority weight for the parameter j , obtained through pairwise comparisons,

w_i is the importance of individual respondent i ; $\sum_{i=1}^n w_i = 1$, and n is the number of respondents.

3.4.4. Ranking of Alternatives and Their Evaluation

After all steps of the MADA were completed, we calculated the utility scores of each repurposing scenario by utilizing the Logical Decisions Software, obtained the ranking of alternatives, and interpreted the results. To calculate the utility scores of alternatives, we input the obtained weights to the Logical Decisions Software to be used in the multi-attribute utility functions in the form shown in Equation 3.3 (W. J. Hahn et al., 2012; G. Smith, 1991).

$$U_g(X) = w_1 U_1(X) + w_2 U_2(X) + \dots + w_n U_n(X) \quad (3.3)$$

where,

$U_g(X)$ is the utility of alternative X for the overall goal/sub-goal/criterion "g",

$U_n(X)$ is the utility of alternative X for the n^{th} member of g (a member is either a sub-goal, a criterion, or an attribute that is included under its upper level in the goals hierarchy), and

w_n is the weight assigned to the n^{th} member of g , and the sum of the w 's = 1.

We obtained the ranking of alternatives based on the utility scores of alternatives for the overall goal (i.e., sustainable repurposing). The results:

- revealed the preferences of each stakeholder group on what the sustainable repurposing of the area should look like
- explored the variability of views about “sustainability” within and among stakeholder groups
- revealed the strengths and weaknesses of each alternative in terms of the economic, social, and environmental sustainability of the mill area
- determined which repurposing scenario better reflected stakeholder preferences and results in the most economically, environmentally, and socially sustainable outcomes.

3.4.5. Sensitivity and Scenario Analysis

After the assessment of the results, we conducted a sensitivity analysis to test how sensitive or robust the ranking of alternatives was to changes in the weights assigned to the subgoals, criteria, and attributes. The sensitivity analysis was performed by running the sensitivity graph function of Logical Decisions, which draws a graph showing the effect of altering the weight of a subgoal, criteria, or attribute on the utility scores of alternatives.

We also conducted two different “what-if scenarios” to understand the effects of smaller representation of stakeholder groups on the final group decision.

Scenario 1: Removing the Outliers in Each Stakeholder Group

We determined the general outliers (i.e., diverging members) in each stakeholder group by creating a spider diagram that showed the weights assigned to the subgoals, criteria, and attributes by all members of that group. After determining the outliers in each stakeholder group, we removed them from the analysis and recalculated the weights and the utility scores of the alternatives. In total, we ran seven simulations (one simulation for each stakeholder group).

Scenario 2: Randomly Removing a) Respondents and b) Each Stakeholder Group

We first randomly removed one respondent at a time from the analysis following the jackknife method. We ran 41 simulations in total, for each of which we calculated the weights assigned and the resulting utility scores of the repurposing alternatives. We calculated the weights for each simulation using MATLAB, and then we inserted those weights in Logical Decisions to obtain each alternative’s utility score. We then followed the same steps for removing one stakeholder group and ran seven more simulations.

3.4.6. Study Limitation

The three repurposing alternatives presented in this study were selected by a jury in the student challenge, including stakeholders from the mining company, community members, and faculty. Many

repurposing alternatives were developed by student groups composed of multidisciplinary graduate and undergraduate students. The student groups, advised by two stakeholder groups (industry advisors and faculty members), collected views of community members and evaluated the environmental and social aspects of their proposed repurposing alternatives. There were more than ten alternatives presented to the jury, and three of them were selected as the best alternatives based on the jury's evaluation. Still, a larger stakeholder engagement would be ideal and is highly recommended for future studies. In practice, repurposing options should be developed in collaboration with stakeholders for a more participatory and deliberative decision-making process.

Moreover, in the student challenge, the main problem statement proposed by the mining company was economically focused and referred to the community losing a significant amount of tax every year after closure. No other important social aspects were mentioned, like cultural disruption or quality of life. In line with the problem statement, student projects also lacked such social aspects. Since the availability of data from the student projects drove our indicator selection process, our final indicator set lacked social indicators related to cultural disruption or quality of life. Although a focus on economic transition is critical for post-closure sustainability, there are several other social aspects of mine closure that should be considered (Bainton & Holcombe, 2018). We believe that these social aspects should also be assessed when considering the potential impacts of proposed repurposing projects.

3.5. Results and Discussion

3.4.7. Stakeholder Priorities

As may be expected, the priorities of the different stakeholder groups were both similar and different depending on the issue area. In general, community members' responses aligned with faculty members, and they shared the closest views on the importance of economic criteria (Level 3), contribution to society attributes (Level 4), and community impacts attributes (Level 4). Similarly, industry advisors and local governments, as well as government agencies and local governments were generally in agreement with each other. Industry advisors shared the closest views with local governments on the importance of the three subgoals of sustainable repurposing (Level 2), social criteria (Level 3), and economic performance attributes (Level 4). Government agencies and local governments shared the closest views on economic performance attributes (Level 4). However, in general, local non-profits' views often diverged from the other groups, and local governments' views contrasted those of the mining company and faculty members. This may indicate that the mining company should pay more attention to local governments' perspectives to better align mine closure with local sustainability criteria, development plans, and priorities and to better contribute to sustainable development at the local level. We also observed that community members' views were generally in line with the combined group decision, which demonstrates the heterogeneity of communities.

At Level 2, the combined group valued the economic aspects of repurposing the most (0.430), followed by environmental (0.340), and finally social (0.230) (Figure 3.5). Industry advisors, government

agencies, community members, and local governments followed this pattern, although the weights they assigned to each attribute differed. Faculty members, the mining company, and local non-profits valued environmental aspects the most. Although social aspects were valued the least in general, the mining company placed the highest importance on them (0.306) compared to the other stakeholder groups. Community members' preferences were the closest to the combined decision at this level.



Figure 3.5. Weight assigned by Stakeholder Group at Level 2 - Sustainable Repurposing Sub-goals

At Level 3 - economic criteria, the combined group decision valued (Figure 3.6) *contribution to society* slightly higher (0.540) than the *economic performance* of the new facility (0.460). However, industry advisors, government agencies, and local governments shared similar views at this level and valued *economic performance* more. Faculty members' and community members' preferences were also aligned, with similar weights on *contribution to society* (0.685 and 0.627, respectively). Among all groups, *contribution to society* was most important to local non-profits (0.838), and *economic performance* was most important to industry advisors (0.656). The mining company's preferences were the closest to the combined decision at this level.



Figure 3.6. Weight assigned by Stakeholder Group at Level 3 - Economic Criteria

At Level 3 - social criteria, the combined group decision valued (Figure 3.7) *employment* slightly higher (0.534) than the *community impacts* of the new facility (0.466), although faculty members and local non-profits valued *community impacts* more than *employment*. Among all groups, *employment* was most important to government agencies (0.726), and *community impacts* were most important to local non-profits (0.727).



Figure 3.7. Weight assigned by Stakeholder Group at Level 3 - Social Criteria

At Level 3 - environmental criteria, the order of importance for the combined group decision was *air pollution* (0.376), *waste* (0.266), *resource consumption* (0.214), and *land use* (0.144), with all stakeholder groups placing *air pollution* as the top priority (Figure 3.8). The mining company and local non-profits diverged from the combined group decision, with the mining company placing *waste* as the next highest priority followed by *land use* and *resource consumption*, and the local non-profits placing more emphasis on *land use* followed by *resource consumption* and then *waste*. Faculty members' and industry advisors' preferences were particularly close to each other, and community members' preferences were the closest to the combined decision at this level.

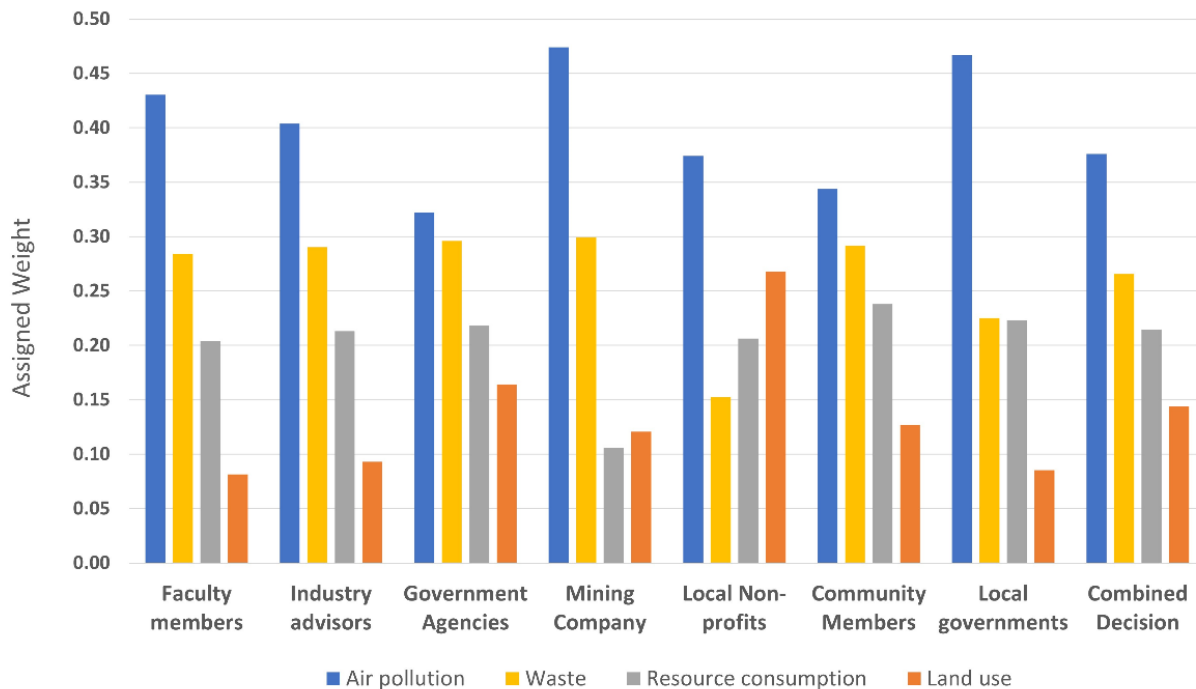


Figure 3.8. Weight assigned by Stakeholder Group at Level 3 - Environmental Criteria

At Level 4, under *contribution to society*, the combined group decision valued *investments in public services* more (0.608) than *income tax payments* by the new facility (0.392) (Figure 3.9). The prioritization of *investments in public services* was prevalent among local non-profits (0.873), faculty members (0.778), community members (0.756), the mining company (0.656), and government agencies (0.553). *Income tax payments* were more of a concern to local governments (0.627) and industry advisors (0.602). The faculty members' and community members' preferences were similar at this level, while industry advisors and local governments shared similar values.



Figure 3.9. Weight assigned by Stakeholder Group at Level 4 - Attributes: Contribution to Society

At Level 4, under *economic performance*, the group valued the *revenue* of the new facility the most (0.528), followed by the *time until full capacity* (0.245), and *production capacity* (0.227) (Figure 3.10). At this level, all stakeholder groups except faculty members valued *revenue* more than the other two attributes; faculty members were the only group who valued *time until full capacity* (0.432) more than *revenue* (0.389). Government bodies' preferences were similar at this level, while industry advisors and the mining company shared similar values.

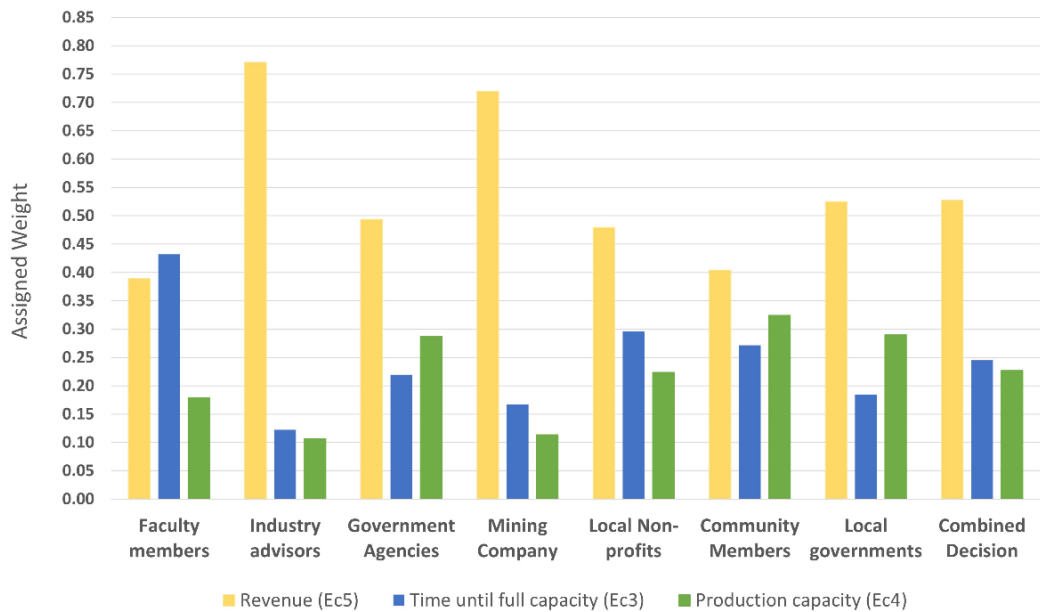


Figure 3.10. Weight assigned by Stakeholder Group at Level 4 - Attributes: Economic Performance

At Level 4, under *community impacts*, the group placed more importance on *nuisance* (0.622) than *traffic* (0.378); however, governmental bodies prioritized *traffic* more than *nuisance* (Figure 3.11). Faculty members' and community members' preferences were similar, as well as to the combined decision at this level. Industry advisors and the mining company also shared similar values.

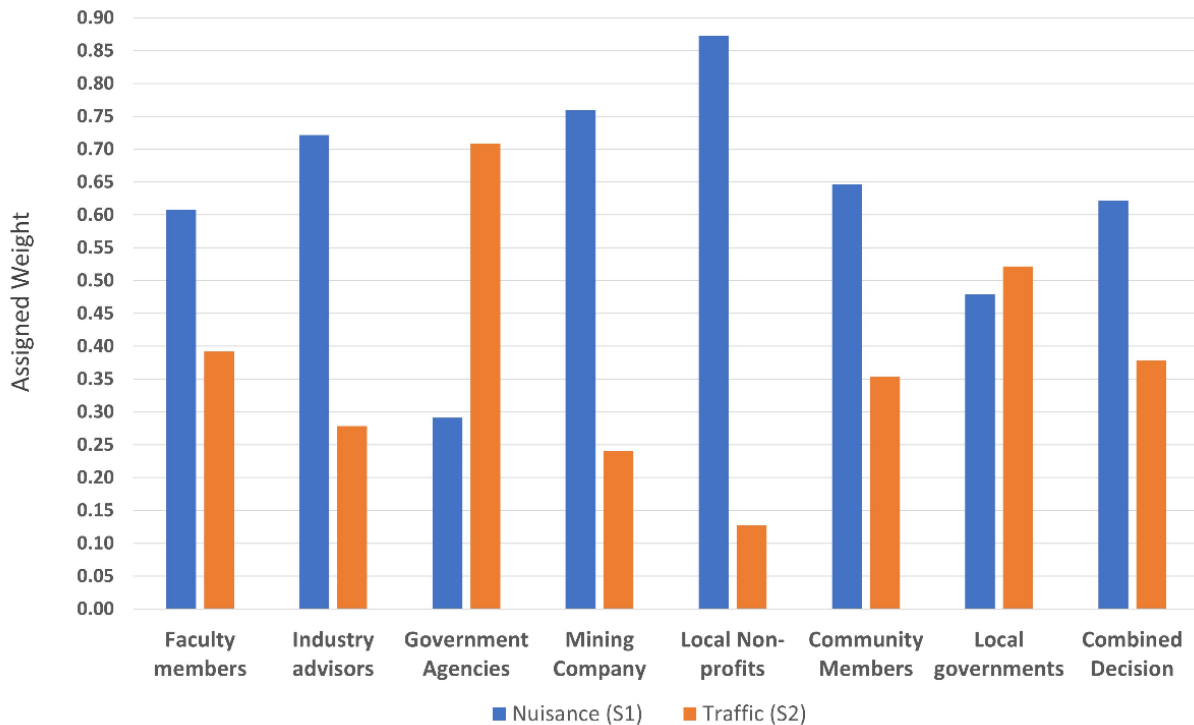


Figure 3.11. Weight assigned by Stakeholder Group at Level 4 - Attributes: Community Impacts

At Level 4, under *employment*, the group prioritized the *annual salary* provided by the new facility (0.400) over the *number of employees* (0.388) and *number of job types* (0.212) (Figure 3.12). Government agencies, the mining company, and local non-profits mirrored this order of importance. The mining company valued *annual salary* considerably higher (0.678) than the other groups while local governments did the same for *number of job types* (0.357). Industry advisors' and community members' preferences were similar at this level while government agencies' views were the closest to the combined decision.

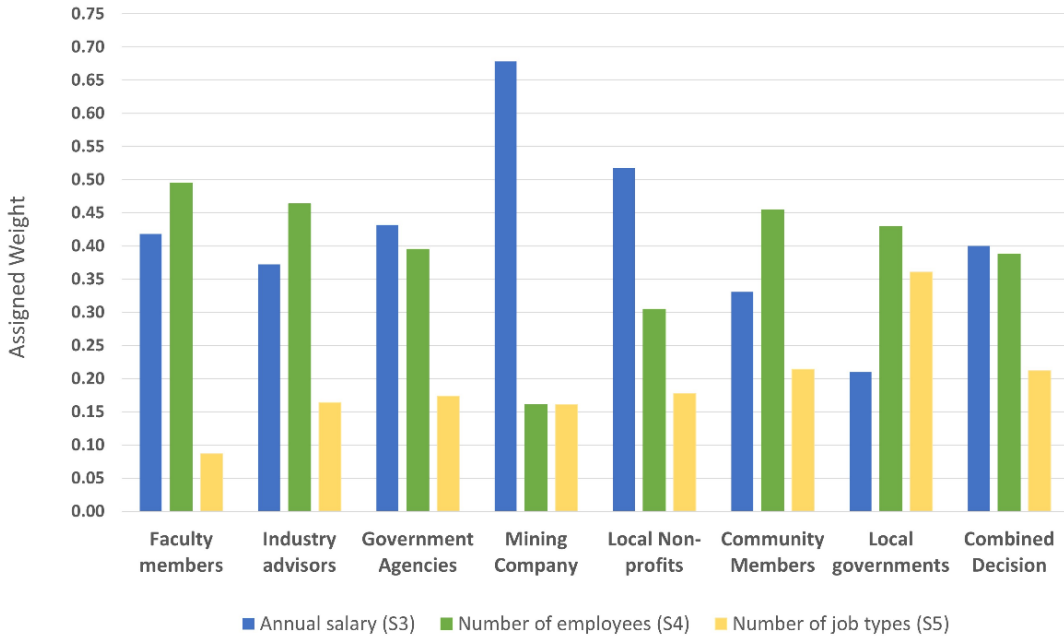


Figure 3.12. Weight assigned by Stakeholder Group at Level 4 - Attributes: Employment

At Level 4, under *resource consumption* (Figure 3.13), the group prioritized the new facility’s *energy use* (0.431) over the *energy supplied by renewables* (0.351) and *recycled input materials* (0.218) (Figure 3.13). Industry advisors, government agencies, the mining company, and local non-profits mirrored this order of importance, while faculty members, communities, and local governments valued *energy supplied by renewables* more than the other resource consumption attributes.

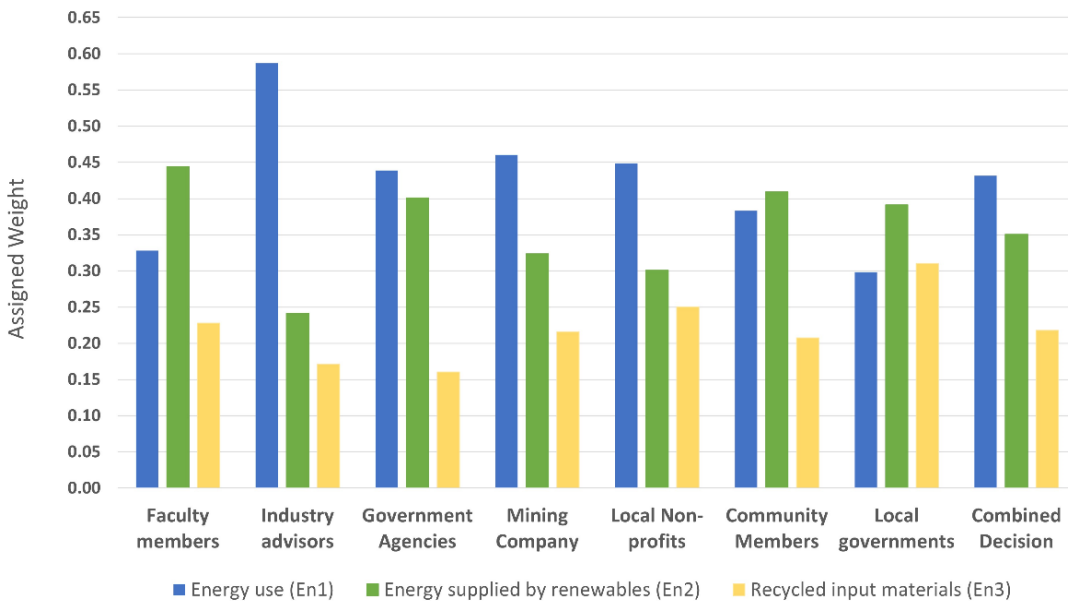


Figure 3.13. Weight assigned by Stakeholder Group at Level 4 - Attributes: Resource Consumption

At Level 4, under *waste* (Figure 3.14), all stakeholder groups, except local non-profits, valued the new facility's *waste production* (0.640) more than *untreated tailings* (0.360), with *waste production* emerging as a significant concern to community members (0.802) (Figure 3.14). Local non-profits placed equal weights to both attributes. Faculty members', industry advisors', and local governments' preferences were similar to each other, as well as to the combined decision at this level. Government agencies and the mining company also shared similar views.



Figure 3.14. Weight assigned by Stakeholder Group at Level 4 - Attributes: Waste

These results show that different stakeholder groups have different opinions about what constitutes sustainable development. Understanding different stakeholder views on sustainable repurposing is essential as a feedback loop for decision-makers and may impact the design of repurposing alternatives. No matter which repurposing alternative is selected, it might be beneficial to modify the project design or plan in some way to specifically address the higher importance placed on some parameters of sustainable repurposing. This would lead to a more transparent and representative closure planning that addresses stakeholder concerns.

3.4.7.1. Convergent and Divergent Views Within Stakeholder Groups

To understand the level of variability of views *within* stakeholder groups, we assessed the ranges in weights (i.e., the difference between the maximum and the minimum weights) assigned by stakeholder groups to each sustainable repurposing parameter (Table 3.2).

Table 3.2. Convergent and Divergent Views within Stakeholder Groups: Higher ranges (shown in orange and red) indicated more divergent views/disagreement among the respondents within each stakeholder group on the importance of a particular parameter, and lower ranges (shown in green and yellow) indicated closer alignment.

Level (L)	Aspect	Parameter	Range in Assigned Weights Within Stakeholder Groups							
			Faculty Memb.	Ind. Adv.	Gov. Agencies	Mining Comp.	Local Non-profits	Commun. Memb.	Local Gov.	All Resp.
L2	Econ	Economic Aspects	0.496	0.369	0.443	0.284	0.597	0.634	0.720	0.731
L2	Soc	Social Aspects	0.347	0.349	0.141	0.108	0.262	0.376	0.406	0.431
L2	Env	Environmental Aspects	0.372	0.353	0.361	0.205	0.481	0.681	0.459	0.681
L3	Econ	Contribution to Society	0.375	0.800	0.333	0.625	0.400	0.775	0.708	0.800
L3	Econ	Economic Performance	0.375	0.800	0.333	0.625	0.400	0.775	0.708	0.800
L3	Soc	Community Impacts	0.708	0.750	0.375	0.708	0.400	0.775	0.775	0.800
L3	Soc	Employment	0.708	0.750	0.375	0.708	0.400	0.775	0.775	0.800
L3	Env	Air pollution	0.349	0.419	0.456	0.067	0.198	0.337	0.377	0.575
L3	Env	Land use	0.099	0.302	0.443	0.225	0.488	0.310	0.104	0.513
L3	Env	Resource Consumption	0.186	0.477	0.238	0.170	0.220	0.386	0.435	0.513
L3	Env	Waste	0.344	0.296	0.063	0.160	0.255	0.332	0.329	0.423
L4	Econ	Income tax payments (Ec1)	0.375	0.708	0.625	0.333	0.067	0.625	0.733	0.800
L4	Econ	Investment in public services (Ec2)	0.375	0.708	0.625	0.333	0.067	0.625	0.733	0.800
L4	Econ	Time until full capacity (Ec3)	0.554	0.198	0.215	0.376	0.593	0.321	0.252	0.638
L4	Econ	Production capacity (Ec4)	0.261	0.200	0.625	0.195	0.205	0.564	0.548	0.659
L4	Econ	Revenue (Ec5)	0.483	0.122	0.515	0.291	0.662	0.658	0.406	0.710
L4	Soc	Nuisance (S1)	0.775	0.400	0.625	0.375	0.067	0.750	0.583	0.775
L4	Soc	Traffic (S2)	0.775	0.400	0.625	0.375	0.067	0.750	0.583	0.775
L4	Soc	Annual salary (S3)	0.375	0.625	0.241	0.337	0.705	0.561	0.593	0.729
L4	Soc	Number of employees (S4)	0.394	0.580	0.423	0.214	0.599	0.346	0.534	0.664

Table 3.2 Continued

Level (L)	Aspect	Parameter	Range in Assigned Weights Within Stakeholder Groups							
			Faculty Memb.	Ind. Adv.	Gov. Agencies	Mining Comp.	Local Non-profits	Commun. Memb.	Local Gov.	All Resp.
L4	Soc	Number of job types (S5)	0.049	0.435	0.215	0.364	0.273	0.389	0.628	0.665
L4	Env	Energy Use (En1)	0.556	0.717	0.689	0.511	0.712	0.691	0.684	0.743
L4	Env	Energy supplied by renewables (En2)	0.434	0.598	0.563	0.685	0.512	0.640	0.604	0.685
L4	Env	Recycled input materials (En3)	0.400	0.278	0.376	0.380	0.363	0.262	0.549	0.632
L4	Env	Untreated tailings (En4)	0.583	0.775	0.775	0.775	0.500	0.400	0.666	0.775
L4	Env	Waste production (En5)	0.583	0.775	0.775	0.775	0.500	0.400	0.666	0.775

Overall, differing perspectives within each stakeholder group increased from Level 2 (sub-goals) to Level 4 (attributes), demonstrating more heterogeneity within groups as the parameters became more specific. At Level 2, there was greater alignment within each group on the importance of the social sub-goals, and at Level 3 there was greater alignment on the importance of the environmental criteria. At Level 4, the respondents within each stakeholder group were most aligned in their prioritization of specific economic attributes.

At Level 2, there was greater disagreement within all stakeholder groups except community members, on the importance of economic aspects. Within most groups, there was more heterogeneity in perspectives on the value of economic and social criteria at Level 3 and environmental attributes at Level 4. In general, economic parameters generated the most diversified views among community members and the most aligned views among local non-profits. Economic attributes, *income tax payments*, and *investment in public services* were in large part not aligned within most stakeholder groups except local non-profit members who were almost in perfect agreement with each other (0.067 range). The group with the closest views on the importance of attributes under *economic performance* (i.e., *time until full capacity*, *production capacity*, and *revenue*) was industry advisors, while there was much less alignment in these parameters within the remaining stakeholder groups. In general, social parameters generated the most diversified views among local governments and the closest views among local non-profits. Faculty members held the closest perspectives on the importance of the social attributes under *employment* (i.e., *annual salary*, *number of employees*, and *number of job types*), and government agencies and the mining

company representatives also shared relatively close internal views on these topics. In general, industry advisors and government bodies held the most diverse perspectives on environmental parameters, while faculty members' views were the most closely aligned. The environmental criteria at Level 3 created an area of general agreement within all responding groups. The importance of the environmental attributes under *waste* (i.e., *untreated tailings*, and *waste production*) created considerable heterogeneity within all stakeholder groups except the community members.

Overall, local non-profits and the mining company had the closest views among their members while local governments and community members had the greatest diversity among their groups. This is to be expected since non-profits and mining companies operate under particular and shared charters across their organizations. The higher heterogeneity among the community members is consistent with our findings in the previous section where community members' views were generally in line with the combined group decision, and it reinforces the literature on the heterogeneity of communities and mineral developments (Boon & Edler, 2018; McGaurr & Lester, 2017; Parsons et al., 2014; Prno, 2013; Prno & Slocombe, 2014).

The more responses are collected, the more representative the assessment will be of the wider public's view. Furthermore, we suggest that the more heterogenous the views are in a stakeholder group, the more members of those groups should be involved in the evaluation to mitigate subjectivity in decision-making methods like MADA. Since community members are a larger and more heterogeneous group than the other groups, instead of considering community members as one stakeholder group, it would be useful to breakdown the community members into smaller groups (e.g., women, vulnerable groups, lions clubs, and other groups that emerge within the community) identified before and during the assessment. Another approach could be to break down the community based on demographic and socio-economic attributes (e.g., education, job type, age, income).

For the mining company, areas where there are more divergent perspectives could signal topics to focus on during future stakeholder engagements. This could help shape more sustainable post-mining land uses.

3.4.8. Overall Ranking of the Repurposing Alternatives

The combined decision of all stakeholders showed that *shrimp* provided the highest utility in terms of sustainable repurposing followed by *hemp* and then *tailings* (Figure 3.15). However, each repurposing alternative had different strengths and weaknesses. For example, *tailings* was particularly strong in terms of economic utility but weak in environmental and social utility (Figure 3.16). And both *shrimp* and *hemp* were strongest in environmental utility and less so in social and economic utility. Interestingly, a different repurposing scenario was the strongest alternative for each dimension. *Shrimp* would provide the highest environmental utility, *tailings* would provide the highest economic utility, and *hemp* would provide the highest social utility among all scenarios.

Combined Decision

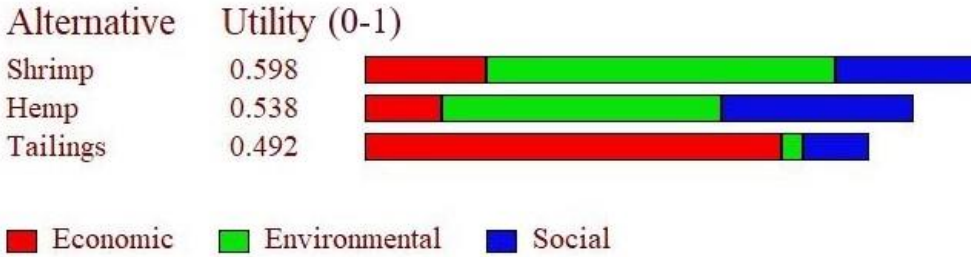


Figure 3.15. The overall ranking result reflecting the combined decision of all stakeholders

Utility scores of alternatives for each dimension

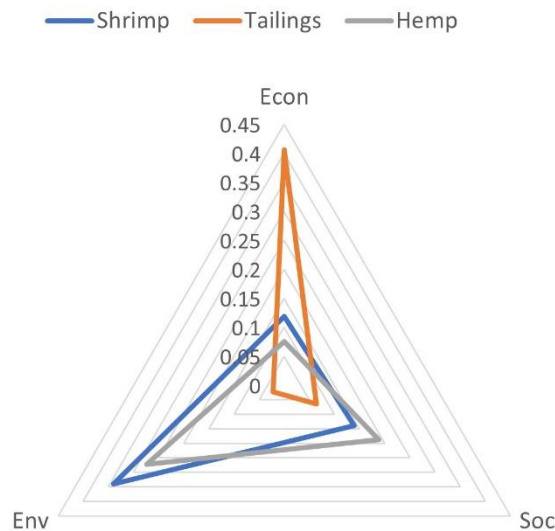


Figure 3.16. Utility scores of repurposing alternatives for economic, social, and environmental aspects

3.4.8.1. Different Rankings for Different Stakeholder Groups

As a result of the different weights assigned to the subgoals, criteria, and attributes by different stakeholder groups, the ranking of repurposing alternatives also varied for each stakeholder group (Figure 3.17). The rankings of community members, the mining company, local non-profits, and faculty members were in line with each other and with the combined decision of all stakeholders ranking *shrimp* first, *hemp* second, and *tailings* third. Industry advisors and local governments ranked *tailings* first, *hemp* second, and *shrimp* third, and government agencies ranked *tailings* first, *shrimp* second, and *hemp* third.

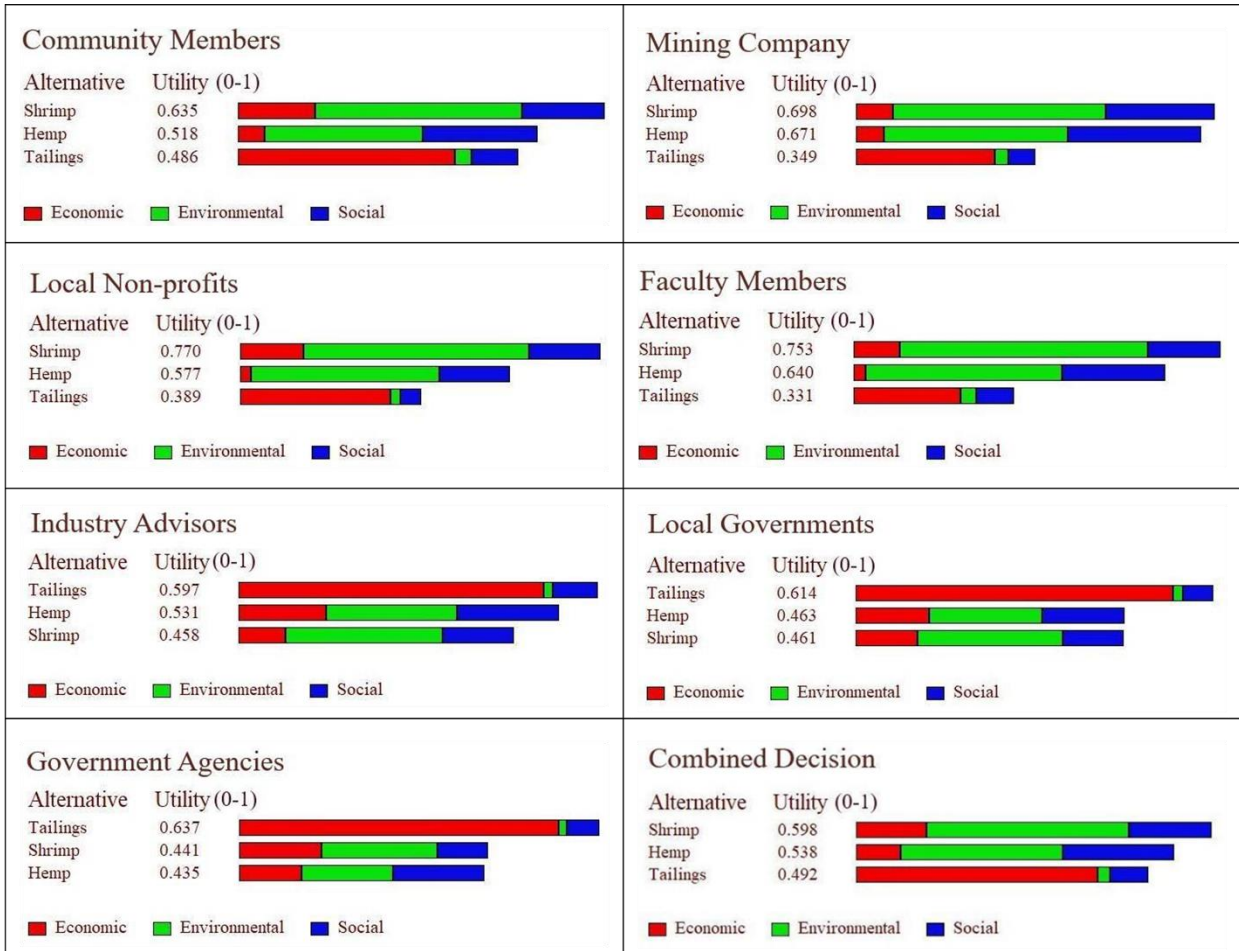


Figure 3.17. Ranking of repurposing scenarios by stakeholder groups

The ranking of the alternatives changed depending on the analysis of the decision makers’ preferences and values. Even though some stakeholder groups shared the same ranking, the utility scores of the alternatives differed based on the importance given to certain sustainability aspects. Industry advisors and government bodies all ranked *tailings* first, which may have been expected considering they all prioritized the economic aspects. Whereas one may not have expected the mining company to prioritize environmental aspects more and *shrimp* and *hemp* to be their top two choices. These data point to the complicated task of determining what sustainability means to different people. It raises important questions, such as how to reconcile different perceptions of sustainability and how to create what is often referred to as “shared value” for productive and sustainable post-mining land use (ANZMEC & MCA, 2000; Australian Government, 2016; Finucane, 2008; ICMM, 2019; IIED & WBCSD, 2002b; Kabir et al., 2015; Limpitlaw, 2004; Monosky & Keeling, 2021). The results also show the impact and importance of soliciting feedback from a variety of groups and actors within those groups.

3.4.9. Sensitivity of the Results

3.4.9.1. Sensitivity to the Weights

Figure 3.18 summarizes a sample of the sensitivity analysis that demonstrates the effect of changing the weights assigned to the economic, environmental, and social sub-goals at Level 2 (refer to the goals hierarchy – Figure 3.4). The results suggested that *shrimp*'s score was sensitive to the changes in the weights of economic and environmental aspects of sustainability repurposing but was more robust to the changes in the weight of social aspects. *Hemp* and *tailings*' scores were sensitive to the changes in the weights assigned to all sub-goals.

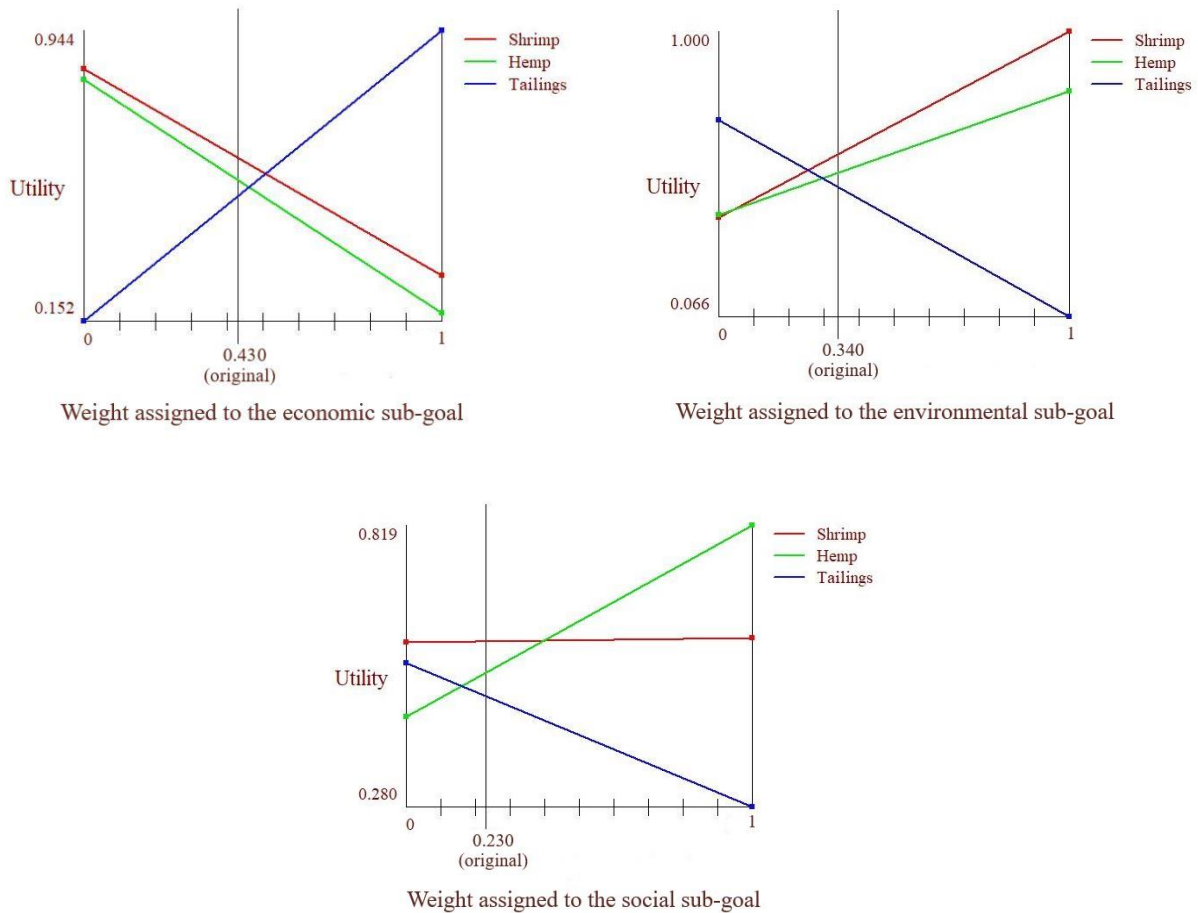


Figure 3.18. Sample sensitivity analysis results that show the effects of changes in weights assigned to sub-goals

The results indicated that decreasing the weight assigned to the economic sub-goal would not change the rank ordering of alternatives. Increasing the weight on the economic sub-goal by 5% (i.e., increasing it to 0.452 from 0.430) would also not change the ranking. However, increasing it by 10% would make *tailings* the second and *hemp* the third-ranked alternatives. Increasing the weight by 15% would make *tailings* the second and *hemp* the third. Finally, increasing the weight by 20% (0.516) would

make *tailings* the first, *shrimp* the second, and *hemp* the third, and the rank order would not change beyond this point.

Increasing the weight allocated to the environmental sub-goal would not change the ranking. Decreasing it by 5% (i.e., decreasing it to 0.323) or by 10% would also not change the ranking. However, decreasing it by 15% would make *tailings* the second and *hemp* the third, and decreasing by 20% (0.272) would maintain this rank order. Finally, decreasing its weight by 25% (0.255) would make *tailings* the first, *shrimp* the second, and *hemp* the third, and the rank order would not change unless the weight allocated to the environmental sub-goal drops to 0.0425, which is highly unlikely.

Increasing the weight allocated to the social sub-goal would not change the ranking unless it is increased by 74% (i.e., increasing it to 0.400 from 0.230), which would make *hemp* the first and *shrimp* the second. Decreasing its weight would also not change the ranking unless it is decreased by 30% (i.e., decreasing it to 0.159), which would make *tailings* the second and *hemp* the third, and the rank order would not change beyond this point.

Overall, these results show that the ranking of repurposing alternatives was the most sensitive to the changes in the importance attached to the economic aspects while it was much more robust to the changes in the weight of social aspects of sustainable repurposing. Also, *shrimp* had the most robust ranking while the rankings of *hemp* and *tailings* were more prone to change. The sensitivity analysis could also be done for the lower levels of the goals hierarchy, but since the changes in the ranking were not dramatic at Level 2, we did not analyze the lower levels.

3.4.9.2. Sensitivity to the Stakeholder Groups' Composition

We conducted two different “what-if scenarios” to understand the impacts of the smaller sample size of individuals within each stakeholder group on the final group decision, as well as the smaller number of stakeholder groups compared. The results showed how robust the scores and rankings of alternatives were to the changes in our respondent sample. For the first scenario, we identified two faculty members, two industry advisors, two government agencies, two mining company representatives, two local non-profits, four community members, and three local government members as the outliers, whose perspectives diverged from other group members. We removed these outliers and calculated the utility score, the mean, and the range (i.e., how much the utility score varied) for each alternative (Table 3.3). The original ranking obtained for the combined group decision did not change for any of the simulations although *shrimp*'s utility score varied the most while *hemp*'s score varied the least.

Table 3.3. Results of What-if Scenario 1

Alternative, original ranking, original utility score	Utility Scores for What-if Scenario 1: Removing the Outliers in Each Stakeholder Group								
	Faculty Members	Industry Advisors	Gov. Agencies	Mining Company	Local Non-profits	Community Members	Local Gov.	Mean	Range (Max-Min)
Shrimp, 1 st , 0.598	0.587	0.601	0.605	0.597	0.581	0.590	0.604	0.595	0.024 (0.605 - 0.581)
Hemp, 2 nd , 0.538	0.526	0.541	0.541	0.534	0.531	0.535	0.542	0.536	0.016 (0.542 - 0.526)
Tailings, 3 rd , 0.492	0.507	0.488	0.487	0.494	0.506	0.502	0.486	0.496	0.021 (0.507 - 0.486)

The results for removing one respondent at a time (Table 3.4) and removing one stakeholder group at a time (Table 3.5) showed that the original ranking obtained for the combined group decision remained for all 48 simulations. However, the removal of particular stakeholder groups showed some rather predictable patterns. For example, the removal of industry advisors, government agencies, and local governments increased shrimp’s utility score the most and decreased tailings’ score the most (Table 3.5). This was consistent with the preference ranking of these two groups. Similarly, the removal of faculty members and local non-profits decreased shrimp’s score the most, as they were the two groups that assigned the highest scores to shrimp. The removal of local governments changed the scores the most, which might suggest that they were the group whose views differed the most from the combined group decision. On the other hand, the removal of community members changed the scores the least, which reinforces this group’s heterogeneity and best reflects the combined group decision. This suggests that larger numbers of community members must be more engaged in decision-making about post-mining land uses (Boon & Edler, 2018; Briassoulis, 2002; N. C. Smith, 2003).

Table 3.4. Results of What-if Scenario 2-a

Alternative, original ranking, original utility score	Utility Scores for What-if Scenario 2-a: Removing each respondent			
	Maximum Score	Minimum Score	Mean	Range (Max-Min)
Shrimp, 1 st , 0.598	0.606	0.587	0.597	0.019
Hemp, 2 nd , 0.538	0.544	0.531	0.537	0.013
Tailings, 3 rd , 0.492	0.502	0.486	0.494	0.016

Table 3.5. Results of What-if Scenario 2-b

Alternative, original ranking, original utility score	Utility Scores for What-if Scenario 2-b: Removing one stakeholder group at a time								
	Faculty Members	Industry Advisors	Gov. Agencies	Mining Company	Local Non-profits	Commun. Members	Local Gov.	Mean	Range (Max-Min)
Shrimp, 1 st , 0.598	0.581	0.622	0.613	0.587	0.575	0.589	0.617	0.598	0.047 (0.622 - 0.575)
Hemp, 2 nd , 0.538	0.532	0.539	0.546	0.521	0.532	0.541	0.553	0.538	0.032 (0.553 - 0.521)
Tailings, 3 rd , 0.492	0.507	0.477	0.481	0.510	0.508	0.497	0.474	0.493	0.036 (0.510 - 0.474)

The fact that the rankings of the different alternatives did not change with any of the simulations shows that this sustainability assessment was relatively robust with this group of people. Although *hemp* had the most robust utility score according to the what-if scenarios and *shrimp* had the least, *shrimp* always ranked first, showing its strength in terms of stakeholder perspectives on sustainability. The results also demonstrate that the challenge itself produced some innovative repurposing ideas that could contribute to sustainable development.

In general, MCDM and MADA have been criticized for being subjective in terms of their implementation, and being prone to manipulation, as they are dependent on the judgments of decision-makers (Janssen, 2001; Korucu & Erdagi, 2012; Munda, 2004; Zardari et al., 2015). On the other hand, the proponents of MCDM claim that it provides a systematic, transparent approach that improves objectivity and generates reproducible results (Janssen, 2001; Macharis et al., 2004; Zardari et al., 2015). Although MADA might be subjective in terms of how it is implemented, our analyses attempted to eliminate subjectivity by systematically selecting the indicator set, including sufficient representation from each stakeholder group in our sample, and conducting the sensitivity analysis. A strong post-mining land use alternative should always rank first regardless of the responder combination, which happened with *shrimp* in this case.

3.6. Conclusions

We provided and utilized a decision support method to evaluate the sustainability of three different repurposing scenarios for the tailings dam area of a mine that is approaching closure. We evaluated how different repurposing scenarios can contribute to sustainable development, identified the strengths and weaknesses of each scenario, and determined which scenario better reflected the preferences of stakeholders and would result in the most economically, environmentally, and socially sustainable outcomes. Through the application of our method, we also provided potentially useful information for the decision-making process, such as different stakeholder perceptions of aspects of sustainability, as well as areas of agreement and disagreement. For example, stakeholder perspectives were more closely aligned

for social aspects on a high level (at Level 2), but this alignment shifted to environmental (Level 3) and economic aspects (Level 4) for more detailed issues. Additionally, we found that the repurposing phase of the mining life cycle was not considered as much as other phases in the literature for developing sustainability indicators because only a small set of indicators were relevant and could be selected for this study out of our large sustainability indicator set. This is in line with the findings of Pimentel et al. (2016), and it shows how sustainability indicators generally have not considered closure and post-closure impacts in forward-looking projections (Pimentel et al., 2016).

Our results show that stakeholders have different ideas about what constitutes sustainable development and different views may arise even within the same stakeholder group. Hence, the ranking of the alternatives changes depending on the decision maker's preferences and values. At this point and time and with our sample size, shrimp was ranked as the first in the actual survey results, as well as in every simulation we ran. This shows our assessment's robustness with this group of people and shows shrimp's strength in terms of supporting sustainability. The results reflect the "consensus" of stakeholders, and they point to which repurposing alternative better addresses the stakeholders' values and needs (Akbar et al., 2020). We recognize that our study reached a limited number of respondents, and if this were to be a real-life exercise, achieving a larger sample size would be beneficial for a more thorough sustainability assessment. The more responses are collected, the more accurate and representative will be the assessment of the general public view. In selecting the sample of respondents, considering the variability of views within stakeholder groups would be beneficial to ensure more involvement of stakeholder groups with higher variability.

Ernst & Young recently named "environmental and social" as the number one business risk for the mining industry, specifically pointing to the need to progressively plan for mine closure to respond to intensifying stakeholder pressure (Mitchell, 2021). We believe that efforts to achieve more responsible and sustainable mine closure and repurposing could help address these risks and increase mining's contributions to the SDGs beyond the life of mine. For instance, to avoid the negative impacts of the boom-and-bust cycle on mining communities, mining companies could support non-mining livelihood opportunities and microfinance initiatives, which might help mining contribute to SDG 1 (No Poverty) (UNDP, 2016). Considering and assessing post-closure land use or repurposing alternatives in closure planning, by involving stakeholders in decision-making, might serve mining better in contributing to SDG 11 (Sustainable Cities and Communities) and SDG 17 (Partnerships for the Goals). Transparent and representative closure planning that involves the discussion of repurposing alternatives and responds to stakeholder concerns might also lead to good community relations and prevent potential company-community conflicts, strengthening mining's contribution to SDG 16 (Peace, Justice, and Strong Institutions) (UNDP, 2016). Lastly, reclaiming mined land and repurposing the land and infrastructure for innovative and sustainable uses might benefit mining companies in contributing to SDG 11, SDG 8 (Decent Work and Economic Growth), and SDG 9 (Industry, Innovation, and Infrastructure). A detailed

overview of identified strengths and areas for improvement for contributing to the SDGs at the site level are provided in Appendix D, together with the corporate and operation levels.

The mining industry has been criticized for being slower than other sectors in incorporating innovation in their operations and practices (Ediriweera & Wiewiora, 2021; Marimuthu et al., 2021; Perdeli Demirkan et al., 2021), and this constitutes an important business risk for the mining industry (Perdeli Demirkan et al., 2021). Our results demonstrated that out of the three winners of the student challenge, shrimp farming provided the most sustainable and innovative repurposing.

We showed that with adequate representation from a variety of stakeholders, a robust assessment, and innovative repurposing alternatives, it is possible to identify projects that meet the most important stakeholder concerns and expectations while also providing the most sustainable outcomes. We conclude that responsible and sustainable mine closure and repurposing should be unique to the settings and needs of various stakeholders, incorporate stakeholder preferences, and adopt a holistic approach that addresses environmental, social, and economic issues.

CHAPTER 4

COMPARISON OF AUTONOMOUS AND CONVENTIONAL HAULAGE TRUCKS IN TERMS OF GHG EMISSIONS AND CONTRIBUTIONS TO THE SDGs

This study has been completed and the journal paper that is derived from this chapter is currently in draft form for submission.

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4.1. Abstract

In the last decade, autonomous haulage trucks (AHT) have increasingly been listed among the low-carbon strategies by large iron ore companies, supported by the claims around diesel consumption savings and the related greenhouse gas (GHG) emissions compared to conventional trucks (CT). Autonomy provides a system change that improves the productivity of a mining operation by reducing the time trucks spend on non-productive activities. However, this system change might result in cascading effects on the workforce and communities. In this paper, we investigate AHT's potential for a lower carbon footprint for haulage by proposing a GHG emission estimation methodology based on the Time Usage Model (TUM) and apply it to a surface iron ore mine in Australia. Our results show that AHT results in higher overall emissions per ton of material moved compared to CT while decreasing the emissions generated from the time spent on non-productive (idling) time elements of the TUM. We also unpack and discuss the broader socio-economic implications of AHT on workers and communities and identified the related strengths and areas for improvement in terms of mining's contributions to the SDGs. We argue that achieving more concrete contributions to sustainable development and the SDGs require the environmental impacts of AHT, including the carbon footprint, to be cautiously balanced against economic and social costs and benefits.

4.2. Introduction

There is a growing interest in carbon emissions accounting and disclosure in the mining industry due to climate change and the need for a low-carbon future. However, it is still challenging to understand the carbon emissions associated with many common materials (e.g., steel, cement) and finished products (e.g., automobiles, wind turbines), especially with modern supply chains that involve multiple companies

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operating internationally. External issues, in particular those related to supply chains, are relatively overlooked in the sustainability reports of mining companies (see Chapter 2). The “embedded emissions” (i.e., supply chain emissions) or those generated from the production and delivery of a product are generally unknown (Natali et al., 2019). This includes emissions generated through raw material extraction, processing of materials, as well as the manufacturing and transportation of the final product. Therefore, it is important to develop a clearer understanding of emissions from the production of key materials like steel to provide insights into the carbon emissions of consumer products like cars, buildings, and phones. Increased carbon accounting for these materials is essential for companies to meet sustainability targets and for consumers to make smarter choices (RMI, n.d.).

Steel is an important engineering and construction material that is used in various settings in daily life, including in cars, ships, and energy infrastructures (World Steel Association, n.d.). Iron ore and metallurgical coal are the two main raw materials for steelmaking. Iron ore is a compound of iron, oxygen, and other minerals, and 98% of the iron ore is used in steelmaking (USGS, n.d.). It is mined in around 50 countries (Arcelor Mittal, n.d.). Australia and Brazil dominate the world's iron ore exports, each having one-third of the global exports (Investopedia, 2022). In 2019, Australia had a 37.5% share in global ore production, and Brazil had a share of 16.5% (Investopedia, 2022). To produce 1,000 kg of crude steel, roughly 586 to 1,370 kg of iron ore is needed (World Steel Association, n.d.). Iron ore is therefore a critical component of steel. To understand the embedded emissions in the supply chain of steel, emissions arising from iron ore mining should be quantified.

Steel is the industrial material with the greatest climate impact (World Steel Association, 2021). In 2020, it accounted for about 8% of global greenhouse gas (GHG) emissions with 2.6 billion tonnes of CO₂ (World Steel Association, 2021). As a critical part of steelmaking, iron ore mining also has a share in this number. In fact, iron ore is one of the major contributing commodities to the mining industry's total emissions, after coal and copper (Azevedo et al., 2021). As a result, there has been a recent increase in low carbon strategies and targets by the largest iron ore mining companies. For example, Vale aims to reduce Scope 1 and 2¹⁴ emissions by 33% by 2030 and achieve net zero emissions by 2050 (Vale, 2021). Rio Tinto aims to reduce emissions by 15% by 2025, 50% by 2030, and net zero emissions by 2050 (Rio Tinto, 2021). FMG Fortescue is attempting to achieve carbon neutrality by 2030 and net zero Scope 3 emissions by 2040 (FMG Fortescue, 2021).

In an operational surface mine site, haulage is the process of moving material via haul trucks from one point to another (Marshall et al., 2016). The majority of the equipment in the loading and haulage fleet uses diesel-powered engines that are energy intensive (Norgate & Haque, 2010). As a result,

¹⁴ Scope 1 accounts for direct GHG emissions occurring from sources that are owned or controlled by the company, for example, emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc. Scope 2 accounts for electricity indirect GHG emissions from the generation of purchased electricity consumed by the company. Scope 3 accounts for all other indirect GHG emissions are a consequence of the activities of the company but occur from sources not owned or controlled by the company. Some examples are business travel, procurement, and use of sold products and services (WBCSD & WRI, 2004).

loading and hauling make the largest contributions to the total GHG emissions for the mining and processing of iron ore (Legge et al., 2021; Mulvaney et al., 2021; Norgate & Haque, 2010). Therefore, efforts to reduce GHG emissions (i.e., *low-carbon strategies*) from iron ore mining should primarily focus on loading and hauling (Norgate & Haque, 2010).

Being a repetitive process, haulage is considered ideal to be replaced with automated equipment to generate significant benefits such as improved safety, productivity, repeatability, and reduced maintenance costs (Marshall et al., 2016; Parreira et al., 2009). Automation can be simply defined as the intelligent management of a system using proper technology so that its operation can occur without direct human involvement (Lynas & Horberry, 2011). Autonomous haulage system (AHS) technology replaces conventional, human-driven trucks with driverless trucks. Automated trucks are controlled by software and global positioning and sensor systems that direct them around the mine site. Human operators monitor vehicle activity from a remote control room and can intervene if needed (Keenan et al., 2019). With significant amounts of production, iron ore mines have been the pioneers of optimizing and automating the mining operations for extracting the maximum tonnage, especially in Australia (Holmes et al., 2022). Mining equipment automation in Australia started with underground hard-rock mining as a safety solution to better protect workers from the hazards of rock falls and mine collapses, as well as to increase mine productivity. Surface mines were slower to adopt automation technology until investments in automation were financially justified with the recent mining boom, rising labor costs, and difficulties in staffing (Bellamy & Pravica, 2011; Flämig, 2016). As a result, the iron ore mining industry sought ways to stay competitive, and AHS has attracted their interest as a way to improve safety and productivity, reduce labor and haulage costs, and enable a more attractive working environment (Bellamy & Pravica, 2011; Keenan et al., 2019; McNab et al., 2013). The use of autonomous haulage equipment, including autonomous haulage trucks (AHT), has been expanding rapidly (Sánchez & Hartlieb, 2020b).

In the last decade, AHS has increasingly been included as a low-carbon strategy by large iron ore companies (Rio Tinto, 2021; Vale, 2021). AHT are claimed to increase production and efficiency (Kirk & Lund, 2018; Parreira, 2013; Parreira et al., 2009) while decreasing diesel consumption and GHG emissions by 10 to 15% (OECD, 2018). Besides such claimed benefits, technological innovations, such as AHT, are believed to significantly challenge the mining industry with broader social impacts on workers and communities (Bellamy & Pravica, 2011; Holcombe & Kemp, 2019; Keenan et al., 2019; McNab et al., 2013), which may bring into question to what extent incorporating AHT into their fleet can enhance a company's contributions to sustainable development, especially the United Nations Sustainable Development Goals (SDGs) (Endl et al., 2021).

This study examines whether AHT are a better low-carbon strategy than CT for surface iron ore mines. Based on the claimed benefits of AHT, we hypothesized that AHT would have a smaller carbon footprint than their conventional counterparts, and therefore would be a better low-carbon strategy. We investigated the potential of AHT to produce a lower carbon footprint for haulage by proposing a GHG emissions estimation methodology based on the Time Usage Model (TUM) and applying it to a surface

iron ore mine in Australia. Our results partially confirm our hypothesis and suggest that AHT result in higher overall emissions per ton of material moved compared to CT; yet they decrease the emissions due to non-productive activity of the trucks, for example through standby or operating delay. Autonomy provides a system change that improves the productivity of a mining operation by reducing the time trucks spend on non-productive activities. However, this system change might result in cascading effects on the workforce and communities. Based on our “systems within systems” approach, these potential cascading effects of AHT should also be considered to have a better understanding of contributions to sustainable development at the third scale (operation-level). Therefore, we also unpack the broader socio-economic implications of AHT on workers and communities and discuss the related strengths and areas for improvement in terms of mining’s contributions to SDGs.

4.3. Literature Review

Previous studies have focused on understanding and improving the efficiency and environmental impacts of conventional haulage equipment, yet autonomous haulage trucks have been relatively overlooked. Yildirim (2021) built an intersection passing algorithm for haulage trucks to determine which truck obtains the right of way when they simultaneously approach an intersection. Calculating the criticality based on various parameters such as load status, speed, and payload, he simulated the effect of the new passing algorithm on productivity, efficiency, and fuel consumption; yet the study was limited to conventional trucks (Yildirim, 2021). Some studies have focused on emissions and other environmental aspects of mines and haulage systems, but they did not cover automated haulage equipment. Tost et al. (2018) examined the reporting of environmental indicators such as GHG emissions, water use, and land use of four principal metals, including iron ore. Their results showed that reporting is still very limited with significant inconsistencies in criteria such as boundary descriptions and input parameter definitions, as well as a lack of reporting at the commodity and site level. The authors argue that such environmental data should be reported consistently at the commodity and at the site levels, or ideally at the operation level (Tost et al., 2018). Some studies conducted life cycle assessments (LCAs) of mining and processing of metals, including GHG emission estimation from hauling (Awuah-Offei & Nasab, 2009; Norgate & Haque, 2010), or investigated ways to decrease trucks’ fuel consumption (Wellman, 2022). Norgate and Haque (2010) showed that loading and hauling make the largest contributions to the total GHG emissions for the mining and processing of iron ore and bauxite, indicating focus areas to reduce the emissions from mining and mineral processing (Norgate & Haque, 2010). In another study, Awuah-Offei & Nasab (2009) performed an LCA of belt conveyor and truck haulage systems for an open-pit gold mine and found that the GHG emissions of the belt conveyor system were considerably greater than that of the truck haulage system. Wellman (2022) qualitatively identified mines’ strategies for reduced diesel consumption and related emissions, including improved truck driver behavior, better tire properties, and minimized idling time.

The majority of the research that involved autonomous haulage systems focused on investigating the social and economic consequences and risks of introducing autonomy to mining operations. One study examined the commercialization of autonomous vehicles in surface mining and showed the advantages of being an early entrant versus a late follower with an economic analysis of savings with AHT (Brundrett, 2014). Bellamy and Pravica (2011) assessed the social and economic consequences of introducing driverless haul trucks in a large remote Australian open pit mine. They found that automation saved labor costs, raised operational productive hours, and reduced the workforce size. Other listed impacts were smaller mining camps, a reduction in the population of the remote mining town, reduced economic opportunities for communities because of the decline in the resident workforce, and a decrease in the lower skilled labor requirements for the mining sector (Bellamy & Pravica, 2011). Greater focus was placed on the social aspects in other studies, including the impacts of autonomous mining technologies on the workforce (Chirgwin, 2021; Lynas & Horberry, 2011; McNab et al., 2013; Rogers et al., 2019), as well as on Indigenous peoples (Holcombe & Kemp, 2019; Keenan et al., 2019; McNab et al., 2013) et al., 2019; McNab et al., 2013). Chirgwin (2021) explored the obstacles faced by mine controllers while examining why technology adaptation does not reach its full potential and why there is a shortage of available candidates for autonomous control. Their results showed that the role of mine controllers has been overlooked, and more robust workplace training practices, coupled with higher education are needed (Chirgwin, 2021). Lynas and Horberry (2011) outlined the importance of considering operators and maintainers when designing and utilizing mining automation to support the workforce in their acceptance and management of the uptake of automation. Similarly, Rogers et al. (2019) discussed the social and political risks of automation in mining and argued that automation needs to be human-centered and not technology-centered, to be able to better manage practical challenges and potential disruption to the workforce that can dramatically affect work satisfaction, performance, safety, and security. McNab et al. (2013) investigated the social dimensions of autonomous and remote mining technologies in Australia and found that these technologies could change future mining workforce requirements and management, disadvantage the existing mining regions and communities, and have a disproportionate impact on Indigenous peoples. Holcombe and Kemp (2019) added to the discussion of mining automation's impacts on Indigenous peoples by arguing that there is little indication that mining is considering the potential negative impacts and suggested an urgent and careful examination of these effects. Keenan et al. (2019) argued that mining companies are projecting an "overwhelmingly positive narrative" about the new autonomous technologies they adopt and are willing to advertise their economic benefits while disregarding the impacts on local communities. The authors emphasized the need to at least identify and understand the social impacts of these new technologies and provide assurance that their use will not put host communities at risk (Keenan et al., 2019).

Only a couple of studies have discussed the contributions to sustainable development or the SDGs. Brueckner et al. (2013) explored the contribution of mining to sustainable development in Western Australia by focusing on the economic, environmental, Indigenous, and social dimensions of the mining

boom, yet automation was not included in the discussion. They found that despite the attitudinal and operational improvements, problem areas remain, and there is a need for a more balanced treatment of the positive and negative impacts of mining for a more robust assessment of mining's contribution to sustainable development in the state (Brueckner et al., 2013). In a recent paper, Endl et al. (2021) performed an exploratory and qualitative assessment of how mining innovations, including autonomous equipment and operations, can contribute to achieving the SDGs in Europe. The authors concluded that almost all innovation concepts show repercussions on individual SDGs, indicating these concepts not only portray synergies between the SDGs but also trade-offs or imbalances between individual SDGs. They also called for further research on the overall environmental impact of technological innovations (Endl et al., 2021).

There is very limited research on the estimation of GHG emissions of AHT, or on the comparison of AHT to their conventional counterparts. Moreau et al. (2020) conducted an LCA to investigate the impacts automation can have on environmental performance by using data collected on mine site productivity and energy consumption for an underground metal mine (zinc-copper-silver-gold). They compared machine fuel efficiency, mine site energy consumption, and length of mine-life for operation with either manual or automated equipment, including not only haulage trucks but also LHDs and drill rigs, to investigate their effects on the environment. Comparing automated equipment to their conventional counterpart, they found that emissions decreased by 18.3% over the mine life period, or 3.7 kg of carbon dioxide equivalent (CO₂eq.) per tonne of ore extracted. The authors concluded that the emission reduction over the mine life was mainly due to lower diesel fuel consumption in the loading and haulage processes, and a 27% shorter operational mine life leading to fewer years of operation and maintenance (Moreau et al., 2020). In another study, Parreira (2013) presented a deterministic/stochastic model to compare an AHS to a conventional system based on several Key Performance Indicators (KPIs) such as productivity, safety, breakdown frequencies, maintenance costs, labor costs, fuel consumption, tire wear, and haulage cycle times but did not account for GHG emissions. Their results showed that an AHS can increase either production or productivity by 21.3% due to increased utilization, improve fuel consumption by 5.3% for L/cycle and 6.1% for L/t, improve tire wear (mm/cycle) by 7.6%, and decrease queuing time by 28.7% compared to the conventional system (Parreira, 2013). To the best of our knowledge, no study has been conducted on GHG estimations of AHT in surface mining and how this compares to emissions from conventional trucks (CT).

In general, AHT's carbon footprint and the technology's implications for sustainable development are insufficiently explored. Further research is required to improve the understanding and quantification of the overall environmental impact of technological innovations like AHT, including in terms of GHG emissions (Brueckner et al., 2013; Endl et al., 2021). Our study addresses these gaps and recommendations by proposing a GHG emission estimation methodology for AHT, and by mapping the potential opportunities and challenges posed by utilizing AHT in terms of contributing to the SDGs.

4.4. Methodology

In this study, we first collected data related to the selected mine site and its haulage truck fleet, truck fuel rates, and benchmark values for Time Usage Model (TUM) elements (Figure 4.1). We then calculated GHG emissions generated by haulage first for the autonomous (current) state, and then for the conventional state, in which the same annual production would be achieved by utilizing conventional trucks (CT) instead of the current autonomous haulage trucks (AHT). We assessed the uncertainties in emission estimations due to varying truck fuel rates. Finally, we conducted scenario analyses where we discussed net-zero haulage technology options for our case study.

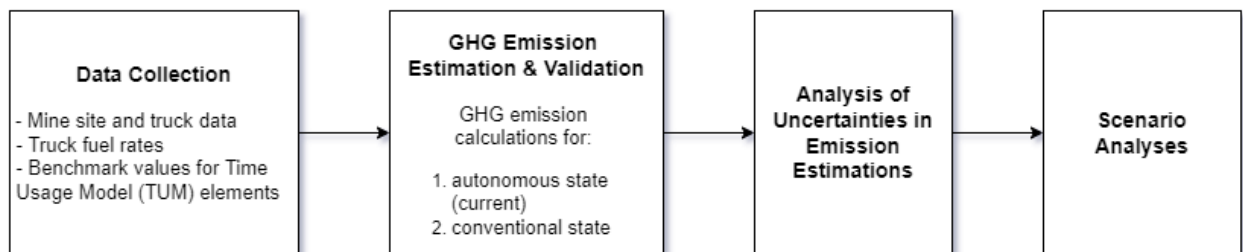


Figure 4.1. Research methodology flowchart

4.4.1. Data Collection

4.4.1.1. Mine Site and Truck Data

Before starting data collection, we needed to identify an open-pit iron ore mine that is currently active and in the operation stage for our case study. For this, we first purchased a dataset from GlobalData¹⁵ (GlobalData, n.d.), which included information on currently active iron ore mines around the world. The dataset included the projects' locations, ownership, ore grade, annual saleable iron ore production and the amount of material moved in terms of run of mine (ROM) and overburden, surface mining machinery (equipment type, make, and model), among others. However, all these data fields were not available for every mine site in the GlobalData dataset. Eventually, we selected the "*Rachel Mine*"¹⁶ since its full equipment and material movement data was accessible and it had an autonomous haulage truck fleet with all trucks being of the same make and model, which was important for our GHG estimation process. Table 4.1 shows the data from the Rachel Mine that we used in our study. It is important to note that the data we used for Rachel Mine was from GlobalData as of April 2022.

¹⁵ GlobalData Plc is a data analytics and consulting company, headquartered in London, UK. The company provides comprehensive datasets for several sectors, including mining

¹⁶ Rachel Mine is the name we chose to refer to the mine site we identified for this study. We cannot provide the actual name of the selected mine site for confidentiality purposes.

Table 4.1. The data we used in our calculations for Rachel Mine (source: GlobalData)

Mining type	Location	ROM (2020) (MTPA)	Overburden (2020) (MTPA)	Number of haulage trucks	Make and model of haulage trucks	Haulage trucks' size (metric tons)
Surface /Open cut	Western Australia	55.783	61.361	52	CAT 793F CMD - Autonomous	232

4.4.1.2. Truck Fuel Rates

For our GHG emission calculations, we needed the CAT 793F CMD autonomous trucks' fuel consumption rates for i) idling state, ii) under full load, and iii) unloaded (empty) state. Since these data are hard to find in the literature or in manufacturers' catalogs, we used the best available data as reference values. Parreira (2013) provided fuel consumption rates measured for CAT 793D for a major international mining company's surface mine. CAT 793D is the predecessor of CAT 793F. The 793F model has an engine with a slightly higher horsepower (2,650 hp) than the 793D (2,415 hp), and a faster top speed (Baltazar, 2012). Other than these differences, the two trucks have identical payload and bodyweight (Caterpillar, n.d.), so we used the fuel rates provided by Parreira (2013) as shown in Table 4.2. Production fuel consumption rates were calculated by taking the average of fully loaded and empty fuel rates with the assumption that trucks travel under full load 50% of the time in a production (haulage) cycle and travel empty in the remaining 50%.

Table 4.2. AHT and CT fuel consumption rates (values taken from Parreira, 2013)

Parameter	Unit	AHT	CT
Fuel Rate - Idling	L/hour	27.0	26.6 – 27.0
Fuel Rate - Under full load	L/hour	381.48	384.19 – 384.44
Fuel Rate - Unloaded (empty)	L/hour	69.5	77.8 – 80.8
Fuel Rate - Production	L/hour	225.49	230.995 – 232.62

4.4.1.3. Benchmark Values for Time Usage Model (TUM) Elements

In an operational surface mine site, *haulage* is the process of moving material (i.e., the desired economic quantity or overburden) via haul trucks from one point to another (Marshall et al., 2016). In a surface mine, broken rocks are often excavated by either *front-end loaders*, *excavators*, or *shovels*, and loaded into *haul trucks* to be transferred to the processing plant or to stockpiles, depending on the load in the truck (Marshall et al., 2016; Norgate & Haque, 2010). The size of the haulage fleet (i.e., the number of haulage equipment) mainly depends on the amount of annual production. Rachel Mine's haulage fleet consists of five loaders, eight excavators, and 52 haul trucks, for an annual production of 45.096 MTPA in 2020.

The round trip a haul truck makes during haulage is called the *truck (haulage) cycle*. Haul trucks perform certain cycle activities including traveling empty, queuing empty, spotting empty, loading,

traveling under full load, queuing under full load, spotting under full load, and dumping (Figure 4.2). The duration of these activities varies depending on the nature of the mine, truck type and size, payload, road conditions, operator performance, and others. The sum of the time spent on truck cycle activities is referred to as the *truck cycle time*. A haul truck must be performing one of these activities to be *productive* unless it is mechanically down or on delay for various reasons (Yildirim, 2021).

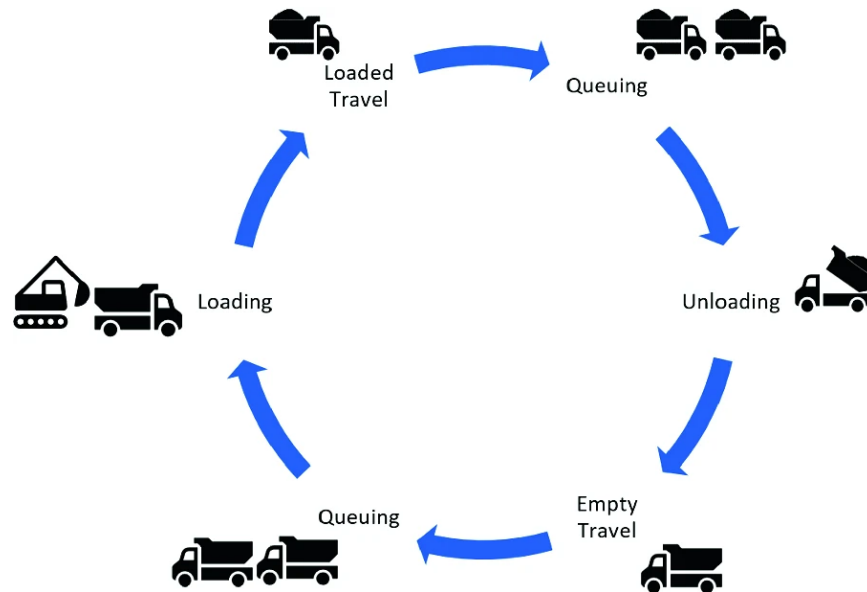


Figure 4.2. Truck cycle activities (Source: Soofastaei et al., 2016)

An optimized arrangement of truck cycle activities is critical in a mining operation for efficient haulage and to minimize the time lost in non-productive time elements. Autonomy reduces the time when the truck is not performing its principal activity (i.e., *idling*) despite being available to operate (Miller, 2022). With this system change, autonomy mainly improves the productivity of a mining operation by decreasing idling time and increasing the time spent on production (Keenan et al., 2019). Increased productivity and decreased costs are among the reasons behind the high demand for autonomy in iron ore mining, where the ore production amounts, and competitiveness are quite high. We acknowledge that autonomy provides other indirect benefits such as increased safety and decreased maintenance cost and time; however, we only focus on the direct operation aspects in this study to highlight GHG emissions from haulage trucks.

Since autonomy mainly impacts the operation in terms of how time is used, we based our calculations on Time Usage Model (TUM) elements. TUM is a time classification framework of common surface mining operational activities, which begins with Calendar Time (CT) and follows by removing non-value-generating time elements (Figure 4.3). In this study, we used the TUM proposed by the Global Mining Guidelines Group (GMG) (GMG, 2020). When autonomy is introduced to base conventional trucks, 20% more calendar hours become available for an operation by immediately removing human-related factors

such as shift changes, brakes, trainings, and meetings (Miller, 2022). Moreover, it is difficult to fairly compare the performance of CT to that of AHT outside of TUM element comparisons since fuel consumption is too complex and depends on several parameters related to road conditions, driver behavior and other human factors, tire wear, swell factor, gear selection, temperature, and others (Kubler, 2015; Parreira, 2013; Soofastaei, 2016)

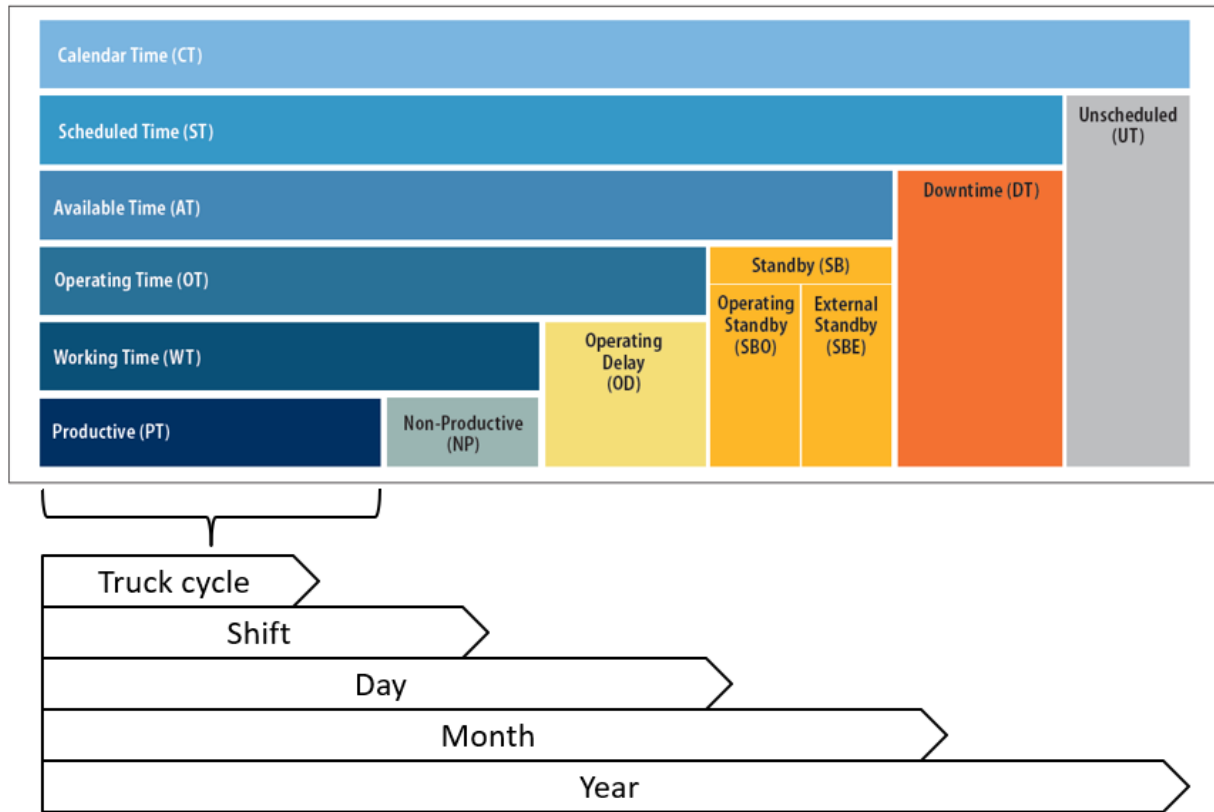


Figure 4.3. Time Usage Model (TUM) (adapted from GMG, 2020, not to scale)

Benchmark data is often utilized for mining feasibility or modeling studies (Miller, 2022), yet it is challenging to find publicly available data that compares the TUM elements for CT and AHT. In this study, we used the benchmark TUM values in Table 4.3 for our GHG emission estimations, which we obtained through personal communication with an expert in this field (Miller, 2022). These benchmark data are rather generic but represent a reasonable basis for comparison of conventional haulage operations to AHS operations (Miller, 2022). They consist of quartile benchmark data for conventional trucks, which have varying idling and productive TUM elements, versus benchmark data for autonomous trucks (Table 4.3).

Table 4.3. Benchmark TUM element values for CT and AHT (adapted from Miller, 2022)



TUM Elements	Unit	CT				AHT
		25th	50th	75th	Best Practice	
Calendar Time (CT)		8,760	8,760	8,760	8,760	8,760
Unscheduled Time (UT)		-	-	-	-	-
Scheduled Time (ST)		8,760	8,760	8,760	8,760	8,760
Downtime (DT)		1,560	1,460	1,360	1,160	1,350
Available Time (AT)	hours	7,200	7,300	7,400	7,600	7,410
Standby (SB)*	/truck	1,100	950	750	770	210
Operating Time (OT)	/year	6,100	6,350	6,650	6,830	7,200
Operating Delay (OD)*		1,500	1,150	850	730	400
Working Time (WT)		4,600	5,200	5,800	6,100	6,800
Non-Productive Time (NP)*		320	260	170	180	160
Productive Time (PT)		4,280	4,940	5,630	5,920	6,640

* TUM elements when the trucks are *idling*, or not performing productive activity.

4.4.2. GHG Emission Estimation and Validation

4.4.2.1. GHG Emission Estimations

We followed the following steps in our GHG emission calculations for both autonomous and conventional states:

1. Calculation of annual fuel consumption of trucks based on TUM elements:

Fuel consumption of trucks is needed as an input “activity data” for the GHG emission estimation formula in Equation 4.5. The annual fuel consumption of trucks was calculated based on TUM elements by applying Equations 4.1 through 4.9. Annual fuel consumption was the summation of fuel consumed during productive time (Equation 4.2) and fuel consumed during idling hours (i.e., standby (SB), operating delays (OD), and non-productive time (NP)) (Equations 4.3 and 4.4).

$$\begin{aligned} & \text{Annual fuel consumption} \\ & = \text{Annual NPF consumption} + \text{Annual PF consumption} \end{aligned} \tag{4.1}$$

$$\text{Annual PF consumption} \left(\frac{L}{\text{truck} * \text{year}} \right) = \text{Productive Time (PT)} \times X \frac{L}{\text{hour}} \tag{4.2}$$

$$\text{Annual NPF consumption} \left(\frac{L}{\text{truck} * \text{year}} \right) = \frac{\text{Idling hours}}{\text{year}} \times Y \frac{L}{\text{hour}} \quad (4.3)$$

$$\text{Idling hours} = SB + OD + NP^* \quad (4.4)$$

*TUM elements vary for the CT for each quartile benchmark data

Where:

Annual NPF Consumption = Annual non-productive fuel consumption (i.e., fuel consumed by trucks during non-productive activities such as time spent on standby or operating delay) in liters per truck per year

Annual PF Consumption = Annual productive fuel consumption (i.e., fuel consumed by trucks during productive activities) in liters per truck per year

$X \frac{L}{\text{hour}}$ = Production fuel rate in liters per hour (For CT, the average value was taken ($X_{CT,avg} = 231.81$ L/hour - Table 4.2)

$Y \frac{L}{\text{hour}}$ = Idling fuel rate in liters per hour (For CT, the average value was taken ($Y_{CT,avg} = 26.8$ L/hour - Table 4.2)

The annual amount of material moved via haul trucks was calculated in terms of the ROM and overburden (Equation 4.5), since in a truck cycle, a haul truck moves economically valuable material as well as mine waste (i.e., overburden). The calculated tons of material moved were then used to achieve fuel consumption per ton of material moved (Equations 4.7 to 4.9).

$$\text{Annual tons of material moved} \left(\frac{\text{tons}}{\text{year}} \right) = ROM \left(\frac{\text{tons}}{\text{year}} \right) + \text{Overburden} \left(\frac{\text{tons}}{\text{year}} \right) \quad (4.5)**$$

$$\text{Annual tons of material moved per truck} \left(\frac{\text{tons}}{\text{truck} * \text{year}} \right) = \frac{\text{Annual tons of material moved}}{\# \text{ of trucks}} \quad (4.6)$$

**The number of trucks for the conventional state was modified in line with the Operating Efficiency (OE) = WT/OT for each quartile benchmark data.

$$\begin{aligned} &\text{Fuel consumption per ton of material moved} \\ &= \text{NPF consumption per ton} + \text{PF consumption per ton} \end{aligned} \quad (4.7)$$

$$\begin{aligned}
& \text{NPF consumption per ton} \left(\frac{L}{\text{ton}} \right) \\
& \text{NPF consumption} \left(\frac{L}{\text{truck} * \text{year}} \right) \\
= & \frac{\text{NPF consumption per ton} \left(\frac{L}{\text{ton}} \right)}{\text{Annual tons of material moved per truck} \left(\frac{\text{tons}}{\text{truck} * \text{year}} \right)} \tag{4.8}
\end{aligned}$$

$$\begin{aligned}
& \text{PF consumption per ton} \left(\frac{L}{\text{ton}} \right) \\
& \text{PF consumption} \left(\frac{L}{\text{truck} * \text{year}} \right) \\
= & \frac{\text{PF consumption per ton} \left(\frac{L}{\text{ton}} \right)}{\text{Annual tons of material movement per truck} \left(\frac{\text{tons}}{\text{truck} * \text{year}} \right)} \tag{4.9}
\end{aligned}$$

2. Estimation of GHG Emission Intensity:

We estimated GHG emissions based on Equation 4.10, which is from an Australian Government guideline to assist entities to comply with their reporting obligations under the National Greenhouse and Energy Reporting Act 2007 (NGER Act) and associated legislation (Australian Government, 2021a).

$$E_{ij} = \frac{Q_i \times EC_i \times EF_{ijoxec}}{1,000} \tag{4.10}$$

where:

E_{ij} is the emissions of gas type (j), carbon dioxide, methane, or nitrous oxide, from fuel type (i) (CO₂eq tonnes).

Q_i is the quantity of fuel type (i) (kiloliters) combusted for transport energy purposes

EC_i is the energy content factor of fuel type (i) (gigajoules per kiloliter or per cubic meter) used for transport energy purposes.

EF_{ijoxec} is the emission factor for each gas type (j) (which includes the effect of an oxidation factor) for fuel type (i) (kgCO₂eq/GJ) used for transport energy purposes.

Adapting Equation 4.10, we estimated GHG emission intensities (i.e., emissions per ton of material moved) with the following calculations:

$$\begin{aligned}
& \text{GHG emissions per ton} \\
= & \text{Non – productive GHG Emission Intensity} \\
& + \text{Productive GHG Emission Intensity} \tag{4.11}
\end{aligned}$$

$$\begin{aligned}
& \text{Non – productive GHG Emission Intensity} \left(\frac{\text{kgCO}_2\text{eq}}{\text{ton material moved}} \right) \\
& = \text{NPF consumption per ton} \left(\frac{\text{L}}{\text{ton}} \right) * EC_{\text{diesel}} * \frac{EF_{\text{CO}_2} + EF_{\text{CH}_4} + EF_{\text{N}_2\text{O}}}{1000}
\end{aligned} \tag{4.12}$$

$$\begin{aligned}
& \text{Productive GHG Emission Intensity} \left(\frac{\text{kgCO}_2\text{eq}}{\text{ton material moved}} \right) \\
& = \text{PF consumption per ton} \left(\frac{\text{L}}{\text{ton}} \right) * EC_{\text{diesel}} * \frac{EF_{\text{CO}_2} + EF_{\text{CH}_4} + EF_{\text{N}_2\text{O}}}{1000}
\end{aligned} \tag{4.13}$$

where;

$EC_{\text{diesel}} = 38.6 \text{ GJ/kL}$,
 $EF_{\text{CO}_2} = 69.9 \text{ kgCO}_2\text{eq/GJ}$
 $EF_{\text{CH}_4} = 0.1 \text{ kgCO}_2\text{eq/GJ}$
 $EF_{\text{N}_2\text{O}} = 0.4 \text{ kgCO}_2\text{eq/GJ}$ (Australian Government, 2021b)

We should emphasize here that this study focuses on GHG emissions from haulage trucks, hence we only focus on Scope 1 emissions. Scope 2 or 3 emissions are not within the scope of this study.

4.4.2.2. Validation of GHG Emission Estimations

For validation purposes, we compared our GHG estimation against reported site-level Scope 1 emission data. The amount of publicly available data in this area is very limited and reporting is inconsistent and not transparent. Even if Scope 1 emissions are reported at site level, it is not broken down into operation-level (i.e., haulage, drilling, blasting, etc.). For this reason, we used the best available data to approximate a ratio of diesel-sourced hauling emissions to Scope 1 mining emissions from a recent McKinsey article (Legge et al., 2021, Exhibit 2), which was $31/63 = 49.2\%$. Reported Scope 1 emission data for each mine site were weighted according to this ratio and to the annual tons of material moved. For confidentiality purposes, the names of the compared mine sites will not be shared, but their reported Scope 1 emissions were found from the CDP¹⁷ database, from their responses to the Climate Change Questionnaire, where available (CDP, n.d.). Access to these reports requires a membership account, so we cannot cite these reports at this time.

4.4.3. Analysis of Uncertainties in Emission Estimations

We made our GHG emission estimations for the conventional state by using the average values for idling and production fuel rates. After GHG emission estimation and validation, we analyzed the uncertainties in our emission estimations due to varying truck fuel rates.

¹⁷ CDP is an international non-profit organization based in the UK that provides a global disclosure platform for investors, companies, cities, states, and regions to manage their environmental impacts.

The analysis was performed by using probabilistic analysis, which is commonly used in the presence of uncertainty in input data required for determining the best estimate of a value. It is a technique to quantify the impact of these uncertainties on results and to establish a range of possible outcomes instead of a single deterministic solution. To do this, we calculated the GHG emissions estimations for the conventional state with i) upper (X_u) and lower (X_l) limit values in our fuel rate range, as well as with ii) mean fuel rates based on five different probability distribution functions (P.D.F.s): uniform distribution (UD), symmetric triangular distribution (STD), upper triangular distribution (UTD), lower triangular distribution (LTD), and truncated normal distribution (TND) (Figure 4.4). A P.D.F. is a statistical function that describes all the possible values and likelihoods that a random variable can take within a given range bounded between the upper and lower limits (Etkin et al., 2017; Hayes, 2022). Among these P.D.F.s, UD, STD, and TND implicitly assume that any value over a specified range is equally likely, or there is no bias within the prescribed range of values. In contrast, the skewed P.D.F.s (i.e., UTD or LTD) assume that there is a bias towards the smaller or larger values (Duzgun et al., 2002). We also calculated the coefficients of variation (c.o.v.'s) for each P.D.F., which is a dimensionless measure that is commonly used in engineering to quantify uncertainties (Duzgun et al., 2002).


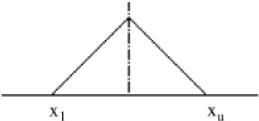
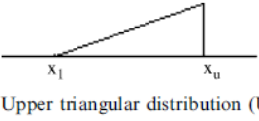
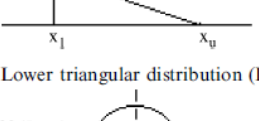
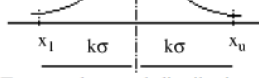
P.D.F.	Mean value, \bar{X}	c.o.v., δ_x or A_x
 Uniform distribution (UD)	$1/2(x_l + x_u)$	$\frac{1}{\sqrt{3}} \left(\frac{x_u - x_l}{x_u + x_l} \right)$
 Symmetric triangular distribution (STD)	$1/2(x_l + x_u)$	$\frac{1}{\sqrt{6}} \left(\frac{x_u - x_l}{x_u + x_l} \right)$
 Upper triangular distribution (UTD)	$1/3(x_l + 2x_u)$	$\frac{1}{\sqrt{2}} \left(\frac{x_u - x_l}{2x_u + x_l} \right)$
 Lower triangular distribution (LTD)	$1/3(2x_l + x_u)$	$\frac{1}{\sqrt{2}} \left(\frac{x_u - x_l}{x_u + 2x_l} \right)$
 Truncated normal distribution (TND)	$1/2(x_l + x_u)$	$\frac{1}{k} \left(\frac{x_u - x_l}{x_u + x_l} \right)$

Figure 4.4. The means and c.o.v.'s for different PDFs (Source: Duzgun et al., 2002)

4.4.4. Scenario Analysis

In this last step, we briefly discussed a “net-zero haulage” scenario, where the same annual production would be achieved by utilizing li-ion battery electric trucks or hydrogen-battery trucks instead of the current AHT. By assuming truck-excavator matching, and by using the truck capacities of the

commercially utilized li-ion battery and hydrogen-battery trucks, we calculated the required number of trucks, and we discussed the feasibility of utilizing these trucks on Rachel Mine.

4.5. Results

4.5.1. GHG Emissions for Autonomous vs. Conventional States

Our GHG emission estimation for the current autonomous state of Rachel Mine showed that the mine's current AHT fleet generated **1.831 kgCO₂eq/ton material moved** for the year 2020, of which 0.025 kgCO₂eq/ton material moved were non-productive GHG emissions (Figure 4.5).

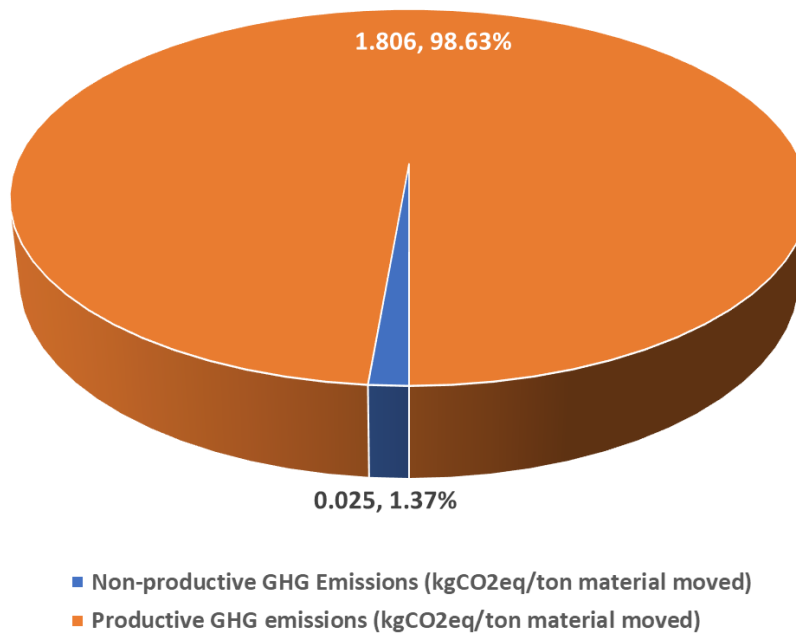


Figure 4.5. Breakdown of the Estimated GHG Emissions for Autonomous State (Current - 52 AHT)

Our GHG emission estimation results for the conventional and autonomous states are shown together in Figure 4.6. Accordingly, to be able to achieve the same amount of production, or material movement in the conventional state, 55 to 65 CT are needed, depending on the TUM element values. In general, with less productive and more idling time, more trucks are needed to obtain the same amount of material movement, and vice versa. With best practice TUM benchmark values, which represent utilizing the most productive time and the least idling time, 55 CT would be needed. On the other hand, for the 25th percentile benchmark values, which denotes the least productive and the most idling time, 65 CT would be needed.

Overall, the conventional state would result in lower *total* GHG emissions per ton of material moved for all benchmark TUM values compared to the current autonomous state. However, the conventional state would result in 2.3 to 4.7 times more *non-productive* GHG emissions compared to the autonomous

state. The more hours spent in the idling TUM elements (i.e., standby, operating delay, and non-productive time), the more *non-productive* emissions would be generated. Similarly, the more hours spent in productive time (PT), the more *productive* emissions would be generated.

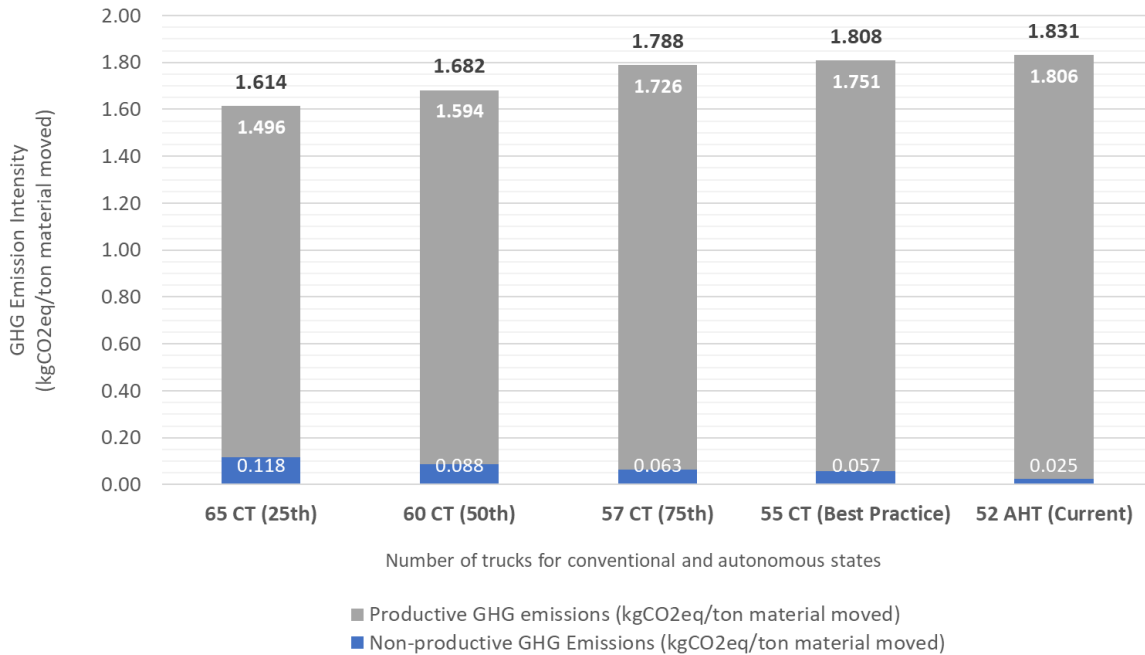


Figure 4.6. GHG Emission Estimations for Conventional and Autonomous States and Their Breakdown

4.5.2. Validation Results

The validation results for our GHG emission estimations for the autonomous state are shown in Table 4.4. Mines A, B, and C are surface iron ore mines in Australia that are also operating an autonomous haulage truck fleet. The values in the table show the reported emissions of Mines A, B, and C weighted according to their annual amounts of material movement.

Table 4.4. Validation Results for the Autonomous State

	Scope 1 Emissions due to Haulage (tCO ₂ eq/year)	Scope 1 Emissions Intensity due to Haulage (kgCO ₂ eq/ton of material moved)	Difference from our estimation
Our Estimation for the autonomous state of Rachel Mine	214,510	1.831	<i>n/a</i>
Mine A	167,331	1.428	- 22%
Mine B	160,378	1.369	- 25%
Mine C	131,378	1.122	- 39%

Overall, our GHG emission estimations for the autonomous state were 22 to 39% higher than the reported emissions. The difference between our estimation and the reported emissions for mine sites with AHT fleet might be due to several reasons. To begin with, all emission estimations inherently have uncertainty to a certain degree, including variation in environmental conditions, methods, models, and assumptions used in estimations, or simply human errors (EIIP, 1996; GHG Protocol, 2003). Adding to this uncertainty, there is very limited reporting of Scope 1 emissions at the site level, and more importantly, reporting is not transparent in terms of the breakdown of Scope 1 emissions, which makes comparisons even more difficult. Finally, we only had one set of benchmark values for TUM elements for AHT (Table 4.3), unlike the quartile benchmark data for conventional haulage. Therefore, utilization of the TUM elements in Mines A, B, and C, might be different from the benchmark values we used in our estimations for Rachel Mine. Due to these reasons, although our estimations are a bit far from the reported emissions, it does not mean that our estimation is inaccurate.

The validation results for our GHG emission estimation range for the conventional state is shown in Table 4.5. The minimum and maximum values for our estimations are calculated by using the lower and upper limit values in our truck fuel rate range. All of the compared mines are surface iron ore mines that are also operating a conventional haulage truck fleet. Mines D and E are in Australia while the remaining mines are located in different countries. The values in the table show the reported emissions of Mines A, B, and C weighted according to their annual amounts of material movement. The values in the table show the reported emissions of the compared mines weighted according to their annual amounts of material movement.

Table 4.5. Validation Results for the Conventional State

	Scope 1 Emissions due to Haulage (tCO₂eq/year)	Scope 1 Emissions Intensity due to Haulage (kgCO₂eq/ton of material moved)	Difference from our estimation
Our Estimation Range for the conventional state of Rachel Mine	Min: 188,350 Max: 212,601	Min: 1.608 Max: 1.815	<i>n/a</i>
Mine D, Australia	186,524	1.592	From min: - 1% From max: - 12%
Mine E, Australia	177,250	1.513	From min: - 6% From max: - 17%
Mine F, Brazil	168,938	1.442	From min: - 10% From max: - 21%
Mine G, South Africa	105,379	0.900	From min: - 44% From max: - 50%
Mine H, India	57,638	0.492	From min: - 69% From max: - 73%
Mine J, Russia	421,690	3.600	From min: + 98% From max: + 124%

Comparison to the reported emissions of Mine D and Mine E, which are both in Australia, showed very close results with as low as a 1% difference. The comparison to Mine F in Brazil also showed relatively close results, with as low as a 10% difference. However, our results were much higher than that of Mine G in South Africa and drastically different than the mines in India and Russia. These results are consistent with the graph in Figure 4.7, which demonstrates the ranges of reported Scope 1 emissions by country. The graph shows that there are significant differences and uncertainties in emission reporting, both between countries and within the same country. Mine J's reported emissions value is as much as 124% higher than our estimation and is consistent with the much larger range observed in emission reporting of Russia compared to that of Australia. Similarly, our estimation is 69 to 73% higher than Mine H in India and is in line with the much lower ranges observed in India (Figure 4.7). Overall, based on the comparisons to the two mines in Australia, the results showed that our estimation method was much more accurate for the conventional state.

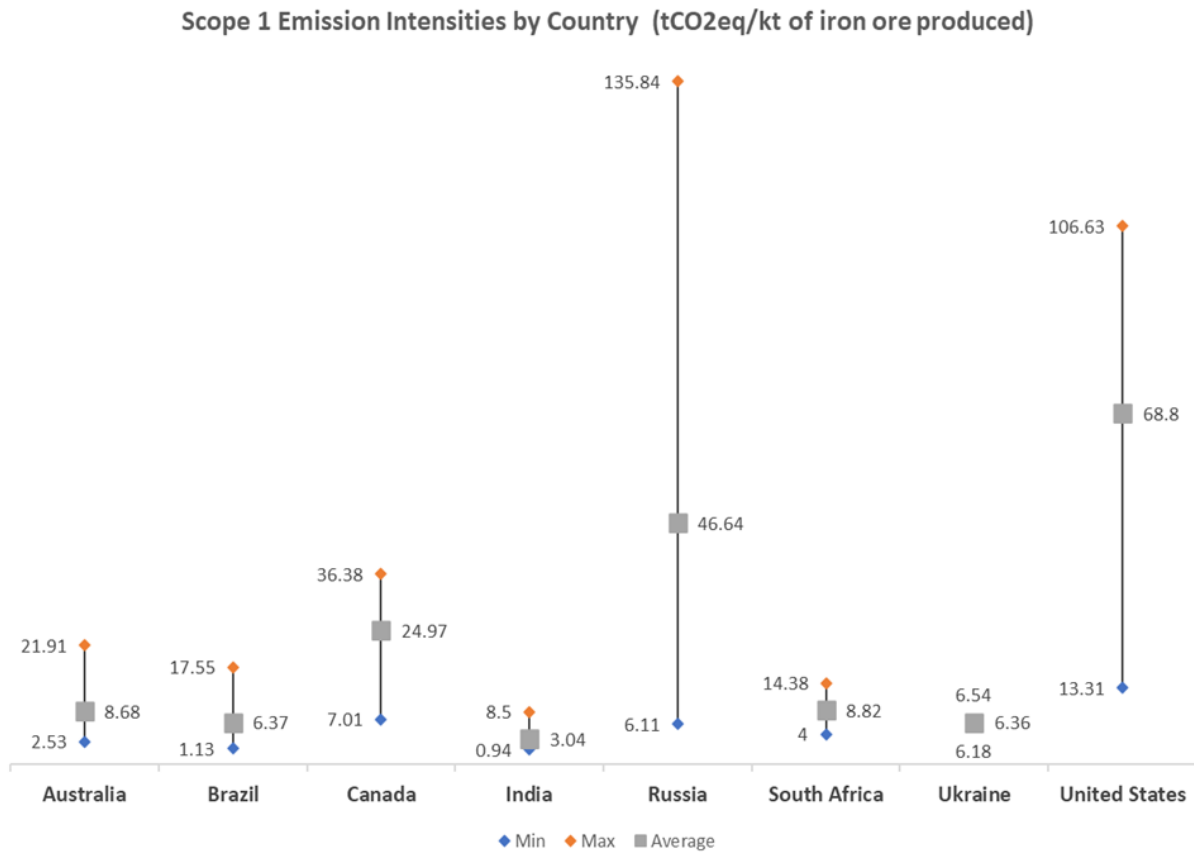


Figure 4.7. Reported Scope 1 emission intensities by country

4.5.3. Uncertainties in Emission Estimations

Table 4.6 summarizes our analysis that demonstrates the effect of changing the truck fuel rates we used in our estimations. In our estimation, we used the mean truck fuel rates by assuming a uniform distribution (UD). The results of the uncertainty analysis suggested that with varying truck fuel rates, our

GHG emission estimation for the conventional state would range between 1.608 and 1.815 kgCO₂eq/ton material moved. This tells us that even the highest possible GHG emission estimated for the conventional state (1.815 kgCO₂eq/ton material moved), was still lower than our estimation for the autonomous state (1.831 kgCO₂eq/ton material moved). Thus, our results did not change with the varied truck fuel rates in our dataset.

Table 4.6. Uncertainties in emission estimations due to varying truck fuel rates

Estimation Results for Scope 1 GHG Emissions Intensity (kgCO₂eq/ton of material moved) with mean truck fuel rates based on different P.D.F.'s and with upper and lower limit fuel rates								
Quartile Benchmarks	Uniform distribution (UD) – <i>Assumed</i>	Symmetric triangular distribution (STD)	Upper triangular distribution (UTD)	Lower triangular distribution (LTD)	Truncated normal distribution (TND)	Upper Limit Fuel Rates (Max)	Lower Limit Fuel Rates (Min)	c.o.v.'s for our estimation range
25 th Percentile (65 CT)	1.614	1.614	1.616	1.612	1.614	1.620	1.608	<ul style="list-style-type: none"> • UD: 0.035 • STD: 0.025 • UTD: 0.028 • LTD: 0.029 • TND: 0.020
50 th Percentile (60 CT)	1.682	1.682	1.684	1.680	1.682	1.688	1.676	
75 th Percentile (57 CT)	1.788	1.788	1.791	1.786	1.788	1.795	1.782	
Best Practice (55 CT)	1.808	1.808	1.810	1.806	1.808	1.815	1.802	

4.5.4. Scenario Analysis for Net-Zero Haulage

Table 4.7 summarizes the number of trucks that would be needed in Rachel Mine to achieve the same annual production if it would utilize li-ion battery trucks or hydrogen-battery trucks instead of the current AHT. The commercially available hydrogen-battery truck with the highest load capacity was the “nuGen™” with 290 tons of load capacity, which was recently launched by Anglo American in South Africa. This truck has a 25% higher capacity than the CAT 793F trucks in Rachel Mine (Anglo American, n.d.; Energy Industry Review, 2022; Moore, 2022). As a result, the required number of hydrogen trucks ranged between 44 and 52. The commercially available li-ion battery truck with the highest load capacity was the “eDumper” with 65 tons of load capacity, which is used in a quarry in Switzerland and had a 72% lower capacity than the trucks in Rachel Mine (Evarts, 2019; Moore, 2021; Rapier, 2019). As a result, the required number of li-ion battery trucks ranged between 196 and 232. It is important to note that the technologies of these zero-emission haulage trucks are still being developed and they are not yet operated autonomously (Moore, 2022).

Table 4.7. Results of Scenario Analysis

Quartile Benchmarks	Number of trucks for different scenarios			
	Conventional State	Hydrogen-battery Trucks	Li-ion battery Trucks	Autonomous State (Current)
25th Percentile	65	52	232	
50th Percentile	60	48	214	52
75th Percentile	57	46	203	
Best Practice	55	44	196	

The results indicate that zero-emission haulage with li-ion trucks would not be feasible since 196 or 232 trucks would result in significant costs. Also, producing this size of the fleet would result in a considerable amount of life cycle emissions. The hydrogen-battery trucks look more promising as they have a high capacity. Still, this is a very recent technology that has just started to be used, and its impacts on the field are yet to be discovered. Furthermore, hydrogen-battery trucks need to be operated autonomously to achieve the maximum safety, utility, and efficiency possible. All in all, the mining industry is making efforts in this area, but zero-emission haulage technologies still need to be researched and improved to be efficiently and feasibly utilized in surface iron ore mines.

4.6. Discussion

4.6.1. Assessment of Low-Carbon Haulage Strategies and Implications for the SDGs

Our GHG emission estimations for Rachel Mine showed that in contrast to the common claims, automation is not a better low-carbon strategy than conventional haulage. Although automation significantly decreased the idling time and the associated *non-productive* GHG emissions, the total Scope 1 GHG emissions generated with the AHT fleet were higher than a CT fleet with the data we used as input parameters in our study. Although the impact of trucks' idling on their overall Scope 1 emissions seems negligible, some might refer to these non-productive emissions as "unnecessary emissions" into the environment from time spent on non-productive activities (Wellman, 2022). With these results, our hypothesis was partially confirmed since AHT resulted in less *non-productive* emissions, but more overall emissions compared to CT.

The results depict a dual impact in terms of contributions to SDG 12 (Responsible Consumption and Production, and SDG 13 (Climate Action). AHT can positively contribute to both SDGs by resulting in less non-productive emissions compared to CT, and a negative contribution to both SDGs by leading to higher overall emissions. Although we found that AHT results in higher overall haulage emissions per ton of material moved, AHT has been shown to improve fuel efficiency and lead to lower fuel rates than CT by delivering more efficient and consistent driving behavior by eliminating the human factor (Parreira, 2013). This might represent a strength for contribution toward SDG 7 (Affordable and Clean Energy).

We acknowledge that our study considered only Scope 1 emissions due to the diesel consumption of haulage trucks in the Rachel Mine and not Scope 2 or Scope 3 emissions, for which this analysis could yield different results. Autonomy reduces the workforce on-site and results in smaller mining camps and less fly-in fly-out movement of the workforce (Bellamy & Pravica, 2011; Miller, 2022), and hence could indirectly contribute to reductions in Scope 2 and Scope 3 emissions of a mine site.

Although the net-zero haulage technologies like the li-ion and hydrogen-battery trucks could theoretically contribute positively to SDG 7, 12, and 13, these are very new technologies that still need to be studied more in-depth to be commercially available, and safely and efficiently utilized in surface mines. In general, it takes around seven to ten years for new technology equipment to be developed and commercialized (Bellamy & Pravica, 2011), but with the global shift to cleaner energy and stricter strategies and policies, we might anticipate faster results. Fortunately, some mining companies and equipment manufacturers have started to take action toward a carbon-neutral future for mining and make more investments in the research and development of technological solutions like net-zero haulage trucks (Das, 2021; FMG Fortescue, 2022; Fortescue Future Industries, n.d.; Sánchez & Hartlieb, 2020b). If more companies follow their lead, the mining industry would contribute positively to SDG 9 (Industries, Innovation and Infrastructure); and to SDGs 7, 12, and 13 if such net-zero technologies are soon utilized in mines.

4.6.1.1. The Uncertainties in Emissions Reporting and the Need for Increased Transparency

Despite the increased commitment of mining companies to sustainability and reporting practices, there are still areas of improvement in terms of consistent and transparent provision of more detailed environmental data (Perdeli Demirkan et al., 2021; Tost et al., 2018). As also mentioned in our validation results, all emission calculations naturally have uncertainty (EIIP, 1996; GHG Protocol, 2003). Even though we observed that companies started reporting more at the site level in recent years to platforms like CDP, there is still very limited reporting of Scope 1 emissions at the site level. This is because emissions reporting to CDP is voluntary and access to these reports is relatively difficult since CDP requires a membership account with a quota to provide free access to these reports. More importantly, reporting is not transparent in terms of the breakdown of Scope 1 emissions into processes like drilling, hauling, etc. These issues in emissions reporting significantly limit the ability to compare reported company data with research data, as also emphasized by other researchers (Tost et al., 2018). We believe that there is a need for more transparency, consistency, and granularity in emissions reporting at the mine site level or preferably operation-level to better support research, modeling, and policy making of low-carbon mining strategies (Tost et al., 2018). More detailed and consistent reporting on *emissions* might serve mining companies better in demonstrating their commitment to improving capacity for climate change mitigation and aligning with the intended nationally determined contributions (INDCs) of the countries they operate in, which might provide a strength to contribute to SDG 13 (Climate Action) (UNDP, 2016). This might also lead to an increased opportunity to better identify and address the focus

areas to achieve the SDGs, and by building more detailed and robust data collection and reporting capacity, mining might improve its contribution to SDG 17 (Partnership for the Goals) (UNDP, 2016).

4.6.2. Broader Impacts of AHT and Implications for the SDGs

Even though our estimations in this study focused on emissions, AHT also have broader social and economic implications. While AHT could provide substantial benefits, including improved operational efficiencies, reduced operating costs, and increased workplace safety (Holcombe & Kemp, 2019; Marshall et al., 2016; Parreira, 2013; Parreira et al., 2009), there are also some common concerns around their large-scale uptake as they might lead to some undesired social impacts on employees and communities (Holcombe & Kemp, 2019; McNab et al., 2013).

4.6.2.1. Workplace Safety

The majority of the mining accidents and fatalities are caused or triggered by human action such as operator errors, violation of rules, use of alcohol, fatigue, and inadequate maintenance or pre-operational checks (Bellamy & Pravica, 2011; Lenné et al., 2012; Patterson & Shappell, 2010; Ruff et al., 2010; Zhang et al., 2014). Moreover, 25% of mine worker injuries and fatalities occur during maintenance and repair of machinery (Löw & Nygren, 2019). Haul trucks are an important part of this picture since they were involved in 42% of the accidents and 60% of the fatalities in surface mining between 1989 and 1991 (Marshall et al., 2016). Haul trucks' potential collision with one another or with other equipment may lead to fatalities (Bellamy & Pravica, 2011).

By reducing human exposure to operational dangers and other risk factors, mine site automation can lead to reduced on-site safety risks and incidents and improve workplace safety (Bellamy & Pravica, 2011; Holmes et al., 2022; Keenan et al., 2019; Knights & Yeates, 2021; Lever, 2011; McNab et al., 2013). This is also reflected in the reported mining incidents since BHP reported that operation of AHT decreased safety accidents arising from CT by 80% in their Jimblebar iron mine in Australia (Jang & Topal, 2020).

Nevertheless, AHT comes with new challenges related to workplace safety that still need to be addressed. AHT are complex robots with sophisticated software, and they are different in many ways from CT, which require proper and continuous training and education to change people's perceptions and help workers adjust to this new technology (Parreira, 2013). A sudden introduction of automation to a mine could create confusion and lead to more safety problems due to a lack of awareness and training. To avoid this, often a staged introduction of AHT is recommended where AHT are isolated from the CT, and the workers are allowed to gradually adapt to new technical and safety procedures (Parreira, 2013). System failures might be another technological challenge for AHT as they may result in injuries, loss of containment of toxic or flammable materials, or catastrophic rupture of equipment (Lynas & Horberry, 2011). For example, the collision protection system and wireless networks are quite sensitive and can be easily influenced by dust, vibration, and poor weather conditions. Hence, the operation of AHT must be

planned considering the weather forecast, and truck operators must always be on standby (Jang & Topal, 2020). There have been a few accidents related to AHT to date. In 2014, a collision occurred between AHT and a human-driving water car at the Jimblebar iron mine of BHP due to the failure of the remote operations center to update the route for AHT. Another accident occurred at FMG's Christmas Creek iron mine in 2019 due to a Wi-Fi network connection problem on site. Finally, an AHT slid off from its designated route due to heavy rain in 2019 at Jimblebar (Jang & Topal, 2020).

If introduced gradually and by providing the necessary training and education, and if implemented carefully by following best practices, AHT might contribute positively to SDG 3 (Good Health and Well-being) by ensuring safer working conditions and leveraging commitment to workplace safety (Endl et al., 2021). Then again, if the necessary precautions are not taken and the AHT fleet is poorly managed, it might impede the achievement of SDG 3.

4.6.2.2. Employment

Automation might potentially have multi-faceted impacts on employment. It might lead to changes in i) employment conditions, by reducing operator salaries due to lower risk, reducing the need for fly-in fly-out workforce, and requiring less physical nature of work; ii) location of work by increasing remote and urban-based roles and decreasing the number of on-site roles, and iii) nature of work by reducing in-pit and operator roles and requiring higher-order workforce skills like data management and systems approach (McNab et al., 2013; Rogers et al., 2019).

Jobs related to haul truck operation account for the highest number of workers on-site and more than 70% of the jobs in a typical large surface mine together with jobs related to drilling, blasting, and train operating (Bellamy & Pravica, 2011; Holcombe & Kemp, 2019; Rogers et al., 2019). The haul truck operator role might be the most impacted role by automation (Rogers et al., 2019). AHT could result in a 50 to 75% decline in the trucking workforce since operators undertake multiple tasks at the same time and the shift changes are removed (Bellamy & Pravica, 2011; Matysek & Fisher, 2016; McNab et al., 2013; Miller, 2022). The truck operator role is likely to disappear over the long term (McNab et al., 2013).

New roles related to equipment maintenance, data and systems analysis, operational control, and mine planning are likely to emerge with AHT (McNab et al., 2013). These roles could include controllers, dispatchers, builders, pit controllers, supervisors, and wireless technicians, and to a certain degree, might be able to be filled with former truck operators (Bellamy & Pravica, 2011; Miller, 2022). However, the overall workforce size is likely to be significantly reduced (Bellamy & Pravica, 2011; Miller, 2022) unless, as claimed by some mining companies, the size of the operation grows and former workers are upskilled and retrained to service and maintain the new technology (Keenan et al., 2019; Matysek & Fisher, 2016). If a company intends to expand operations with automation, it should plan a long-term employment scheme that reflects the evolving positions to enable a smoother and more successful transition and growth (Parreira et al., 2009).

The new roles introduced with AHT require many different competencies compared to more conventional and lower-skilled roles, such as knowledge and skills in science, mathematics, and information technology (Bellamy & Pravica, 2011; Matysek & Fisher, 2016). Former lower-skilled workers need to be upskilled by mining companies to retain their employment and benefit from higher quality jobs, increased workplace safety, and better pay and rosters introduced with AHT (Bellamy & Pravica, 2011; EY, 2019; Matysek & Fisher, 2016). Therefore, mining companies should identify and provide the necessary training to upskill their personnel, yet some issues have been found recently with technology integration and the job design and training of mine controllers (Chirgwin, 2021). Accordingly, mining companies need to develop more robust workplace training practices to ensure the availability of adequate and relevant skills among their workforce for an ever-changing and technology-intensive future (Chirgwin, 2021; Parreira et al., 2009). Successful implementation of AHT also requires its gradual and careful introduction to support workplace culture and acceptance of these new technologies (Keenan et al., 2019; Lynas & Horberry, 2011; McNab et al., 2013). Employees should understand and adopt the benefits and risks of automation to avoid significant challenges related to work satisfaction, performance, and safety (Rogers et al., 2019). However, Keenan et al. (2019) suggest that there is not enough indication that mining companies are introducing AHT at a pace that considers the ability of the workforce to adapt.

Companies must understand and balance these opportunities and risks of automation with regard to employment (Parreira et al., 2009). Even though AHT might negatively contribute to SDG 8 (Decent Work and Economic Growth) by reducing the overall trucking workforce; if mining companies manage to balance these opportunities and risks, they might also contribute positively to SDG 8 by achieving higher levels of productivity through technological upgrading and innovation (UNDP, 2016), and by upskilling their workforce to match the labor market demands and support their transition to a decent job (Endl et al., 2021; UN, 2020). Training and educating the workforce in these emerging skills might also be a strength for contributing to SDG 4 (Quality Education) (Endl et al., 2021). If properly implemented, the potential benefits of these new roles, such as decreased reliance on long-distance commuting, more flexible shifts, and a safer and more professional workplace, are believed to promote the participation of women and older workers in the workforce (EY, 2019; McNab et al., 2013). This might lead to a positive contribution toward increased diversity and ensuring women's equal rights to economic resources and employment. This could help the industry contribute to SDG 1 (End Poverty), and SDG 5 (Gender Equality) (UNDP, 2016).

4.6.2.3. Community Impacts

The potential disruptions to the workforce composition from shifting to AHT might also extend to local communities (Keenan et al., 2019), especially to remote mining towns such as those that are common in Australia. Such towns traditionally attract mine workers with young families, and the presence of this residential workforce supports a related services sector in the local communities, such as transport, retail,

education, and health care (Bellamy & Pravica, 2011; Keenan et al., 2019). With AHT resulting in a downsized workforce on-site and smaller mining camps, there could be a more than 20% decline in the resident workforce population of remote mining towns, which could, in turn, affect the towns' viability by reducing the existing economic opportunities for local communities (Bellamy & Pravica, 2011; Keenan et al., 2019; McNab et al., 2013). Given that many remote mining communities already have narrow economies and limited employment opportunities, the disadvantages for these towns might be greater than expected (Keenan et al., 2019). The shift to automation might also lead to reduced goods and services required to support the mine workforce and traditional mining equipment, which are often supplied by local businesses. Although it might lead to new opportunities for local businesses related to the installation or maintenance of autonomous equipment, it is unlikely for many local businesses to readily have the capital and technical expertise needed for automation (McNab et al., 2013).

The shift to autonomous operations could also disproportionately impact Indigenous Peoples. In remote mining regions, especially in Australia and Canada, employment and other business development opportunities in mining have become an unprecedentedly important source of income for Indigenous Peoples in the last two decades (Holcombe & Kemp, 2019; McNab et al., 2013). Land use agreements between mining companies and traditional landowners in these regions often require the companies to provide employment and training opportunities for the landowners and Indigenous Peoples (McNab et al., 2013). As a result, mining has emerged as the most significant employer of Indigenous Peoples in Australia by representing 18% of their total employment between 2011 and 2016 (Holcombe & Kemp, 2019), and the majority have been employed in lower-skilled roles like truck driving (McNab et al., 2013), which is a common target of automation. Upskilling for the new roles emerging with AHT might be particularly difficult for Indigenous Peoples with lower education levels and skill sets (McNab et al., 2013). Holcombe and Kemp (2019) argue that the mining industry lacks sufficient consideration of the downsides of AHT for Indigenous Peoples and urgently call for a more careful and critical examination of these impacts.

The mine-community relations are inherently complex, and the shift to AHT is likely to further complicate these relations given the cultural barriers and fears about automation, as well as the potential for diminished economic benefits to local and Indigenous communities (Keenan et al., 2019; Parreira et al., 2009). Employment is an important contribution that mining provides to communities and is one of the cornerstones in companies' relation with communities, their reputation, and social license to operate (Parreira et al., 2009). If the complexities and downsides of AHT are not addressed properly, it may become even more difficult for companies to gain and maintain the social license to operate (Carvalho, 2017; Endl et al., 2021).

Instead of ignoring these broader community impacts of AHT, mining companies should identify, understand, and manage them to ensure that these technologies will not put local and Indigenous communities at risk (Keenan et al., 2019; Lovells, 2018). This is critical not only for the well-being of communities but also for the continuation of innovation and growth of companies. Mining companies

could alleviate these impacts by working with impacted communities to help them diversify their employment base or support human capital development in other sectors (McNab et al., 2013). Companies could also investigate the potential for enhancing Indigenous Peoples' participation in the automated workforce and plan for upskilling the existing Indigenous workers through education and training (McNab et al., 2013). Companies could also collaborate with government bodies and other local industries to broaden the range of non-mining employment and business opportunities for local and Indigenous communities or support schools in these communities as a longer-term strategy to build capacity in the skillset demanded by the emerging roles (McNab et al., 2013).

If not addressed properly, the impacts of AHT on local and Indigenous communities could be an area for improvement for mining's contributions to:

- i) SDG 8 (Decent Work and Economic Growth), by reducing employment and other economic opportunities for local communities (Bellamy & Pravica, 2011; Holcombe & Kemp, 2019)
- ii) SDG 1 (Poverty Reduction), and SDG 10 (Reduced Inequalities), by jeopardizing the recruitment and business opportunities of Indigenous Peoples, and
- iii) SDG 16 (Peace, Justice, and Strong Institutions), by making way for mine-community conflict, and risking social license to operate (Carvalho, 2017; Endl et al., 2021),

However, there are also strengths identified for mining companies to mitigate these community impacts, which might improve mining's contributions to:

- i) SDG 8 (Decent Work and Economic Growth), by helping impacted communities to diversify their employment base, or supporting human capital development in other sectors
- ii) SDG 4 (Quality Education), and SDG 10 (Reduced Inequalities), by training, recruiting, and increasing the employability of Indigenous Peoples (UNDP, 2016)
- iii) SDG 16 (Peace, Justice, and Strong Institutions), by preventing mine-community conflict, decreasing the risk for obtaining social license to operate, respecting to the rights of Indigenous Peoples, and collaborating with government or other local industries to facilitate non-mining employment and business opportunities for local and Indigenous communities (UNDP, 2016), and
- iv) SDG 1 (Poverty Reduction) by promoting inclusive recruitment including Indigenous Peoples.

4.7. Conclusions and Recommendations

We proposed a TUM-based method for estimating haulage-related Scope 1 GHG emissions for both autonomous and conventional trucks and applied our method to Rachel Mine. Comparing our estimations for AHT and CT, we determined which scenario resulted in a lower carbon footprint and might be a better low-carbon strategy for large-scale surface iron ore mining. We also discussed, at a high level, a net-zero

haulage scenario based on li-ion and hydrogen-battery haulage trucks. Our study provided potentially useful information including the strengths and weaknesses of each haulage scenario and the potential implications for contributions to sustainable development by mapping to the SDGs. We also discussed the broader socio-economic implications of AHT, including the impacts on workplace safety, employment, and local and Indigenous communities, and the related strengths and areas for improvement in terms of mining's contributions to SDGs. A detailed overview of identified strengths and areas for improvement for contributing to the SDGs at the operation level is provided in Appendix D, together with the site and corporate levels.

Our results demonstrate that AHT results in higher overall haulage emissions per ton of material moved, yet, significantly decreases *non-productive* emissions compared to CT. Our results also highlight the uncertainties in emission estimations and reporting, and that there is still very little reporting of emissions at mine site level. We contend that Scope 1 emissions should be i) reported more at the site level, ii) easier to be accessed by the public, iii) more transparent in terms of its breakdown by operation/process for better research, modeling, and policy-making purposes (Tost et al., 2018). This is critical for researchers and mining companies to better detect and address the focus areas to achieve a low-carbon future and improved contribution to SDGs 7, 12, 13, and 16. We also show that the net-zero haulage technologies like li-ion and hydrogen-battery trucks are still new and relatively undeveloped technologies that should be improved to be safely and efficiently utilized in surface mines. Indeed, some mining companies and equipment manufacturers already started to invest in the research and development of net-zero technology solutions for haulage (Das, 2021; FMG Fortescue, 2022; Fortescue Future Industries, n.d.; Sánchez & Hartlieb, 2020b), which is a strength in contributing to SDG 9.

AHT could provide several benefits and opportunities for contributing to sustainable development, such as improved workplace safety, which could be an opportunity for contributing to SDG 3. Yet, there might also be some undesired social impacts associated with the uptake of this technology on the workforce and local and Indigenous communities (Bellamy & Pravica, 2011; Holcombe & Kemp, 2019; Keenan et al., 2019; McNab et al., 2013; Rogers et al., 2019). Some researchers argue that the mining industry has been focusing on the benefits of automation technology in mining while not paying much attention to the significant risks to these people (Holcombe & Kemp, 2019; Keenan et al., 2019; McNab et al., 2013). It is critical not to overlook these social impacts and risks in “the rush to innovate” (McNab et al., 2013) to avoid hindering mining's ability to meet commitments to SDGs 1, 4, 5, 8, 10, and 16. Therefore, we believe that mining companies, at a minimum, should identify, understand, and respond to the potential negative externalities that AHT might cause to society (Keenan et al., 2019; McNab et al., 2013).

Our research informs a discussion that draws attention to the need for a more transparent data and knowledge exchange and a broader understanding and acknowledgment of the strengths and areas for improvement posed by AHT for mining to achieve more concrete contributions to sustainable development and the SDGs. This also requires the environmental impacts of AHT, including its carbon

footprint, to be cautiously balanced against its economic and social costs and benefits. Given the limited amount of research and publicly available data on this subject, our method is a preliminary, initial attempt to estimate the carbon footprint of autonomous haulage trucks. With expectedly more refined and public data available over time, more sophisticated methodologies could be developed. Finally, our study was limited to Scope 1 emissions due to the diesel consumption of haulage trucks in Rachel Mine, and not Scope 2 or Scope 3 emissions. AHT might possibly indirectly contribute to reduced Scope 2 and 3 emissions in a mine site by downsizing the workforce on-site; therefore, future studies might consider these emissions as well.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1. Summary

This research develops an indicator-based quantitative framework to assess mining companies' contributions to sustainable development at varied temporal and spatial scales by using the SDGs as an organizing framework. The framework employs three scales, which vary in the level of detail and the spatial and temporal scales, to understand mining's contributions to sustainable development and proposes quantification methods for each scale. Adopting a "systems within systems" hierarchy approach, the dissertation identifies the differences between mining companies' contributions to sustainable development at the *corporate*, *site*, and *operation levels*, and at the *closure/post-closure* and *production* phases of mining. The approach and methods of the dissertation inform the hierarchy theory and its application to mining and sustainable development. This section summarizes the conclusions of each of the dissertation's research questions.

What are the trends, strengths, and weaknesses in sustainability reporting of the mining industry? How does sustainability reporting in the mining industry compare to that in the oil and gas industry?

The first research study found that although the two extractive industries have been reporting for several years and they cover a large number of indicators in their reports, there are still areas for improvement in terms of the representativeness of the issues and goals related to sustainable development that appear in their reports. Both industries reported more on internal indicators (related to the companies' internal operating processes, business principles, or employee management) with lower temporal variability than external indicators (related to a company's relations with communities, customers, suppliers, and other stakeholders). As a result, there is room for improvement in addressing externally focused contributions to sustainable development. Social indicators were reported on less as the required level of detail increased, which pointed to the need for more detailed and robust data collection, and increased transparency and accountability in both industries to avoid the risk of being critiqued for "greenwashing". The supply chain traceability issue was a particular area that could improve in reporting of both industries. The low reporting on *customer health and safety*, *product/materials stewardship*, and *suppliers and contractors*, suggested that the further down the supply chain from the company to which an indicator referred, or the more "external" the issue was to the company, the less it was reported. Similarly, both industries minimally reported on the environmental impacts resulting from their interactions with third parties and on activities conducted at the upper and lower ends of the supply chain, such as *material use* and *transport and logistics*. Given the increased global attention to supply chain issues among investors, consumers, and governments, these results suggested that these lesser

reported aspects of the supply chain need to be more represented in sustainability reports. Both industries demonstrated similar temporal variabilities in their reporting over time, although overall, mining companies showed more inconsistency than oil and gas companies. Hypothesis testing with statistical tests showed that most of the temporal variabilities observed in reporting were statistically significant. These temporal variabilities reflect companies' divergent approaches to sustainability reporting and introduce a level of subjectivity that obscures a robust assessment of contributions to sustainable development. Although variability in reporting is to a certain extent inevitable, in the long run, it would be beneficial for companies in both industries to learn from each other and attempt to unite around similar reporting structures with less variability to better assess the progress and challenges in contributing to the SDGs.

An important difference that was detected between the environmental reporting of the two industries was the *energy* category. In mining reports, the water-energy nexus was well covered, as they were the top two disclosed categories. However, in oil and gas reports, *energy* was reported much less than *water consumption*. The two industries showed significant differences in their economic reporting. Although *customers* category was reported the least by both industries, oil and gas had a much higher reporting rate (0.24) than mining (0.02). This suggested that mining companies might benefit more from better addressing customer-related indicators in their reports since customers have been placing more importance on sustainability reports and companies' contributions to sustainable development. Similarly, although both industries had limited reporting on *resource intensity*, oil and gas again had a much higher reporting rate than mining. The most significant difference between the economic reporting of the two industries was in *technology*. Oil and gas reported on technology in almost half of their reports (0.49), while mining's reporting on this topic was quite minimal (0.13). This might suggest that mining companies' investments in technology are limited. With the current efforts to transition to a low carbon economy, companies might benefit from communicating their investments in innovation and R&D more proactively and consistently to investors and other stakeholders.

How can quantification be used to assess the mining industry's contributions to sustainable development at different spatial and temporal scales?

By proposing different quantification methods for each scale, this dissertation showed that different spatial and temporal scales require different approaches for assessing contributions to sustainable development, depending on the individual circumstances. The first study used a data-driven approach to examine the scope and consistency of sustainability indicators used in the sustainability reports of eight oil and gas and eight mining companies from 2012 to 2018. The study provided the baseline of what companies are reporting at the *corporate level* through content analysis and relevant statistical methods. The second study assessed mining's contributions to sustainable development at the *site level* for the *closure/post-closure* phase by using stakeholder input to evaluate and compare three different repurposing alternatives for the tailings dam area of a mine that is approaching closure. This scale

required understanding different stakeholder perspectives on mine closure and repurposing and converging toward a preferred solution where there are multiple objectives or attributes, such as environmental, social, and economic aspects. Therefore, this study used the multi-attribute utility theory (MAUT) as an analytical approach for making logical decisions in such complex circumstances. Finally, the third study analyzed mining's contributions to sustainable development at the *operation level* for the *production* phase, with a sub-goal of investigating low-carbon haulage strategies. This study specifically required understanding and comparing the carbon footprints of autonomous and conventional haulage trucks. Therefore, the third study proposed an emission estimation methodology based on the Time Usage Model (TUM) and applied it on a surface iron ore mine in Australia.

What indicators relate to the closure/post-closure phase of the mining life cycle? How do different stakeholders prioritize these indicators?

The second study found that a much smaller number of indicators used at the corporate-level related to the closure/post-closure phase at the site level. This is partly because the closure/post-closure phase of the mining life cycle was not considered as much as other phases in the literature for developing sustainability indicators. The second study used a final set of 17 indicators (attributes) in total, broken down into five economic, five social, and seven environmental indicators. These indicators focused on the outcomes of the post-closure transition, more specifically the new facilities being considered for repurposing, and their impact on the community and the environment. For example, economic indicators considered the new facility's economic contributions to the community, such as tax payments, or investment in public services. Social indicators focused on the new job opportunities offered as well as nuisances, hazards, and the traffic that might be generated by the new facility. The focus of environmental indicators was on the new facility's energy use, land use, waste production and management, and emissions.

The results showed that stakeholders had different ideas about what constitutes sustainable development and different views may arise even within the same stakeholder group. As might be expected, the priorities of the different stakeholder groups were both similar and different depending on the issue area. Stakeholder perspectives were more closely aligned for social aspects on a high level, but this alignment shifted to environmental and economic aspects for more detailed issues. In general, community members' responses aligned with faculty members. Similarly, industry advisors and local governments, as well as government agencies and local governments were generally in agreement with each other. However, in general, local non-profits' views often diverged from the other groups, and local governments' views contrasted those of the mining company and faculty members. This might suggest that the mining company should pay more attention to local governments' perspectives to better align mine closure with local sustainability criteria, development plans, and priorities and to better contribute to sustainable development at the local level. The study also showed that community members' views were

generally in line with the combined group decision, which demonstrated the heterogeneity of communities.

What indicators relate to the production phase of the mining life cycle, and specifically for low-carbon haulage technologies?

The third study represented the third and most detailed scale in our framework. The production phase is the longest and the most dynamic phase, hence the chapter focused on the *haulage* process for simplification and scaling purposes. Therefore, this study used only one emissions-related sustainability indicator for the proposed quantification method. The indicator was “GHG emissions generated per ton of material moved”, which was the summation of “non-productive GHG emission intensity” and “productive GHG emission intensity”, which refer to the emissions generated as a result of time spent on productive or non-productive (idling) time elements of the time usage model (TUM). In addition to this particular indicator, we also used broader socio-economic attributes related to the impacts of shifting to AHT on employees and communities for discussion purposes. These indicators were associated with workplace safety, the decline in on-site positions, emerging positions, the upskilling opportunities, training, and education required for the emerging positions, and some potential disruptions to the local and Indigenous communities.

How does the contribution of mining to the SDGs compare for the closure/post-closure and production phases? How does the contribution of mining to the SDGs compare at the operation-, site-, and corporate levels?

Table 5.1. provides a summary of the strengths and areas for improvement for contributing to the SDGs identified by this dissertation. Accordingly, the second and third studies showed that strengths and areas for improvement for contributing to the SDGs were quite different for *closure/post-closure (site-level)* and *production (operation-level)*. The main strengths identified for the *closure/post-closure* phase were for contributing to SDG 11 (Sustainable Cities and Communities), SDG 16 (Peace, Justice, and Strong Institutions), and SDG 17 (Partnerships for the Goals). Both areas for improvement and strengths were identified for this phase in terms of contributing to SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth).

Operation-level was the scale where this dissertation identified the most strengths in terms of contributing to the SDGs. The main strengths identified for the *production* phase were for contributing to SDG 4 (Quality Education), SDG 5 (Gender Equality), SDG 7 (Affordable and Clean Energy), and SDG 9 (Industry, Innovation, and Infrastructure). Both areas for improvement and strengths were identified for this phase in terms of contributing to SDG 1 (No Poverty), SDG 3 (Good Health and Well-being), SDG 8 (Decent Work and Economic Growth), SDG 10 (Reduced Inequalities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Lastly, the *production* phase was required areas for improvement for contributing to SDG 17 (Partnerships for the Goals).

Results of the first study showed that contributions to the SDGs at the *corporate level* also differed from the *site-* and *operation levels*. Corporate-level was the scale where this dissertation identified the most areas for improvement in terms of contributing to the SDGs. Accordingly, only areas for improvement were identified at the corporate level in demonstrating contributions to SDG 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), SDG 15 (Life on Land), and SDG 17 (Partnerships for the Goals). Both areas for improvement and strengths were identified for this phase in terms of contributing to SDG 1 (No Poverty), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water). Lastly, only strengths were identified at the corporate level for contributing to SDG 5 (Gender Equality) and SDG 6 (Clean Water and Sanitation). A detailed overview of the identified strengths and areas for improvement for contributing to the SDGs at all three scales is provided in Appendix D.

Table 5.1. Summary of Identified Strengths and Areas for Improvement for Contributing to the SDGs ((S): strengths, (AI): areas for improvement)

Sustainable Development Goals (SDGs) – by Goal Number

Findings/Identified Aspects	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
STUDY 1: Scale 1 - Corporate-Level																	
Employment practices and labor/mng. relations	(S)				(S)			(S)									
OHS, forced labor, and child labor			(AI)					(AI)									
Supply chain trace. (customers, customer H&S, product stew., suppl. & contr.)												(AI)					
Social indicators requiring quantitative data or demonstrable proof																	(AI)
Inconsistent reporting over the years																	(AI)
Env. Inv., water consumption, energy, env. mng., and polluting incidents						(S)	(S)					(S)		(S)			
Material use, transport and logistics, emissions, solid waste, biodiversity											(AI)	(AI)	(AI)	(AI)	(AI)		
Indirect econ. impacts and local proc. of goods & services	(S)							(S)	(S)								
Resource intensity, technology, economic aspects of employment	(AI)						(AI)		(AI)			(AI)					
STUDY 2: Scale 2 - Site-Level (Closure/Post-closure)																	
Employment losses, declines in local cash flow and tax revenues, services and infrastructure	(AI)							(AI)	(AI)								
Support non-mining livelihood opportunities and microfinance initiatives	(S)																
Participatory planning											(S)					(S)	(S)
Reclaiming mined land and repurposing the land and infrastructure								(S)	(S)		(S)						
STUDY 3: Scale 3 - Operation-Level (Production)																	
Utilizing AHT instead of CT in surface iron ore mining in Australia	(S)		(S)	(S)	(S)		(S)	(S)		(S)		(S)	(S)			(S)	
	(AI)		(AI)					(AI)		(AI)		(AI)	(AI)			(AI)	
Investing in R&D of net-zero haulage							(S)		(S)			(S)	(S)				
Uncertainties and the need for transparency and granularity													(AI)				(AI)

5.2. Conclusions

The overall results of this dissertation showed the following for the *process*, *site*, and *corporate levels*:

- i) the strengths and areas of improvement in mining's contributions to sustainable development,
- ii) the similarities and differences in terms of relevant sustainable development aspects and indicators, and
- iii) the strengths and areas for improvement in terms of contributing to the SDGs.

The dissertation identified very different focus areas, and hence very different strength and areas for improvement for contributing to the SDGs for the three scales we employed in our assessment (i.e., corporate, site, and operation levels). This indicates that the varied spatial and temporal scales of mining are complementary to each other in contributing to sustainable development and the SDGs. In tracking and assessing their progress towards achieving the SDGs, mining companies should review the whole system (i.e., the corporate level) together with its subsystems (i.e., site-level and operation-level). This adds to the “systems within systems” hierarchy approach we adopted in our study in examining interacting and simultaneously operating systems at varying levels of complexity.

There is a two-way feedback loop in hierarchy theory, which acknowledges both top-down and bottom-up influences (J. Wu, 2013). This suggests that a two-way flow of experience and knowledge between the upper (corporate-level) and lower levels (site and operation levels) might assist mining in maximizing the strengths for contributing to the SDGs. Indeed, the results show that the whole system's contributions to the SDGs can only be maximized if only the three scales complement each other. For example, some strengths identified at the *operation level*, such as contribution to SDG 4 (Quality Education), or SDG 10 (Reduced Inequalities), were not identified for the other two levels (Table 5.1). Similarly, the strength to contribute to SDG 6 (Clean Water and Sanitation) or SDG 14 (Life Below Water) was only identified for the corporate level. Such strengths that were identified for only one scale should shed a light on mining companies' practices at the other scales to be able to contribute to the “missing” SDGs. For example, by learning from the strengths identified for contributing to SDG 9 at the operation level, mining companies could explore ways to expand the opportunities for marginalized groups and populations at site level, and such good practices might inform their reporting at the corporate level. Alternatively, the application of the demonstrated contributions at the corporate level regarding reducing water consumption and mitigating polluting incidents might be cross-checked and ensured at the site and operation levels.

There are also lessons to be learned from the identified areas for improvement for each scale. For example, this research identified only an area for improvement, and only at the corporate level, for contribution to SDG 15 (Life on Land). This was because mining companies' reporting was limited on *biodiversity*. To turn this area for improvement into a strength, mining companies might increase their practices for preserving ecosystem services and biodiversity at the site level, which might, in turn, inform their reporting practices at the corporate level. Moreover, the majority of the identified areas for

improvement, especially at the operation level, are “convertible” into strengths if the relevant recommendations in the literature are followed (Appendix D). For example, shifting to an AHT fleet from a CT fleet is likely to improve workplace safety and contribute to SDG 3 (Good Health and Wellbeing) if automation is introduced gradually and by providing the required time and training for the workforce to adapt. Similarly, if the broader and undesired socio-economic impacts of shifting to AHT are managed properly without the rush to innovate, it is likely to prevent potential mine-community conflicts, resulting in a strength to contribute to SDG 16 (Peace, Justice and Strong Institutions). Mining companies might benefit from these *convertible* strengths/areas for improvement by managing undesired impacts and cautiously balancing the environmental, social, and economic impacts of their practices.

The findings of this dissertation informed a discussion of the usefulness of systems-based methodologies for tracking progress towards sustainable development. By approaching different scales with different assessment methods, this research was able to identify the differences between the three scales and develop links between them via the SDGs and arrive at a more robust assessment of the mining industry’s contributions to sustainable development.

5.3. Potential Applications and Recommendations for Future Work

The methodology and findings of this dissertation may have practical implications that could be of interest to mining companies, NGOs, policy-makers, investors, academicians, researchers, consultants, and other professionals in the sustainable development field. Being both a part of the problem and the solution, we believe that the mining industry has the potential to significantly contribute to the SDGs, and the methodology and findings of this dissertation might be an additional guideline for converting areas for improvement into strengths for their contributions.

Future studies might consider applying this framework to the mining phases that this dissertation did not cover at the site level, such as exploration, feasibility and planning, or development and construction. This might further improve the findings in terms of strengths and areas for improvement that the mining industry might face throughout the mining life cycle. Similarly, mining’s contributions to sustainable development at the operation level might be furthered by focusing on processes other than haulage, such as drilling and blasting, or ore processing. This might also further inform the embedded emissions across the entire supply chain of common materials and finish products, as well as the broader social and economic impacts. The SDGs are interdependent and interlinked goals that entail a certain level of complementarities or synergies along with trade-offs or tensions (Endl et al., 2021). Therefore, understanding or quantifying the synergies and trade-offs among different SDGs is another impactful opportunity for future work. This dissertation showed with the first and third studies that there is room for improvement in the mining industry’s data collection and reporting practices. Future studies might also consider working on ways to improve the mining industry’s data collection and reporting practices at all levels to better identify the focus areas for improvement in maximizing contributions to sustainable development and the SDGs.

Finally, by adopting the “systems within systems” hierarchy approach, this dissertation developed a framework that has been successful in exploring and explaining mining’s overall contributions to sustainable development and the SDGs. Even though this framework can be further developed with the recommendations listed above for future work, a fundamental and even more important area for improvement lies within the education of mining engineering students and professionals. An interdisciplinary and more comprehensive approach to understanding and researching mining is still insufficient in the universities and the industry. Therefore, the education of next-generation students and professionals should be improved in terms of an interdisciplinary approach that cooperates more with researchers and practitioners in other disciplines, especially from social science backgrounds. This would further improve progress toward capturing and addressing the broader social, economic, and environmental impacts of mining, achieving sustainable development, and advancing the SDGs.

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APPENDIX A
INDICATOR LIST

Table A.1 List of the indicators in the literature indicators set broken down by indicator category.

Indicator Category (Number of Indicators)	ECONOMIC
Compliance and Public Sector (4)	Amount of money paid to political parties and institutions whose prime function is to fund political parties or their candidates
	Fines paid for non-compliance (economic, environmental, and social)
	Total fund for mine closure and rehabilitation, including mitigating the post-closure environmental unit and social impacts
	Total investment for pollution prevention and control (air, water, and solid waste)
Customers (2)	Geographic breakdown of markets, disclosing contribution to GDP greater than 5%
	Geographic breakdown of markets, disclosing national market share greater than 25%
Economic Performance (4)	Coverage of the organization's defined benefit plan obligations
	Financial implications and other risks and opportunities for the organization's activities due to climate change
	Net sales
Employees (5)	Significant financial assistance received from government
	Health, pension, and other benefits and redundancy packages provided to employees as percentage of total employment costs
	Investment in employee training and education as percentage of net sales
	Percentage of employees that are shareholders in the company
	Total cost of employment as percentage of net sales
Indirect Economic Impacts (1)	Total payroll costs and benefits (including pension and redundancy payments) broken down by region or country
	Understanding and describing significant indirect economic impacts, including the extent of impacts
Market Presence (3)	Policy, practices, and proportion of spending on locally based suppliers at significant locations of operation
	Procedures for local hiring and proportion of senior management and workforce hired from the local community at location of significant operation
	Range of ratios of standard entry level wage compared with local minimum wage at significant locations of operation
Procurement Practices (3)	Cost of goods, materials, and services purchased
	Equity
Products (1)	Percentage of purchasing from local supplier to our of region
	Breakdown by product type
Providers of capital (4)	Average capital employed
	Distributions to providers of capital broken down by monetary interest on debt and borrowings and dividends on all classes of shares
	Percentage of ethical investments relative to total investments
	Return on average capital employed (ROACE)
Resource Intensity (4)	Produced goods or services per land input

Table A.1 Continued

	Produced goods or services per energy input
	Produced goods or services per material input
	Transport intensity
Technology (2)	Innovation and R&D Investment
	Wastewater treatment (% efficiency)
ENVIRONMENTAL	
	Description of the major impacts on biodiversity associated with company activities and/or products and services in terrestrial, freshwater, and marine environments
Biodiversity (4)	Identity, size, protected status, and biodiversity value of water bodies and related habitats significantly affected by the reporting organization's discharges of water and runoff
	Loss of wildlife habitat due to noise emissions
	Significant impacts of activities, products, and services on biodiversity in protected areas; description of high biodiversity value outside protected areas
	Number of awards for rehabilitation and a summary, if applicable
Closure and Rehabilitation (5)	Number of mines closed
	Number of sites officially designated for biological, recreational, or other interest as a result of rehabilitation
	Number of sites rehabilitated
	Summary of the policy for closure and rehabilitation
	CH4
	CO ₂
	Emissions of acid gases (NO _x , SO ₂ , and other), breakdown by substance
	Emissions of ozone depleting substances, breakdown by substance
	Emissions of particles
	Equivalent number of fully grown trees that would be required for sequestration of the total CO ₂ emissions
	HFCs
	Initiatives to reduce greenhouse gas emissions and reductions achieved
	Loss of wildlife habitat (due to emissions)
Emissions (19)	N ₂ O
	Net emissions of CO ₂ (total CO ₂ emissions minus CO ₂ emissions potentially sequestered by trees)
	O ₃
	Other emissions; breakdown by substance
	Other relevant indirect greenhouse gas emissions by weight
	PFCs
	SF ₆
	The amount of CO ₂ emissions that can (theoretically) be sequestered by the trees planted by the company
	Toxic emissions (including heavy metals, dioxins, 40 crystalline silica, and others), breakdown by substance
	VOCs
	Breakdown by type of the amount of the primary energy used (including natural gas, diesel, LPG, petrol, and other fuels) (Direct energy consumption by primary energy source)
Energy (10)	Breakdown by type of the amount of the secondary energy used (electricity and heat) used and exported (if applicable)
	Energy from renewable sources used and exported (if applicable)
	Energy saved due to conservation and efficiency improvements

Table A.1 Continued

	Indirect energy consumption by primary source
	Initiatives to provide energy efficient or renewable energy-based products and services and reductions in energy requirements as a result of these initiatives
	Initiatives to reduce indirect energy consumption and reductions achieved
	Percentage of renewable energy used relative to total energy consumption
	Summary of energy policy
	Total primary and secondary energy used
Environmental Investments and Activities (2)	Summary of any other environmental voluntary activities
	Total environmental protection expenditures and investments by type
	Initiatives to mitigate environmental impacts of products and services, and extent of impact mitigation
	Monetary value of significant fines and total number of non-monetary sanctions for noncompliance with environmental laws and regulations
Environmental Management (6)	Percentage of planning permissions refused on environmental and social grounds relative to the number applications for permissions
	Percentage of sites certified to an EMS (e.g., ISO % 14001/EMAS)
	Summary of any assessments of suppliers and contractors quality and environmental performance
	Total number of prosecutions for environmental non-compliance and a summary for each region and country if applicable
	Breakdown of substances discharged with liquid effluents
	Describe any measures put in place to prevent acid main drainage, if applicable
Liquid Effluents (6)	Percentage of permitted sites causing downstream and/or underground water quality problems relative to the total number of permitted sites
	Total volume of tailings and disposal methods
	Total volume of water discharge into waterways
	Total water discharge by quality and destination
	Breakdown by type and the total amount of packaging used
	Breakdown by type and the total amount of chemicals used
Material Use (6)	Materials used by weight or volume
	Percentage of materials used that are recycled input materials
	Percentage of recycled or re-used packaging relative to the total amount of packaging
	Percentage of waste chemicals (processed or unprocessed) used from both internal and external sources
	Breakdown of the amount of each saleable primary resource extracted
Mineral Resources (2)	Total products' yield as percentage of the amount of saleable products relative to the total amount of material extracted
	Discomfort and possible diseases due to noise emissions
Nuisance (3)	Loss of wildlife habitat due to infrastructure problems caused by operations
	Total number of external complaints related to noise, road dirt and dust, visual impact, and other nuisance
	Amount of hazardous materials that may affect human health or ecosystems
	Area possibly affected due to accidents/incidences polluting air, water, soil
Polluting Incidents (9)	Describe any measures put in place to prevent tailings dam(s) failure
	Effect of accidents/incidences polluting air, water, soil
	Frequency of accidents/incidences polluting air, water, soil
	Number of environmental accidents and a summary for each region or country, as applicable

Table A.1 Continued

	Possible effect of hazardous materials in case of accidents/incidences
	Recovery period in case of damage
	Total number and volume of significant spills
Solid Waste (6)	Percentage of permitted sites that have a problem of land contamination relative to the total number of permitted sites
	Percentage of products sold and their packaging materials, reclaimed by category
	Total hazardous solid waste and breakdown by type and description of disposal methods
	Total non-hazardous solid waste and breakdown by type and description of disposal methods
	Total weight of waste by type and disposal method
	Weight of transported, imported, exported, or treated waste
Transport and Logistics (4)	Percentage of distance for transport of products to customers covered by road, rail, and water transport, breakdown by type
	Significant environmental impacts of transporting products, goods and materials used for the organization's operations and transporting members of the workforce
	Total distance for all transport per ton of products
	Total transport distance, including in the mine/quarry, transport of products to customers, business travel, and commuting for "fly-in, fly-out" operations
Water Consumption (5)	Percentage and total volume of water recycled and reused
	Percentage of water recycled and reused (e.g., cooling, waste, rainwater) relative to the total water withdrawn from source
	Proportion of total water resources affected
	Total water use for production of mineral resources
	Water use intensity by activity
SOCIAL	
Business Ethics (17)	Actions taken in response to incidents of corruption
	Commitment to strategy of corporate citizenship irrespective of laws in place and government approach to enforcement
	Corporate compliance and accountability with respect to international, national, and regional regulations, restrictive measures, and laws
	Group policies with reference to internal, external CSR benchmarks, and human rights issues
	Investigate more equitable "rent-sharing" agreements
	Monetary value of significant fines and total number of non-monetary sanctions for noncompliance with laws and regulations
	Number and percentage of operations with closure plans
	Percentage and total number of business units analyzed for risks related to corruption
	Percentage of employees trained in organization's anti-corruption policies and procedures
	Proven commitment to CSI as a mechanism for contributing to local and regional development plans in countries of operation
	Proven commitment to government stakeholder dialogue and engagement as a systematic principle of corporate policy from the outset to the end of a project/investment
	Public policy positions and participation in public policy development and lobbying
	Summary of the policy for managing political contributions and lobbying
	Summary of the policy on addressing bribery and corruption that meets (and goes beyond) the requirements of the OECD Convention on Combating Bribery
	Sustained commitment to corporate social investment
	Total number of legal actions for anticompetitive behavior, anti-trust, and monopoly practices and their outcomes
	Total value of financial and in-kind contributions to political parties, politicians, and related institutions by country

Table A.1 Continued

Child Labor (3)	Operations identified as having significant risk for incidents of child labor and measures taken to contribute to the elimination of child labor
	Specify any verified incidences of non-compliance with child labor national and international laws
	Summary of the policy on excluding child labor as defined by the ILO Convention 138
Community Engagement/ Impacts (13)	Alcoholism due to the company's operations
	Awards received for social and ethical behavior in relation to local communities
	Cultural disruption due to the company's operations
	Nature, scope, and effectiveness of any programs and practices that assess and manage the impacts of operations on communities
	Number and description of significant disputes relating to land use, customary rights of local communities, and Indigenous Peoples
	Percentage of sites with "fly-in, fly-out" operations relative to the total number of sites
	Prostitution due to the company's operations
	Specify any community projects in which the company has been involved
	Summary of Community Sustainable Development Plan to manage impacts on communities in areas affected by its activities during the mine operation and post-closure
	Summary of the policy for liaison with local communities
	Summary of the policy on stakeholder involvement, including the mechanisms by which stakeholders can participated in decision-making on the issues that concern them
	The extent to which grievance mechanisms were used to resolve disputes relating to land use, customary rights of local communities, and Indigenous Peoples and the outcomes
	Total number of health and safety complaints from local communities, with a summary, if applicable
Customer Health and Safety (5)	Life cycle stages in which health and safety impacts of products and services are assessed for improvement
	Number and type of instances of non-compliance with regulations concerning customer health and safety, including the penalties and fines assessed for these breaches
	Percentage of significant products and services categories subject to health and safety impacts of products and services are assessed
	Summary of the policy for preserving customer health and safety during use of products
	Total number of incidents of non-compliance with regulations and voluntary codes concerning health and safety impacts of products and services during their life cycle, by type of outcomes
Diversity and Equal Opportunity (8)	Composition of governance bodies and breakdown of employees per category according to gender, age group, minority group membership, and other description diversity indicators
	Ratio of basic salary of men to women by employee category
	Total number of incidents of discrimination and actions taken
	Percentage of ethnic minorities employed relative to the total number of employees, with an explain of how representative that is of the regional or national population makeup
	Percentage of ethnic minorities in senior executive and senior and middle management ranks
	Percentage of women employed relative to the total number of employees
	Percentage of women in senior executive and senior and middle management ranks
Summary of the equal opportunity policy	
Employment Practices (6)	Benefits provided to full-time employees that are not provided to temporary or part-time employees, by major operation
	Breakdown by region or country of the number of direct employees (on company payroll)
	Employee turnover expressed as percentage of employees leaving company relative to the total number of new employees
	Number of indirect employees (e.g., contractors, consultants) expressed as full-time equivalents
	Total number and rate of employee turnover by age group, gender, and region
	Total workforce by employment type, employment contract, and region

Table A.1 Continued

Forced or Compulsory Labor (2)	Operations identified as having significant risk for incidents of forced or compulsory labor and measures to contribute to the elimination of forced or compulsory labor
	Summary of the policy to prevent forced and compulsory labor as specified in ILO Convention No. Description 29, Article 2
Human Rights (7)	Identification of human rights issues and commitment to their protection
	Percentage and total number of significant investment agreements that include human rights clauses or that have undergone human rights screening
	Percentage of security personnel trained in the organization's policies or procedures concerning aspects of human rights that are relevant to operations
	Percentage of significant suppliers and contractors that have undergone screening on human rights and actions taken
	Statement on whether the company conforms with the ILO Conventions on the Right to Organize (no. 87 and 98)
	Summary of the policy concerning human rights relevant to company's activities
	Total hours of employee training on policies and procedures concerning aspects of human rights that are relevant to operations, including the percentage of employees trained
Indigenous Peoples (3)	Percentage of quarries/mines on sites sacred for Indigenous Peoples relative to the total number of quarries/mines
	Summary of the policy to address the needs and particularly the land rights of Indigenous Peoples
	Total number of incidents of violations involving rights of Indigenous Peoples and actions taken
Labor/ Management Relations (6)	Freedom of association and collective bargaining
	Minimum notice period(s) regarding operational changes, including whether it is specified in collective agreements (Description)
	Number of strikes and lock-outs exceeding one week's duration, by country
	Percentage of employees covered by collective bargaining agreements
	Policy procedures involving consultation and negotiation with employees over changes in the company (e.g., restructuring, redundancies, etc.)
	Ranking of the company as an employer in the internal ranking and surveys
Occupational Health and Safety (11)	Education, training, counselling, prevention, and risk-control programs in place to assist employees, their families, or community members regarding serious diseases
	Health and safety topics covered in formal agreements with trade unions
	Lost-time accidents
	Lost-time accidents relative to the total hours worked
	Number of compensated occupational diseases
	Number of fatalities at work
	Percentage of hours of training regarding health and safety relative to the total number of hours worked
	Percentage of total absence hours on health and safety grounds relative to the total hours worked
	Percentage of total workforce represented in formal joint management-worker health and safety committees that help monitor and advise on occupational health and safety programs
	Rates of injury, occupational diseases, lost days, and absenteeism and number of work-related fatalities by region
	Summary of the policy on HIV/AIDS
Product/Materials Stewardship (10)	Monetary value of significant fines for noncompliance with laws and regulations concerning the provision and use of products and services
	Practices related to customer satisfaction, including results of surveys measuring customer satisfaction
	Programs and progress relating to materials stewardship
	Programs for adherence to laws, standards, and voluntary codes related to marketing communications, including advertising, promotion, and sponsorship

Table A.1 Continued

	Summary of consumer satisfaction and complaints
	Summary of the policy related to product information and labelling
	Total number of incidents of non-compliance with regulations and voluntary codes concerning marketing communications, including advertising, promotion, and sponsorship by type of outcomes
	Total number of incidents of non-compliance with regulations and voluntary codes concerning product and service information and labelling, by type of outcomes
	Total number of substantiated complaints regarding breaches of customer privacy and losses of customer data
	Type of product and service information required by procedures and percentage of significant products and services subject to such information requirements
Social Performance Management (7)	Demonstrable use of Social Impact Assessment (SIA) tools throughout project life, including closure
	Ongoing group social audit and verification processes conforming to AA 1000
	Socially responsible approach to personal development
	Socially responsible communication strategy and employee involvement
	Socially responsible employment and working conditions
	Socially responsible management policies and system
	Sustained commitment to social performance evaluation, reporting at local and corporate level
Suppliers and Contractors (2)	Percentage of contracts that are paid in accordance with agreed terms
	Percentage of local suppliers, relative to the total number of suppliers
Training and Education (5)	Average hours of training per year per employee by employee category
	Number of employees that are financially sponsored by the company for further education
	Percentage of employees receiving regular performance and career development reviews
	Percentage of hours training (excluding Health and Safety) relative to the total hours worked (e.g., management, production, technical, administrative, cultural, etc.)
	Programs for skills management and lifelong learning that support the continued employability of employees and assist them in managing career endings

APPENDIX B
STATISTICAL TEST RESULTS

Table B.1 Statistical test results showing change over the study period for social reporting of oil and gas companies. (Tests were conducted at 95% confidence level.)

Social Indicator Category	ANOVA Result	Friedman's Test Result	Different Year Pairs Based on Post Hoc Pairwise Test
Suppliers and Contractors	Not significant ($p = 0.190$)	Not significant ($p = 0.151$)	-
Forced or Compulsory Labor	Not significant ($p = 0.750$)	Not significant ($p = 0.799$)	-
Training and Education	Not significant ($p = 0.500$)	Not significant ($p = 0.581$)	-
Indigenous Peoples	Not significant ($p = 0.379$)	Not significant ($p = 0.449$)	-
Child Labor	Not significant ($p = 0.843$)	Not significant ($p = 0.936$)	-
Community Engagement/Impacts	Not significant ($p = 0.483$)	Not significant ($p = 0.531$)	-
Labor/Management Relations	Not significant ($p = 0.429$)	Not significant ($p = 0.461$)	-
Human Rights	Not significant ($p = 0.436$)	Not significant ($p = 0.486$)	-
Social Performance Management	Not significant ($p = 0.525$)	Not significant ($p = 0.579$)	-
Product/Materials Stewardship	Not significant ($p = 0.141$)	Not significant ($p = 0.092$)	2013 and 2015
Employment Practices	Not significant ($p = 0.278$)	Not significant ($p = 0.258$)	2012 and 2017
Business Ethics	Not significant ($p = 0.123$)	Not significant ($p = 0.071$)	<ul style="list-style-type: none"> • 2012 and 2014 • 2012 and 2017 • 2012 and 2016 • 2015 and 2016
Customer Health and Safety	Not significant ($p = 0.070$)	Significant ($p = 0.036$)	<ul style="list-style-type: none"> • 2013 and 2018 • 2014 and 2018
Diversity and Equal Opportunity	Not significant ($p = 0.084$)	Significant ($p = 0.037$)	<ul style="list-style-type: none"> • 2012 and 2013 • 2013 and 2018
Occupational Health and Safety	Significant ($p = 0.049$)	Significant ($p = 0.019$)	<ul style="list-style-type: none"> • 2014 and 2017 • 2015 and 2017 • 2015 and 2018

Table B.2 Statistical test results showing change over the study period for social reporting of mining companies. (Tests were conducted at 95% confidence level.)

Social Indicator Category	ANOVA Result	Friedman's Test Result	Different Year Pairs Based on Post Hoc Pairwise Test
Suppliers and Contractors	Not significant ($p = 0.350$)	Not significant ($p = 0.353$)	-
Forced or Compulsory Labor	Not significant ($p = 0.577$)	Not significant ($p = 0.666$)	-
Training and Education	Not significant ($p = 0.384$)	Not significant ($p = 0.398$)	-
Indigenous Peoples	Not significant ($p = 0.345$)	Not significant ($p = 0.343$)	-
Employment Practices	Not significant ($p = 0.490$)	Not significant ($p = 0.609$)	-

Table B.2 Continued

Child Labor	Not significant ($p = 0.155$)	Not significant ($p = 0.119$)	<ul style="list-style-type: none"> • 2015 and 2017 • 2016 and 2017
Occupational Health and Safety	Not significant ($p = 0.313$)	Not significant ($p = 0.308$)	2017 and 2018
Human Rights	Not significant ($p = 0.329$)	Not significant ($p = 0.327$)	2016 and 2017
Community Engagement/Impacts	Not significant ($p = 0.148$)	Not significant ($p = 0.134$)	<ul style="list-style-type: none"> • 2015 and 2016 • 2016 and 2017
Diversity and Equal Opportunity	Not significant ($p = 0.326$)	Not significant ($p = 0.328$)	2014 and 2016
Labor/Management Relations	Not significant ($p = 0.492$)	Not significant ($p = 0.549$)	2016 and 2017
Social Performance Management	Not significant ($p = 0.072$)	Significant ($p = 0.012$)	-
Customer Health and Safety	Significant ($p = 0.027$)	Significant ($p = 0.002$)	<ul style="list-style-type: none"> • 2012 and 2015 • 2012 and 2016 • 2012 and 2017 • 2013 and 2015 • 2013 and 2017
Product/Materials Stewardship	Significant ($p = 2.73 \times 10^{-11}$)	Significant ($p = 2.2 \times 10^{-18}$)	<ul style="list-style-type: none"> • 2012 and 2013 • 2012 and 2014 • 2012 and 2015 • 2012 and 2016 • 2012 and 2017 • 2012 and 2018 • 2013 and 2015 • 2013 and 2016 • 2013 and 2017 • 2013 and 2018 • 2014 and 2015 • 2014 and 2016 • 2014 and 2017 • 2014 and 2018
Business ethics	Significant ($p = 0.019$)	Significant ($p = 0.006$)	<ul style="list-style-type: none"> • 2012 and 2017 • 2013 and 2017 • 2014 and 2017 • 2015 and 2017 • 2016 and 2017 • 2017 and 2018

Table B.3 Statistical test results showing change over the study period for environmental reporting of oil and gas companies. (Tests were conducted at 95% confidence level.)

Environmental Indicator Category	ANOVA Result	Friedman's Test Result	Different Year Pairs Based on Post Hoc Pairwise Test	
Nuisance	Not significant ($p = 0.529$)	Not significant ($p = 0.777$)	-	
Environmental Investments	Not significant ($p = 0.333$)	Not significant ($p = 0.423$)	-	
Biodiversity	Not significant ($p = 0.924$)	Not significant ($p = 0.975$)	-	
Transport and Logistics	Not significant ($p = 0.404$)	Not significant ($p = 0.441$)	-	
Mineral resources	Not significant (same data over the years)	Not significant (same data over the years)	-	
Liquid Effluents	Not significant ($p = 0.225$)	Not significant ($p = 0.181$)	-	
Solid Waste	Not significant ($p = 0.799$)	Not significant ($p = 0.926$)	-	
Polluting Incidents	Not significant ($p = 0.770$)	Not significant ($p = 0.889$)	-	
Material Use	Not significant ($p = 0.190$)	Not significant ($p = 0.134$)	-	
Energy	Not significant ($p = 0.091$)	Not significant ($p = 0.057$)	<ul style="list-style-type: none"> • 2012 and 2014 • 2012 and 2015 	<ul style="list-style-type: none"> • 2013 and 2014 • 2013 and 2015 • 2013 and 2017
Environmental Management	Significant ($p = 0.247$)	Not significant ($p = 0.225$)	2017 and 2018	

Table B.3 Continued

Closure and Rehabilitation	Significant ($p = 0.029$)	Significant ($p = 0.014$)	• 2013 and 2017 • 2013 and 2018
Emissions	Significant ($p = 8.52 \times 10^{-5}$)	Significant ($p = 1.195 \times 10^{-6}$)	<ul style="list-style-type: none"> • 2012 and 2014 • 2012 and 2015 • 2012 and 2016 • 2012 and 2017 • 2012 and 2018 <ul style="list-style-type: none"> • 2013 and 2014 • 2013 and 2015 • 2013 and 2016 • 2013 and 2017 • 2013 and 2018
Water Consumption	Significant ($p = 0.036$)	Significant ($p = 0.009$)	<ul style="list-style-type: none"> • 2012 and 2014 • 2013 and 2014 <ul style="list-style-type: none"> • 2014 and 2016 • 2015 and 2016

Table B.4 Statistical test results showing change over the study period for environmental reporting of mining companies. (Tests were conducted at 95% confidence level.)

Environmental Indicator Category	ANOVA Result	Friedman's Test Result	Different Year Pairs Based on Post Hoc Pairwise Test	
Nuisance	Not significant ($p = 0.177$)	Not significant ($p = 0.135$)	-	
Environmental Investments	Not significant ($p = 0.457$)	Not significant ($p = 0.526$)	-	
Biodiversity	Not significant ($p = 0.213$)	Not significant ($p = 0.169$)	-	
Transport and Logistics	Not significant ($p = 0.275$)	Not significant ($p = 0.253$)	-	
Mineral Resources	Not significant (same data over the years)	Not significant (same data over the years)	-	
Liquid Effluents	Not significant ($p = 0.439$)	Not significant ($p = 0.470$)	-	
Environmental Management	Not significant ($p = 0.461$)	Not significant ($p = 0.514$)	-	
Emissions	Not significant ($p = 0.186$)	Not significant ($p = 0.157$)	2012 and 2014	
Energy	Not significant ($p = 0.277$)	Not significant ($p = 0.267$)	2015 and 2017	
Polluting Incidents	Not significant ($p = 0.056$)	Significant ($p = 0.032$)	<ul style="list-style-type: none"> • 2015 and 2016 • 2015 and 2018 <ul style="list-style-type: none"> • 2016 and 2017 • 2017 and 2018 	
Material Use	Significant ($p = 0.0063$)	Significant ($p = 0.0001$)	<ul style="list-style-type: none"> • 2012 and 2014 • 2012 and 2015 • 2012 and 2016 • 2012 and 2017 • 2012 and 2018 <ul style="list-style-type: none"> • 2013 and 2014 • 2013 and 2015 • 2013 and 2016 • 2013 and 2017 • 2013 and 2018 	
Solid Waste	Significant ($p = 0.0208$)	Significant ($p = 0.0048$)	<ul style="list-style-type: none"> • 2012 and 2017 • 2013 and 2017 <ul style="list-style-type: none"> • 2015 and 2018 • 2017 and 2018 	
Closure and Rehabilitation	Significant ($p = 0.0060$)	Significant ($p = 0.0028$)	<ul style="list-style-type: none"> • 2012 and 2016 • 2014 and 2017 • 2015 and 2016 <ul style="list-style-type: none"> • 2015 and 2017 • 2016 and 2017 • 2016 and 2018 	
Water Consumption	Significant ($p = 0.0011$)	Significant ($p = 9.67 \times 10^{-6}$)	<ul style="list-style-type: none"> • 2012 and 2016 • 2012 and 2017 • 2012 and 2018 • 2013 and 2015 • 2013 and 2016 <ul style="list-style-type: none"> • 2013 and 2017 • 2013 and 2018 • 2014 and 2015 • 2014 and 2016 • 2014 and 2017 • 2014 and 2018 	

Table B.5 Statistical test results showing change over the study period for economic reporting of oil and gas companies. (Tests were conducted at 95% confidence level.)

Economic Indicator Category	ANOVA Result	Friedman's Test Result	Different Year Pairs Based on Post Hoc Pairwise Test
Customers	Not significant ($p = 0.294$)	Not significant ($p = 0.277$)	-
Employees	Not significant ($p = 0.689$)	Not significant ($p = 0.827$)	-
Technology	Not significant ($p = 0.269$)	Not significant ($p = 0.238$)	-
Economic Performance	Not significant ($p = 0.647$)	Not significant ($p = 0.877$)	-
Products	Not significant ($p = 0.351$)	Not significant ($p = 0.423$)	-
Indirect Economic Impacts	Not significant (same data over the years)	Not significant (same data over the years)	-
Resource Intensity	Not significant ($p = 0.817$)	Not significant ($p = 0.953$)	-
Market Presence	Not significant ($p = 0.483$)	Not significant ($p = 0.677$)	-
Providers of Capital	Not significant ($p = 0.526$)	Not significant ($p = 0.632$)	-
Procurement Practices	Not significant ($p = 0.079$)	Significant ($p = 0.036$)	2012 and 2018
Compliance and Public Sector	Not significant ($p = 0.073$)	Significant ($p = 0.023$)	2013 and 2018

Table B.6 Statistical test results showing change over the study period for economic reporting of mining companies. (Tests were conducted at 95% confidence level.)

Economic Indicator Category	ANOVA Result	Friedman's Test Result	Different Year Pairs Based on Post Hoc Pairwise Test
Customers	Not significant ($p = 0.443$)	Not significant ($p = 0.544$)	-
Employees	Not significant ($p = 0.405$)	Not significant ($p = 0.469$)	-
Technology	Not significant ($p = 0.526$)	Not significant ($p = 0.587$)	-
Economic Performance	Not significant ($p = 0.711$)	Not significant ($p = 0.809$)	-
Products	Not significant ($p = 0.508$)	Not significant ($p = 0.677$)	-
Indirect Economic Impacts	Not significant ($p = 0.170$)	Not significant ($p = 0.062$)	-
Procurement Practices	Not significant ($p = 0.129$)	Not significant ($p = 0.076$)	-
Compliance and Public Sector	Not significant ($p = 0.608$)	Not significant ($p = 0.647$)	-
Market Presence	Not significant ($p = 0.116$)	Not significant ($p = 0.055$)	<ul style="list-style-type: none"> • 2012 and 2016 • 2012 and 2017
Resource Intensity	Not significant ($p = 0.054$)	Significant ($p = 0.020$)	<ul style="list-style-type: none"> • 2012 and 2018 • 2013 and 2018
Providers of Capital	Not significant ($p = 0.086$)	Significant ($p = 0.021$)	-

APPENDIX C
SURVEY QUESTIONS

Table C.1 Survey Questions

QUESTIONS	ANSWER CHOICES
Demographic Information	
What is your age?	Under 18 18-24 25-34 35-44 45-55 Over 55 Prefer not to answer
To which gender identity do you most identify?	Female Male Transgender Female Transgender Male Gender Variant/Non-conforming Not listed [with a space if they want to specify] Prefer not to answer
What is the highest degree or level of school that you have completed? <i>(If you are currently enrolled in school, please indicate the highest degree you have received)</i>	Less than a high school diploma High school diploma or equivalent Bachelor's degree (e.g., BA, BS) Master's degree (e.g., MA, MS, MEd) Doctorate (e.g., PhD, EdD) Other (please specify) Prefer not to answer
Which stakeholder group do you identify with the most?	Local community member Faculty member Industry advisor for the challenge Government agency Non-governmental organization Other (please specify) Prefer not to answer

Table C.1 Continued

ECONOMIC – Financial Contributions and Economic Performance	
<p>Q1. Option A: The new facility's income tax payments Option B: New facility's investments in public services for the community (e.g., road maintenance, housing assistance)</p> <p>Q2. Option A: The time it will take for the new facility to reach its maximum production amount Option B: The maximum number of products that the new facility can produce</p> <p>Q3. Option A: The time it will take for the new facility to reach its maximum production amount Option B: The amount of money the new facility makes from the sales of their goods and services</p> <p>Q4. Option A: The maximum number of products that the new facility can produce Option B: The amount of money the new facility makes from the sales of their goods and services</p> <p>Q5. Option A: Contributions to Society (i.e., taxes and public services) Option B: Economic Performance</p>	<p><i>(The answers below apply to all remaining questions)</i> Preference Direction (Dropdown menu): A is more important than B B is more important than A Both are EQUALLY important Prefer not to answer Intensity of Importance (Dropdown menu): SLIGHTLY more important MODERATELY more important STRONGLY more important EXTREMELY more important Does not apply Prefer not to answer</p>
SOCIAL - Community Impacts and Employment	
<p>Q6. Option A: Nuisances (e.g., odor) or hazards (e.g., fire) that may arise from the new facility and could impact the nearby communities Option B: The potential traffic volume around the project site</p> <p>Q7. Option A: Annual salary offered for employees by the new facility Option B: Number of employees that can work in the new facility</p> <p>Q8. Option A: Annual salary offered for employees by the new facility Option B: Number of different job types offered by the new facility</p> <p>Q9. Option A: Number of employees that can work in the new facility Option B: Number of different job types offered by the new facility</p> <p>Q10. Option A: Negative community impacts (i.e. nuisances, hazards) Option B: Employment</p>	<p><i>(Same as above)</i></p>

Table C.1 Continued

ENVIRONMENT – Waste, Emissions, Resource Consumption, and Land Use	
Q11.	<i>(Same as above)</i>
Option A:	The new facility's energy use
Option B:	The amount of energy that the new facility gets from renewable energy resources such as solar roof panels
Q12.	
Option A:	The new facility's energy use
Option B:	The amount of recycled materials used by the new facility to produce their products
Q13.	
Option A:	The amount of energy that the new facility gets from renewable energy resources such as solar roof panels
Option B:	The amount of recycled materials used by the new facility to produce their products
Q14.	
Option A:	The amount of unremoved mine waste remaining in the new project area after 15 years
Option B:	The amount of waste to be produced by the new facility
Q15.	
Option A:	Air Pollution <i>(The amount of gases released to the air by the new facility)</i>
Option B:	Total land area used by the new facility
Q16.	
Option A:	Air Pollution <i>(The amount of gases released to the air by the new facility)</i>
Option B:	Resource Consumption
Q17.	
Option A:	Air Pollution <i>(The amount of gases released to the air by the new facility)</i>
Option B:	Amount of waste produced by the new facility
Q18.	
Option A:	Total land area used by the new facility
Option B:	Resource Consumption
Q19.	
Option A:	Total land area used by the new facility
Option B:	Amount of waste produced by the new facility

Table C.1 Continued

Q20.

Option A: Resource Consumption

Option B: Amount of waste produced by the new facility

General Aspects of Sustainability (Sub-goals)

Q21.

(Same as above)

Option A: Economic Aspects

Option B: Environmental Aspects

Q22.

Option A: Economic Aspects

Option B: Social Aspects

Q23.

Option A: Environmental Aspects

Option B: Social Aspects

APPENDIX D

IDENTIFIED STRENGTHS AND AREAS FOR IMPROVEMENT FOR CONTRIBUTING TO THE SDGs

																		
Findings/Identified Aspects	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16	SDG 17	
Corporate-Level																		
Reporting rates higher for employment practices and labor/management relations	(S): number of direct and indirect jobs, workforce broken down by gender (inclusive employment)				(S): track progress for recruiting more women (equal access for women to jobs)			(S): protect labor rights, decent job creation										
Reporting rates lower for OHS, forced labor, and child labor			(AI): need for more OHS monitoring and reporting					(AI): focus on eliminating forced and child labor and protecting labor rights										
Supply chain traceability issues (reporting rates lower for customers, customer H&S, product stewardship, suppliers and contractors)												(AI): incorporate life cycle thinking in analyzing mineral and chemical products, extend responsible sourcing to suppliers, engage consumers						
Reporting rates lower for social indicators requiring quantitative data or demonstrable proof																		(AI): building more detailed and robust data collection and reporting capacity
Inconsistent reporting over the years (creates subjectivity)																		(AI): building more detailed and robust data collection and reporting capacity

Figure D.1 Identified Strengths (S) and Areas for Improvement (AI) at all Scales (Source of SDG images: (United Nations, n.d.))

Figure D.1 Continued


















																		
Findings/Identified Aspects	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16	SDG 17	
Reporting rates higher for environmental investments, water consumption, energy, environmental management, and polluting incidents						(S): incorporate water reporting, and track progress for reducing water consumption, and increasing water recycle	(S): incorporate energy reporting, track progress for improving energy efficiency and reducing energy demand, incorporate renewable energy, invest in clean energy					(S): track progress for minimizing waste and effluents, and for mitigating polluting incidents		(S): track progress for minimizing waste and effluents, and for mitigating polluting incidents				
Reporting rates lower for material use, transport and logistics, emissions, solid waste, biodiversity											(AI): reduce adverse environmental impacts via proper waste management	(AI): incorporate life cycle thinking in analyzing mineral and chemical products, extend responsible sourcing to suppliers, engage consumers, reduce waste	(AI): reduce, measure and report emissions, improve capacity on climate change mitigation, align with INDCs	(AI): properly dispose of tailings/waste	(AI): preserve ecosystem services and biodiversity, avoid impacts to critical habitat, and mitigate biodiversity impacts			
Reporting rates higher for indirect economic impacts and local procurement of goods and services								(S): track progress for driving economic growth with local procurement, working with local suppliers, and catalyzing indirect employment	(S): track progress for driving industrialization by supporting local procurement									
Reporting rates lower for resource intensity, technology and R&D investment, economic aspects of employment (employee benefits, labor costs, etc.)	(AI): need for more reporting on social protection provided to employees, such as benefits and pensions						(AI): need for more reporting on energy efficiency in produced goods and services		(AI): Need for more work and reporting on promoting research and development initiatives			(AI): need for more reporting on resource efficiency in produced goods and services						

Figure D.1 Continued




















																		
Findings/Identified Aspects	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16	SDG 17	
Site-Level (Closure/Post-closure)																		
Poorly managed closure worsening the "bust" in the boom and bust cycle; employment losses, declines in local cash flow and tax revenues, decline in services and infrastructure provided to communities	(AI): employment losses, decline in local procurement and tax revenues							(AI): declined direct and indirect employment, declined local procurement	(AI): challenging industrialization due to decline in local procurement, decline in infrastructure provided to communities									
Support non-mining livelihood opportunities and microfinance initiatives to avoid the negative impacts of the boom-and-bust cycle on mining communities	(S): help improve non-mining livelihood options																	
Participatory planning: Considering and assessing post-closure land use or repurposing alternatives in closure planning by involving stakeholder inputs											(S): involving stakeholders in post-closure land use and repurposing planning					(S): Transparent and participatory closure planning that responds to stakeholder concerns might lead to good community relations and prevent potential company-community conflicts	(S): Dialog actively with governments, NGOs, and other development partners in planning post-closure transition	
Reclaiming mined land and repurposing the land and infrastructure for innovative and sustainable uses								(S): planning operational post-closure opportunities for generating new jobs and business opportunities.	(S): Planning innovative and sustainable repurposing options		(S): reclaiming mined land and planning operational post-closure land use opportunities							

Figure D.1 Continued

																		
Findings/Identified Aspects	SDG 1	SDG 2	SDG 3	SDG 4	SDG 5	SDG 6	SDG 7	SDG 8	SDG 9	SDG 10	SDG 11	SDG 12	SDG 13	SDG 14	SDG 15	SDG 16	SDG 17	
Operation-Level (Production)																		
Utilizing AHT instead of CT in surface iron ore mining in Australia	(S): Promoting the participation of women and older workers in the workforce, promoting inclusive recruitment including Indigenous Peoples		(S): If introduced gradually, by providing the necessary training and following best practices, AHT might provide safer working conditions and leverage workplace safety	(S): Training and upskilling the workforce for the emerging skills required with the introduction of AHT; Training, recruiting, and increasing employability of Indigenous Peoples	(S): Promoting the participation of women in the workforce		(S): Resulting in lower fuel rates than CT by delivering more efficient and consistent driving behaviour due to elimination of human factor	(S): upskilling the workforce to match the labor market demands and support their transition to a decent job, helping impacted communities diversify their employment base or supporting human capital development in other sectors (S): Increased productivity through technological upgrade and innovation		(S): Training, recruiting, and increasing employability of Indigenous Peoples		(S): Resulting in less non-productive emissions compared to CT	(S): Resulting in less non-productive emissions compared to CT			(S): If impacts are managed properly, by preventing mine-community conflict, decreasing the risk for obtaining social license to operate, respecting the rights of Indigenous Peoples, and collaborating with government or other local industries to facilitate non-mining employment and business opportunities for local and Indigenous communities		
Investing in R&D of net-zero haulage technologies like lithium and hydrogen-battery trucks	(AI): Jeopardizing recruitment and business opportunities of Indigenous Peoples		(AI): If introduced in a rush without taking the necessary precautions and if the AHT fleet is poorly managed, AHT might jeopardize workplace safety					(AI): reducing the overall trucking workforce, reducing employment and other economic opportunities for local communities		(AI): Jeopardizing recruitment and business opportunities of Indigenous Peoples		(AI): Resulting in more overall emissions compared to CT	(AI): Resulting in more overall emissions compared to CT			(AI): If impacts are not addressed properly, by making way for mine-community conflict, and risking social license to operate		
Uncertainties in Emissions Reporting at Site-level and the need for increased transparency and granularity							(S): potential for carbon-neutral haulage if necessary technologies are developed and become ready to be utilized in surface mines		(S): promoting R&D activities for net-zero haulage			(S): potential for carbon-neutral haulage if necessary technologies are developed and become ready to be utilized in surface mines	(S): potential for carbon-neutral haulage if necessary technologies are developed and become ready to be utilized in surface mines				(AI): reduce, measure and report emissions, improve capacity on climate change mitigation, align with INDCs	(AI): building more detailed and robust data collection and reporting capacity

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Yes, you can reproduce it as long as it is cited in your references and appropriately credited in the caption according to the style you are using for your dissertation.

More out of curiosity, what is the topic of your dissertation?

A high-quality copy of the figure can be downloaded here: <https://gmggroup.org/wp-content/uploads/2021/09/Figure-2-Time-Usage-Model-1024x407.jpg>

If you make any adaptations/modifications, please identify that the adaptations are your own.

Please let me know if there is anything else you need from us.

Thanks,

Francine Harris
Technical Publications Manager, GMG

From: Cansu Perdeli Demirkan <perdeli@mines.edu>
Sent: August 9, 2022 11:58 AM
To: Heather Ednie <hednie@gmggroup.org>; Francine Harris <fharris@gmggroup.org>
Subject: RE: [External] RE: Material Reproduction Request

Hi Heather and Francine,

Thank you for your response. I am on a tight deadline for the submission of my dissertation so I will be looking forward to hearing more from you.

Regards,
Cansu

From: Heather Ednie <hednie@gmggroup.org>
Sent: Tuesday, August 9, 2022 8:42 AM
To: Cansu Perdeli Demirkan <perdeli@mines.edu>; Francine Harris <fharris@gmggroup.org>
Subject: [External] RE: Material Reproduction Request

Hi Cansu,

Sounds good – we'd love to see your dissertation down the road! I've copied our technical publications manager, Francine, to let you know how to proceed.

Thanks,
Heather

From: Cansu Perdeli Demirkan <perdeli@mines.edu>
Sent: August 9, 2022 1:04 AM
To: Heather Ednie <hednie@gmggroup.org>
Subject: Material Reproduction Request

Dear Heather,

I hope you are doing well. I am reaching out to request your permission to reproduce Figure 2 in Global Mining Guideline's Group's document "A STANDARDIZED TIME CLASSIFICATION FRAMEWORK FOR MOBILE EQUIPMENT IN SURFACE MINING: Operational Definitions, Time Usage Model, and Key Performance Indicators" as part of my doctoral dissertation.

Thank you, and best regards,
Cansu

6) Permission to use Table 4.3 from Miller, 2022 (personal communication) is expressed below.

Ben Miller <ben@autonomouscorrect.com>

Mon 7/11/2022 9:20 AM

To: Cansu Perdeli Demirkan <perdeli@mines.edu>

Sorry for the late reply.

Please consider this permission to utilize the information that I submitted to you. It is not officially published work, so I do not know how to cite the information. Maybe personal communication is the best route? The GMG document that I forwarded to you will require permission from the GMG but they were easy to work with on my PhD for some of the same documentation. I am happy to have a chat to discuss how to get what you need.

-Ben

On Wed, Jul 6, 2022 at 12:26 PM Cansu Perdeli Demirkan <perdeli@mines.edu> wrote:

Hi Ben,

I hope you have been doing well since we last spoke! I wanted to catch up with you about our discussion regarding my paper on Autonomous trucks. The information and the sources you provided to me were invaluable to me, and I would like to thank you again for your help.

I made my calculations by using the benchmark values from the TUM for AHS document you shared with me. I am planning to defend my PhD at the end of July. As per the copyright rules, I wanted to ask your permission to use this data as part of my dissertation.

If you permit, we also talked about touching base if I need to cite your work. So I wanted to ask if it is published yet, or if there were any way you would like me to cite it? If you would feel more comfortable, I can cite it as *personal communication*. Please let me know your thoughts.

Thank you, and best regards,
Cansu

- 7) Permission to use Figure 4.4 from Duzgun et al., 2002 from the *International Journal of Rock Mechanics and Mining Sciences* is expressed below.

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