GAME THEORY, MULTIPLE-CRITERIA DECISION MAKING, AND SUSTAINABILITY FOCUSED DECISIONS FOR MINERAL DEVELOPMENT

By

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Abstract

The use of mining and metals has a significant impact on society's push towards a more sustainable future. Decisions on selecting mining methods, post-closure land use, mine waste management methods, and mineral processing methods are some of the key problems for mining's contribution to sustainability. For sustainable outcomes in decision making, the mining industry must consider Indigenous communities, the environment, regulators, stakeholders, and mine profitability. The mining industry can greatly struggle to achieve environmental sustainability goals due to mineral development's trade-offs of long-term environmental impacts for economic gains. To position the mining industry to create sustainability focused outcomes, we need decision making methods that can consider the complexities of the benefits and impacts of mining. Society needs methods to be clear on the criteria prioritization and sustainability trade-offs that take place. This thesis explores and develops decisions making techniques and processes that can prioritize criteria and balance the wants, needs, and values of mining stakeholders. Through applying sustainability focused decision making, this research gleans how environmental innovation and extraction methods can be better aligned to a sustainable future.

After an analysis of available decision making methods, techniques from multiple-criteria decision making (MCDM) and game theory are adapted to some major sustainability issues in the mining industry. Game theory provides a structured tool to investigate the interactions between mine stakeholders to understand their choices under given conditions. MCDM, which is an operational research technique, provides the ability to use different criteria and value systems. This research develops methodologies and tools for sustainability focused strategies for impact and benefit agreements, mine closure planning, social license to operate, and mining in the

Arctic. The case studies explored in this research are predominantly in Canada, but the methods created are developed to be adaptable to any region. This work is grounded in and of interest to disciplines such as mining engineering, environmental engineering, mineral economics, ecological economics, and operations research. This research discusses the challenges of incorporating multiple-criteria and game theory into decision making as well as the specific issues with modelling environmental management problems for the mining industry. Designing for flexibility, open stakeholder engagement, and collaborative criteria selection are some of the critical recommendations gleaned from the developed tools.

Résumé

L’exploitation minière et l’utilisation des métaux ont des répercussions considérables sur une société tournée vers un avenir plus durable. Les décisions sur la sélection des méthodes d'exploitation minière, l'utilisation des terres après fermeture, les méthodes de gestion des déchets miniers et les méthodes de traitement des minéraux sont quelques-uns des enjeux clés en lien avec la contribution de l’industrie minière au développement durable. Pour obtenir des résultats durables dans la prise de décision, l'industrie minière doit tenir compte des communautés autochtones, de l'environnement, des organismes de réglementation, des nombreux acteurs et de la rentabilité de la mine. L'industrie minière peut faire face à de nombreux obstacles pour atteindre des objectifs de développement durable en raison des compromis entre gains économiques à court terme et répercussions environnementales à long terme. Pour positionner l'industrie minière dans une optique de développement durable, nous avons besoin de méthodes décisionnelles qui peuvent tenir compte de la complexité des avantages et des répercussions de l'exploitation minière. La société a besoin que ces méthodes soient claires sur la priorisation des critères et les compromis environnementaux qui sont faits. Cette thèse explore et développe des techniques et des processus décisionnels qui peuvent hiérarchiser les critères et équilibrer les désirs, les besoins et les valeurs des acteurs du secteur minier. En appliquant une prise de décision axée sur la durabilité, cette recherche explore comment l'innovation environnementale et les méthodes d'extraction peuvent être mieux alignées pour un avenir durable.

Après une analyse des méthodes décisionnelles disponibles, les techniques de prise de décision multicritères (MCDM) et la théorie des jeux sont adaptées à certains enjeux majeurs de durabilité dans l'industrie minière. La théorie des jeux fournit un outil structuré pour étudier les interactions entre les acteurs du secteur minier afin de comprendre leurs choix dans des conditions données. Le MCDM, qui est une technique de recherche opérationnelle qui offre la possibilité d'utiliser différents critères et systèmes de valeurs. Cette recherche développe des méthodologies et des outils visant la mise en place de stratégies axées sur la durabilité, les accords sur les répercussions et les avantages, la planification de la fermeture des mines, le permis social d'exploitation et l'exploitation minière dans l'Arctique. Ce travail se fond sur des disciplines telles que le génie minier, le génie de l'environnement, l'économie minérale, l'économie écologique et la recherche opérationnelle. Cette recherche traite des défis liés à l'intégration de critères multiples et de la théorie des jeux, ainsi que des problèmes spécifiques liés à la modélisation des problèmes de gestion environnementale pour l'industrie minière. Les outils développés permettent d’émettre des recommandations critiques sur les méthodes et stratégies à adopter, notamment qu’elles laissent place à beaucoup de souplesse, qu’elles favorisent l'engagement ouvert des divers acteurs du secteur minier et une collaboration dans la sélection des différents critères.

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Contributions of Authors

The author of this thesis is the primary author for all manuscripts contained within. Prof. Mustafa Kumral is the supervisor of the Ph.D. candidate, and is included as a second author for each of these manuscripts.

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Chapter 1 - Introduction

Society's relationship with metals is on the edge of major change. Monumental shifts to the mining industry are imminent stemming from our planet's need for environmentally focused development (Kronenberg, 2013). Mines are becoming more expensive, and permits are becoming more difficult to receive as communities are greatly concerned with the potential negative trade-offs that mining can bring (Singh et al., 2020). Mining companies are pushing to be more efficient and environmentally conscious through autonomous technologies, advanced data analytics, and sustainability reporting, yet impacts to the environment and local communities continue to grow (Bardi, 2013). The demand for metals will also continue to grow as we shift towards renewable energy, which has a high-requirement for mined-materials (Ali et al., 2017; Alonso et al., 2012; Corona et al., 2016; Larcher and Tarascon, 2015; Noori et al., 2015). Society needs to balance the impacts on communities and ecosystems with technological advancements that mineral resources can bring. This thesis aims to add to this discussion by developing decision making methods and analytical techniques that balance the complex and multi-faceted impacts and benefits of mining.

Finding the balance between resource use, environmental impacts, sustainable land use, and energy consumption will continue to weigh heavily on our planet on both local and global scales (Johnson et al., 2021). The entire lifecycle of the specific non-renewables being used (mining, processing, smelting, manufacturing, recycling) needs to be understood and factored into determining the environmental impacts of a technology (Giurco & Cooper, 2012). The environmental impacts of mining can include water usage, soil degradation, effluents to the environment, acid rock drainage, greenhouse gas (GHG) emissions, and ecosystem devastation

(Environment and Climate Change Canada, 2014; Spiegel et al., 2018). The impacts of mining can be substantial. For example, it is estimated that mining and metal production consumes about 10% of global energy (Bardi, 2013).

Mining projects can also greatly impact the use of the area for local and Indigenous communities for employment, traditional practices, socio-environmental relationships (Ali, 2003). Decision making techniques for mining companies, governments, stakeholders, and Indigenous communities need to be able to consider and trade-off sometimes incommensurable criteria for all types of decisions during mineral and resource development (Martinez-Alier et al., 1998).

The mining industry is tied to how society sets up its economy. Our current growth first economy is the backbone to the ever expansion of the mining industry without real regard for environmental limits and waste capacities of our ecosystems (Victor, 2010). Ecological economists push for an economy bounded by our planetary constraints for waste production and ecosystem regeneration. There will always be a need for new materials such as metals and a minimal resource throughput, as discussed by Daly (1980). This minimal throughput relates well to circular economy discissions, which employs that society needs to keep resources in the economy for as long as possible, minimizing waste and environmental degradation (Lèbre et al., 2017).

Given mining's impacts, society needs to be very conscious of how to consume, use, and develop non-renewable resources. Metal recycling rates and technologies currently are inadequate to supply society with the metals needed for the future. Society will always be reliant on mineral development, especially for developing clean energy technologies (Smil, 2017). For example, to reach the Paris Climate Change Agreement goals, the clean energy share of total demand will need to rise to 40% for copper, 40% for rare earth elements, 60-70% for nickel and cobalt, and

90% for lithium (IEA, 2021). Lithium, cobalt, and graphite production will need to increase by 500% by 2050 (World Bank, 2017).

To protect our fragile ecosystems and limit climate change, there is no doubt society will need to slow down and realign the consumption patterns of metals. Different minerals have different uses and impacts, requiring tailored considerations. This thesis develops techniques using mineral economics, ecological economics, mining engineering, environmental engineering, and decision science that can bring together the multi-dimensional issues seen in mineral development. If the mining industry cannot minimize the impacts of mining, there are significant concerns that there will be lags in mineral production for future low carbon technologies (Ali and Katima, 2020).

1.1 Research Motivation

Mineral development has two main challenges related to efficiency and scale that motivate this research. Firstly, in terms of efficiency, the mining industry needs to find engineering practices to reduce its growing environmental impacts. Secondly, in terms of scale, the mining industry will need to balance its impacts and benefits as the demand of metals for renewable energy is predicted to grow.

It is unclear how society can make decisions and push development to balance the impacts of mining with its benefits. Impacts and benefits from mineral development affect communities, mining companies, regulators, non-governmental organizations, and nearby businesses in very different ways. During decision making, decision makers must find ways to consider all affected stakeholders and select the most appropriate alternatives for mining methods, mine waste methods, hiring policies, environmental management, and mine closure, as examples. It is often unclear for many affected groups why certain alternatives were selected, or why potentially preferable alternatives were not analyzed. This dissatisfaction has led to countless conflicts, protests, blockades, litigation, human rights violations, environmental destruction, and inequality (Ali, 2003; Figueroa, 2013; Martinez-Alier, 2001; Saes et al., 2021).

Mitigating climate change by transitioning to a low carbon economy is one of today's biggest challenges. A major issue for this transition is sustainably sourcing the metals needed for renewable energy (e.g., wind and solar) (Fortier et al., 2021; Graedel et al., 2012). It is expected that to source the metals needed—metals, such as lithium, rare-earth metals, cobalt, nickel, and copper—the scale of environmental impacts from mining will increase significantly (Ali and Katima, 2020; Eggert, 2017; IEA, 2021; Lapko et al., 2019; Smil, 2017). Water use, land use, chemical use, and waste production will all increase as mining expands to satisfy the new demand for the critical minerals in renewable energy (Ali et al., 2017; Bardi, 2013). Each mined material has varying degrees of environmental and social impacts, but these impacts are generally not considered in greenhouse gas reduction scenarios (World Bank, 2017).

Society needs decision making methods that can communicate the trade-offs that take place between key sustainability criteria and between affected groups during mineral development, and resource development in general. This thesis aims to explore trade-off and decision making methods, and develop processes that can bring to light the balancing of environmental impacts, economic opportunities, and immense changes that mineral development brings to communities, regions, ecosystems, and our planet. This research explores game theory, multiple-criteria decision making (MCDM), and environmental sustainability management systems with applications in mine closure, impact and benefit agreements, and social license to operate.

1.2 Research Objectives

To develop processes that can consider multiple stakeholders, criteria, value-systems, and alternatives, this thesis has the following research objectives:

1. Explore decision making methods, currently in use by the mining industry and mining academics, that consider both market and non-market criteria (e.g., environmental indicators and social indicators).
2. Analyze the interactions of mining stakeholders under both competition and cooperation using a game theoretic approach.
3. Investigate approaches to incorporate multiple sustainability criteria into a game theoretic approach using learnings from MCDMs.
4. Apply findings to cases in the Canadian North for decisions on mine closure planning and impact and benefit agreements.
5. Analyze the key considerations for impact and benefit agreements and mine closure planning to develop game theoretic approaches.
6. Explore the application of social license to operate terminology to mines in Canada.
7. Develop recommendations for mining companies, local communities, and governments for more sustainably focused projects.
8. Discuss how the methods developed can be implemented by Indigenous communities to help make informed decisions about mineral development in their territory.
9. Discuss where technological innovation and mining design must focus to create outcomes that can better bring together the impacted stakeholders, mining companies, and regulators.

1.3 Original Contributions

This thesis develops a novel method that combines game theory and MCDM, with theoretical approaches from ecological economics and mineral economics. This method is applied to the mining industry, which struggles to make long-lasting positive contributions to regions and communities and lacks the sophisticated trade-off methods to manage multiple criteria and stakeholders. Game theory has great potential to predict likely decisions of stakeholders during complex negotiations between two or more groups but has never been fully explored for the mining industry on most levels, and especially for sustainability focused negotiations. Merging the teachings from ecological economics combined with mineral economics is also uncommonly done but can provide an analysis focused on planetary health during mining decisions. This research distills, uncovers, and analyzes some of the difficult questions that society and mining companies will face as we push towards a better future. Other contributions of this thesis are as follows:

1. Developed a Monte Carlo simulation framework for unknown value-functions within an MCDM and game theoretic model.
2. Created a structured approach to analyze impact and benefit agreements and recommended how to best develop alternatives.
3. Undertook a game theoretic approach to look at the mine closure process and decisions that are made throughout the mine-life cycle.
4. Critiqued sustainability guidelines and terminology such as *social license to operate* for being the basis of sustainability focused decision making.

5. Discussed how the field of mineral economics can adapt to environmental constraints seen by our planet to bring us to a more sustainable relationship with metals.

1.4 Thesis Outline

The outline of this thesis by chapter is as follows:

Chapter 1 provides an overview of the thesis research along with its motivation, objectives, and contributions.

Chapter 2 analyzes relevant literature in MCDM, non-cooperative game theory, cooperative game theory, ecological economics, social license to operate, sustainability in the mining industry, and the circular economy, to provide a basis for this thesis' analysis and discussion.

Chapter 3 analyzes decision making techniques currently in use by the mining industry and develops a process to make environmentally focused decisions. The Canadian Arctic's mining industry is analyzed and the developed environmentally focused decision process is adapted to the region's challenges.

Chapter 4 explores how to take a game theoretic approach and apply it to the mining industry for environmental management. Different game theory categories and assumptions are investigated. The details for creating potential players out of mining stakeholders—such as mining companies, communities, and regulators—are outlined. Potential games are discussed and analyzed.

Chapter 5 takes the approaches explored in Chapter 4 and goes into further detail within the application of impact and benefit agreements. A bargaining game is developed that incorporates

MCDM. A Monte Carlo simulation is created for the unknown value functions of the community. The scenarios modelled differ in the amount they trade-off the impacts and benefits between criteria.

Chapter 6 develops non-cooperative game theory approaches to analyze decisions during the mine-life cycle that impact mine closure risks. MCDM approaches are again implemented to develop payoff functions based on the change in economic potential, environmental risk, and company reputation. Nash equilibrium functions are developed to show the relationship between outcomes and multiple criteria.

Chapter 7 explores the use of the term social license to operate and the challenges of sustainability for the mining industry through three case studies in Canada.

Chapter 8 concludes this decision making research and recommends future studies that this thesis has uncovered.

Chapter 2 - Literature Review

2.1 Overview

In this section, a review of literature pertinent to this thesis is presented. The nature of this sustainability focused research requires an interdisciplinary approach and therefore a discussion of many related fields. First, at a high level, an overview of sustainability challenges for the mining industry is presented. Technical challenges and the impacts regarding mine design, mine waste and tailing management, water usage, and emissions are discussed. The impacts of the mining industry are strongly tied to the nature of our society's economic systems. Concepts related to ecological economics and the circular economy are thus presented which challenge our growth first and environmentally destructive society. Teachings from these fields underpin this research's incorporation of criteria related not just to economics but also environmental and social factors. To incorporate multiple-criteria a review of related methods is investigated; literature on life-cycle analysis, environmental management systems, and multiple-criteria decision making are discussed.

A central method for this research, game theory, is then introduced. Game theory has a rich academic history with numerous applications across many fields of research. Applications focused on environmental management are discussed to assist in developing models for this research. Literature on game theory's use in the mining industry is discussed as well as other articles that attempt to incorporate MCDM or different criteria. This section will discuss how this study fits within the literature analyzed to create more all-encompassing and sustainability focused decisions for the mining industry.

2.2 Sustainability Challenges in the Mining Industry

There are many ways to define and apply sustainability concepts. Its definition, when applied to the mining industry, continues to adapt as society and mining companies become more aware of the multi-faceted impacts of mineral development (Moran et al., 2014). A distinction needs to be made however between weak vs. strong sustainability. Weak sustainability is grounded in environmental economics and generally allows the transformation of natural capital (e.g., mined materials) to human capital (e.g., buildings, roads, hospitals) (Shang et al., 2019). Strong sustainability does not agree that this transformation is interchangeable. Natural capital and human capital are both useful and must be valued by our political, economic, and legal systems (Victor et al., 1998). See Figure 2-1, adapted from Giddings et al. (2002) and Morandín-Ahuerma et al. (2019), it shows how in strong sustainability the economy and society are embedded in our planet's capacity. Meaning that our systems respect the natural world's limits

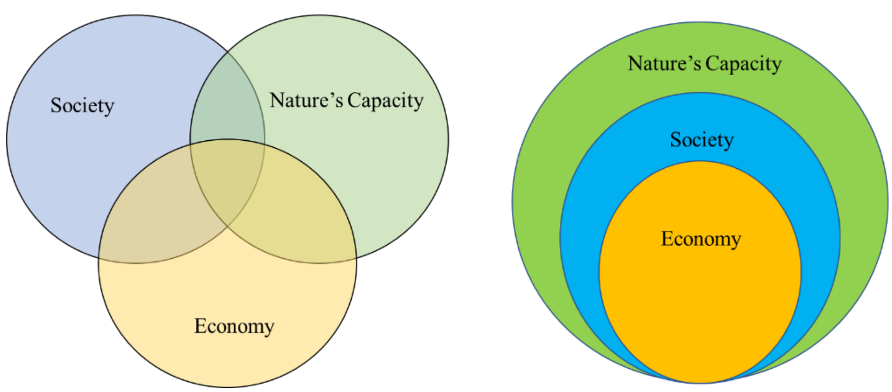

Figure 2-1 - Weak (L) vs. Strong (R) Sustainability adapted from Giddings et al. (2002) and Morandin-Ahuerma et al. (2019)

for waste and regeneration. Weak sustainability sees the three as separate and tries to find solutions that maximize all three, which often conflicts.

The Brundtland report is commonly quoted by the mining industry, which adds an inter-generational component to impacts, by saying that sustainability is when the needs of future generations are not compromised by the needs of today (World Commission on Environment and Development, 1987). There is also commonly a discussion of the importance of considering criteria from the "*three pillars of sustainability*" which are social, economic, and environmental (Gibson, 2006). A major issue is that these pillars are often siloed and that criteria are placed in one pillar or another. It is more complex than that, criteria from each pillar are connected to the other pillars. For example, impacts to the environment can affect nearby businesses such as farming or fishing, which then impacts economic criteria for a region. There continues to be criticism that mining is inherently unsustainable and causes impacts that can never be fully reclaimed or remediated. The way this research looks at sustainability in the mining industry is that it is a trade-off. Mining decisions must look at the trade-offs between different criteria and determine if the trade-off is suitable environmentally, socially, and economically.

The impacts of mining projects can be immense. Environmental impacts are seen through water usage, soil degradation, waste and tailing, effluents to the environment, acid rock drainage, greenhouse gas (GHG) emissions, and ecosystem devastation (Environment and Climate Change Canada, 2014). Socially and economically, projects can greatly impact the use of the area by local and Indigenous communities for employment and cultural practices (plant collection, hunting, water collecting, spiritual ceremonies, etc.) (Meadows et al., 2019; Menzies, 2006). Mining projects are a significant part of the economy and are often viewed as important industries by policies and legislature. The benefit vs. impact trade-off can be very complex, regulators need to be very selective of which projects to approve. We need to have a robust assessment process to fully understand the potential environmental impacts.

It is important to note that we are not running out of minerals, but as we deplete our highest-grade resources, costs will go up as we will mine our lower-grade deposits (Bardi, 2013). From this, the energy required per unit of metal is increasing. This is having larger and larger impacts on our environment (Tost et al., 2018a). At some point, it will be too costly to mine the way we mine today both environmentally and economically. We need to understand how the energy requirement of mining will increase over time and how that will impact our environment (Norgate and Haque, 2010). With such, we need to be very selective of what is environmentally acceptable from our mineral projects.

The technical challenges related to environmental impacts for mining industry are truly multi-faceted. Some of these environmental challenges, which are pertinent to this thesis, are discussed in the next sections.

2.2.1 Energy

Mines can produce significant amounts of GHG emissions depending on the energy source used, materials handling systems (e.g., truck and shovels), the size of the mine, mining methods, and processing methods (Azadi et al, 2020; Katta et al., 2020; Norgate and Haque, 2010). Mines are generally located in remote areas where there is no electricity grid. These mines run their own energy systems, which are predominantly highly carbon-emitting diesel generators. Even though mining methods are becoming more efficient, considering mining head grades are decreasing around the world, the energy output per unit of mined metal is generally increasing (Norgate and

Jahanshahi, 2011). The GHG emissions of mines continue to become a major sustainability concern and regulatory risk, as stricter carbon pollution policies, like carbon taxes and cap-and-trade systems, are implemented around the world (Tost et al., 2018b). This is a major risk for operations because if regulators increase carbon taxes or cap emissions, operating costs will increase significantly. Literature on energy consumption in the mining industry has generally analyzed energy use between mining steps as seen in Norgate and Haque (2010) and Ballantyne and Powell (2014), e.g., comminution and material handling systems. The energy of mining operations is also often tracked in life-cycle assessments as discussed in Memary et al. (2012), Yellishetty et al. (2009), and Awuah-Offei (2011). As noted by Tost et al. (2018), there are currently significant data challenges for researchers to calculate energy use by the mining industry. As they noted, there are serious consistency issues for criteria such as "*as boundary descriptions, input parameter definitions, [..] allocation method descriptions as well as a lack of commodity and/or site specific reporting of environmental data at a company level*". The mining industry needs to find ways to use less energy and use low-carbon energy sources, and reporting of energy use needs to be consistent and comparable.

2.2.2 Water usage and quality

For mining properties, considering both the water quality leaving the mine site and the amount of water used for extraction processes are critical environmental considerations (Northey et al., 2016). Water usage for mines can be immense, and water issues will continue to grow as noted by Kunz (2020). The amount of water used depends on the mineral processing methods used, but generally, comminution, flotation, leaching, and many other processes require significant amounts of water. Sourcing the water for these processes can be a major issue in arid or water stressed regions, where mining typically has to share local water resources with the region's other users, as seen in case studies from Garcés and Alvarez (2020) and Mhlongo (2018) for Chile and South Africa, respectively. Sourcing water for these operations can be one of the most significant operating expenditures in these areas. Applying for and receiving the necessary permits to source water from a region can be a major risk and hurdle for any mining project (Kunz, 2016; Schoderer et al., 2020). For areas of high precipitation, the large quantities of water entering the mine site pose risks to water storage, tailings dams, and slope stability of mine infrastructure (Burritt and Christ, 2018). As climate change continues to alter water sources, water will continue to grow as a key environmental issue for mineral development.

In addition to the usage of water, the water quality leaving the mine site is another critical risk for mining. The impacts on water quality depend on the site's mineralogy and the processing methods selected. A major risk for water quality is the potential for acid rock drainage (ARD) (Kuyucak, 2021). It is a process when sulfates mix with water and oxygen to create acid. If this occurs, a combination of risk reduction through storage (water, waste rock, or tailings storage) and water treatment is needed to ensure heavy metals are not leached and released into local water sources (Akcil and Koldas, 2006). If proper water risk management does not occur throughout the mine life, water quality and treatment can be a major cost in perpetuity during and after mine operations (Brodie, 2013). Water risks, as mentioned by many scholars, will continue to grow in complexity for the mining industry and must be carefully considered with a cumulative impact and holistic approach going forward.

2.2.3 Mine waste and tailing management

The immense challenges and risks associated with mine waste from waste rock and tailings have caused horrific environmental damage and, in cases of tailings dam collapses, loss of human life and the destruction of ecosystems (Burritt and Christ, 2018; Demajorovic et al., 2019; Fawcett et al., 2015). After the mineral processing stage, important minerals are extracted from the ore and the rest is considered tailings, which need to be stored. Often these are stored through massive tailings earth dams, which unfortunately have a history of collapsing, and causing monumental damage, as seen in the recent Samarco and Mount Polley tailings dam failures (Demajorovic et al., 2019; Mount Polley Independent Expert Engineering Investigation and Review Panel, 2015). For tailings dam, water is separated from the tailings, treated (if needed), and released to the environment (Reid et al., 2009). Best practices continue to push for less risky and more expensive tailings storage methods, but in the end, tailings are still a major and growing environmental consideration for any mining property (Australian Government, 2007a; Edraki et al., 2014).

Mine waste rock, which are the unprocessed materials that need to be removed to get to the ore, need to be stored (Lefebvre et al., 2001). Depending on their mineralogy, they can react with water and heavy metals can be leached into the environment (Lottermoser, 2010). To manage this risk sometimes caps, covers, and water treatment systems need to be established (Kalonji-Kabambi et al., 2021). With mines growing in size to keep up with demand, the amount of and risk of waste material is growing from mines (Edraki et al., 2014; Singh et al., 2020). A major challenge for research and the mining industry is improving the sustainability of mine tailings and reducing the risk of mine waste through finding further uses for the material. There are numerous endeavors, but some recent cases are seen in Ahmed et al. (2021) who use gold mine tailings as a quartz sand alternative, José Gomes de Faria et al. (2020) who use limestone tailings for fertilization, Maruthupandian et al. (2021) who analyze using tailings for cementitious binders, and Veiga Simão et al. (2021) who explore sulphidic mine waste for ceramic roof tiles. Cases have some success at smaller scales but to sustainably use the immense amount of tailings we produce, there are siginificant economic and technical challenges going forward.

2.2.4 Mine closure and financial assurance

The last stage of a mine life-cycle is mine closure: when careful planning is critical for the long-term health of the area. Mine closure is when mineral production has ended, infrastructure is no longer needed and is decommissioned, and the site is re-aligned to another land use if possible. Closure work that occurs during the mine-life is called progressive closure (Manero et al., 2021). It can only take place if the area to be progressively reclaimed will not be impacted going forward, which is not typical for many areas of a mine. Progressive reclamation opportunities need to be carefully created during long-term mine planning (Collins, 2015).

A mine closure plan is generally submitted at the permitting stage, but as mineral resources and mineral development have a great amount of uncertainty, a mine closure plan is subject to considerable change during the mine life (Jones, 2011; Manero et al., 2020). Mine closure must consider all of the major environmental risks discussed previously and ensure they are managed in perpetuity (Lima et al., 2016). After regions being economically and socially devasted after mining, mine closure plans must take an integrated approach to sustainability as discussed by the ICMM (2019) and many other mining sustainability best practice guidelines (Australian Government, 2006; MAC, 2008; Rio Tinto, 2014). Social, economic, and environmental impacts of mines closing must all be considered in a mine closure plan (Kovacs et al., 2021).

Closure guidelines often used in Canada—like the Mining Association of Canada (MAC) (2004) and ICMM (2019)—provide a high-level discussion of what is needed in a reclamation and closure plan. This includes reclamation objectives, progressive reclamation, removal of structures, standards for tailings and waste rock disposal, water resources, re-vegetation (when possible), and ongoing monitoring plans (ICMM, 2019). They discuss that Indigenous and local knowledge should be considered in closure planning, and closure activities should provide benefits to local communities as much as possible (MAC, 2008).

Mine closure planning must be aligned to the local communities' wants and needs, to ensure the site will not harm the area after mining, and that it can continue to provide benefits (O'Faircheallaigh and Lawrence, 2019; Syahrir et al., 2021). There are unfortunately many poor examples of mine closure, where the mine site has become a major environmental liability, the mining company goes bankrupt, and the taxpayers are left with paying for the clean up (Ali, 2003; Sandlos and Keeling, 2016). The polluter pays principle is commonly employed by regulators during mine closure (Government of Canada, 2019). The principle states that the producers should pay and be responsible for their pollution. The issue is that often companies go bankrupt and are thus unable to pay for their environmental responsibilities. The mine then becomes the responsibility of the regulators, and reclamation is paid for by tax dollars or left polluting the environment. In the United States, there are unfortunately many closed mines that have become part of the "*Superfund*" program of the Environmental Protection Agency (EPA) (EPA, 2021), which is a fund to clean-up sites of considerable environmental risk.

Closure bonds are now typically required by regulators to ensure there are adequate funds to clean up the site if the company goes bankrupt, but other financial assurance instruments could be used like financial accruals and sinking funds (van Zyl et al., 2002). Additionally, as a penalty, closure bonds can be utilized if the company does not follow the regulations outlined in the mine permit (Otto, 2010). The amount of financial assurance that is necessary depends on the type of operation, the environmental risks, and agreed upon end land use (Nehring and Cheng, 2016; Peck and Sinding, 2009)**.** When determining the financial assurance system, the mine's risks at the end of mineral extraction need to be analyzed (Brodie, 2013; Peck and Sinding, 2009).

At the permitting stage, the closure bond is often determined when it is difficult to accurately determine the site's closure costs, which creates many uncertainties to adequately estimate the closure bond costs (Bingham, 2011). Often, the contingency value is the largest line item in closure costing and has the greatest amount of uncertainty (Brodie, 2013). As the mine progresses, this uncertainty does decrease, providing a more accurate closure cost estimate. It is argued by Lopes da Costa (2020) that the closure costs and financial responsibilities need to be flexible and adapt to changing environmental risks, regulations, and community expectations. In addition, changes in technologies and costs are common over a long operation and should be updated periodically (Collins, 2015). In many jurisdictions, closure plans and bonds need to be updated periodically, but even in jurisdictions without a clear closure planning process, mining companies who follow best practices should update their closure plans as much as possible (Nakazwe, 2017). If the operator goes into bankruptcy and fails to reclaim the site, poor financial assurance can greatly affect all mining stakeholders. Unfortunately, there is limited literature on the success of closure bonding requirements with communities and stakeholders.

In British Columbian (BC), closure and reclamation plans must be updated every five years(BC Ministry of Energy and Mines, 2017). As part of the Major Mine Permitting Office (MMPO), applications are reviewed by either a regional Mine Development Review Committee (MDRC) or a project specific committee. These groups are comprised of technical staff from the regulatory agencies and chaired by the district inspector of mines (Government of British Columbia, 2019; Schmitt et al., 2008). Local governments, Indigenous community members, and public representatives are invited to provide input. The MDRC establishes requirements as specified in the regulations for land-use objectives, water quality, productivity, stability of structures, baseline studies, and environmental impact studies.

In the end, land use and closure goals need to be integrated into all stages of the mine-life cycle (Getty and Morrison-Saunders, 2020; Laurence, 2006). Decision making processes for all areas of a mine property must consider their closure implications (e.g., tailings dams, waste rock piles, mine openings, and infrastructure) (Collins and Kumral, 2020b).

2.2.5 Social license to operate

The term social license to operate (SLO) was developed to recognize and communicate the risks of operating a mine without approval from the area's local community and stakeholders (S. Joyce and Thomson, 2000; Thomson and Boutilier, 2011). An SLO framework can give mining companies a goal when dealing with complex social challenges, wants, needs, and values. Thomson and Boutilier (2011) discuss that SLO brings a sense of "*quality*" into analyzing company-community relationships. In addition, that trust, credibility, and legitimacy define lead to project acceptance, and eventually potentially co-ownership.

The increased use of the social license term has succeeded in bringing social challenges to the forefront of mineral development discussions but unfortunately has not brought enough suggestions to solve them (Collins and Kumral, 2021). Receiving an SLO is impossible to quantify. By saying one has achieved an SLO, it can mask the issues that communities continue to be affected by. The term is sometimes seen as being championed by mining proponents with the main goal of a stable investment (Hitch et al., 2020; Owen and Kemp, 2013). Nevertheless, with the emergence of the term bringing social challenges into the conversation industrial activities around the world, is an important first step (Koivurova et al., 2015; Komnitsas, 2020; Lesser et al., 2020; Lindman et al., 2020; Ofori and Ofori, 2019; Saenz, 2019). When working around the world, community wants, needs, and values can be drastically different. Flexible goals and tailored methods are needed for each community. This is true even within one nation like Canada, which is home to many diverse Indigenous communities who have unique histories, impacts, and scars from colonial regulations. This concept will be further discussed in Chapter 7.

2.2.6 Indigenous communities and mining in Canada

The term Indigenous is used in Canada to encompass First Nations, Inuit, and Métis communities who have unique histories, cultures, wants, needs, and values, but share the intergenerational trauma caused by cultural genocide (Government of Canada, 2021). The impacts of mineral development are unequally shared in our society (Ali, 2003; Horowitz et al., 2018). Mineral development negatively impacts Indigenous communities much more than non-Indigenous communities (Collins and Kumral, 2021; MacInnes et al., 2017). After generations of systemic exclusion, there is now some governmental and societal will to have Indigenous communities considered in mineral development decisions on their territory (Mahoney, 2019; Meadows et al., 2019; UN General Assembly, 2007) In Canada, this is seen through non-regulatory documents like impact and benefit agreements, and during government-led processes like environmental assessments.

The term cultural genocide is often used in the Canadian context to convey how colonial governments of the British and French Empire established Canada's legal, political and economic systems, which destroyed the culture and social structures of Indigenous communities; excluding them from decisions impacting their territories (Mahoney, 2019). The Canadian Government created residential school systems which forced Indigenous children to live under a Western/Christian pedagogy and was severely abusive physically, sexually, emotionally, and spiritually (Hutchings, 2016). At these residential schools, Indigenous children were often physically beaten if they showed any connection with their Indigenous culture. The trauma caused by these schools is ongoing today and throughout every Indigenous community in Canada (The Truth and Reconciliation Commission of Canada, 2015a).

Given the colonial history of knowledge production (Smith, 2012) and the imperative of reconciliation (The Truth and Reconciliation Commission of Canada, 2015a) any research should have the goal to contribute to the protection of the rights of Indigenous communities. As Smith (2012) has argued, research has often been both "*worthless*" to Indigenous peoples while "*useful*" for colonial ends, such as dispossession, exploitation, and environmental racism. While this research does not collect traditional knowledge directly from Indigenous communities, this thesis acknowledges the importance of sharing data with Indigenous communities. Following the "*Ownership, Control, Access and Possession*" (OCAP) and the "*Collective Bargaining, Authority to Control, Responsibility, and Ethics*" (CARE) principles are essential tools for research with Indigenous communities (First Nations Information Governance Centre, 2021; Global Indigenous Data Alliance, 2019). Any research or collaboration that does not follow these principles—which historically has not—greatly lacks any authority or relevance to help Indigenous communities.

Indigenous community collaboration and partnerships are a major priority for mining companies, especially in Canada (Towards Sustainable Mining, 2008). Sustainability guides continue to push mining companies to be more inclusive of a community's wants, need and values in decision making (ICMM, 2020). The environmental challenges discussed earlier in this section outline some common technical issues that come up during negotiations between mining companies and Indigenous communities. Contract preferences, compensation, environmental monitoring partnerships, and intergovernmental planning committees are some of the strategies mining companies use to create more benefits for Indigenous communities and reduce the risk of conflicts. Compensation is often dictated through impact and benefit agreements (IBA), which could be in the form of lump sum payments, and variable payments based on mine performance (e.g., net smelter return).

Conflicts from protests, blockages, and legal action with communities have led to many costly delays (Andrews et al., 2017). Local community impacts consistently rank as one of the top risks that mining companies face (E.Y., 2021). Mining companies try to reduce this risk as much as possible through following best practices and investing in engagement activities. However, the methods for collaboration and the benefits provided by mining companies have not been successful in creating flourishing and healthy communities. For example, Nunavut, which is home to a number of Inuit communities spread out throughout the large territory, has seen significant opportunities and economic growth from mineral development, but there continues to be significant issues for the local communities. Several social indicators remain unacceptable; the Canadian government partnered with local industry need to do more. For example, as noted in Collins and Kumral (2021) (See Chapter 7) "*over 20% of the Nunavut population are considered "heavy drinkers", the rate of teenage pregnancy is more than 10 times the national* *rate, the area has the highest level of food insecurity in Canada and is increasing (36.7% of households as compared to 13% nationally), unemployment rates are consistently over 50%, overcrowding in dwellings continues to be an issue, the percentage of Inuit peoples without any education certificate has dropped but still remains high at 60%, and finally the rate of suicide for Inuit communities is unacceptably high with 72.3 deaths per 100,000 person-years at risk, which is approximately nine times higher than the non-Indigenous rate* (Government of Nunavut, 2018; Statistics Canada, 2016a)." As shown, even though the local mining industry attempts to help these communities with economic opportunities and developing social programs, there still is a long way to go. The challenges these communities continue to face from the ongoing impacts of generations of cultural genocide are evident. This is just one case, but unfortunately, there are many other Indigenous communities that struggle while mining companies profit in their territory.

Throughout Canada, in regions of historically limited economic development, mining can contribute to a dramatic shift from a traditional land-based economy to a mixed-wage based economy (Rixen and Blangy, 2016). In Northern Canada specifically, many Indigenous community members have struggled with this shift, and have generally preferred traditional trapping based life-styles (Carter, 2013). This is one key reason why Indigenous employment and retention, especially in highly-paid positions, can be very low (Collins and Kumral, 2021; Peterson, 2012). Thus, fewer economic benefits from mining stay in the region. Mining companies have an important role in ensuring traditional practices like hunting, trapping, and fishing can continue long-after mining operations end, and that all community members are able to upkeep their traditional practices during the entire mine-life. However, currently in the Canadian North, it is shown, by LeClerc and Keeling (2015), and Rixen and Blangy (2016), that mining and especially closure planning has failed to produce long-lasting benefits both socially and economically to these communities.

2.3 Sustainability Standards and Guides

In the late 1990s, from the mounting pressure from communities and the poor reputation of the mining industry, the world's top mining companies came together to form the Mining, Minerals and Sustainable Development (MMSD) project to analyze the industry's contribution towards sustainable development (IISD, 2002; Owen and Kemp, 2013). This had led to the creation of other initiatives such as the International Council of Mining and Metals (ICMM) (2020), and the nation focused groups like the Mining Association of Canada's Towards Sustainable Mining (2004) and Australia's Leading Practice by the Australian Government (2006, 2007). These groups publish sustainability guides to help mining companies manage risks with communities, stakeholders, and environmental impacts. A major issue however is that the use of these guides can sometimes be used to show the benefits that are provided and mask the issues. Just following these guides does not necessarily mean best practices are being followed. These guidelines are often critiqued because they are both developed and regulated by the mining industry, without an independent voice.

A main issue with the mining industry following these guidelines is that these guides do not discuss sustainability prioritization and trade-offs (Collins and Kumral, 2021). There must be better methods to deal with the complex sustainability trade-offs that take place during mineral development decisions. It is unclear which criteria should be prioritized and when. Or, during negotiations, which groups should have the final say in the decisions. In addition, another issue is that data in these reports fail to provide comparable and helpful information between projects and companies (Boiral et al., 2019; Collins and Kumral, 2020a, 2020b; Fonseca et al., 2012).

Further to these guides, there are several reporting standards for sustainability commonly used by the mining industry. This includes the Global Reporting Initiative's (GRI) standards for sustainability reporting which mining companies often follow for their sustainability reports. The recently launched Initiative for Responsible Mining Assurance (IRMA) provides a third-party verification and certification of best practices. IRMA is a multi-stakeholder led organization, where they must find consensus to approve motions (IRMA, 2021).

New standards and assurances like IRMA are important steps for improving practices, but the implementation of guides continues to be a challenge; measurable outcomes and improvements remain unseen globally (Boiral et al., 2019; Sethi and Emelianova, 2011). Although these voluntary initiatives continue to push the mining industry for better practices, the improvement of laws and regulations around the world would ensure that environmental and social responsibility is better applied to all companies.

2.4 Environmental Assessments and Regulations in Canada

Environmental assessments (EAs) are regulatory tools used in Canada to assess "*to identify, predict and evaluate the potential environmental effects of a proposed project*" before a project is approved (Impact Assessment Agency of Canada, 2016). There are assessment processes for other countries, but this research focuses on the Canadian setting, which is an advanced mining nation (Natural Resources Canada, 2019). Developing countries can at times have less stringent and developed mining policies, but as recommended groups like the United Nations (2015) and

ICMM (2020) companies should continue to push for following best practices like in Canada to reduce risk, improve mining's global reputation, and create more sustainably focused outcomes.

Canada's policies and decisions on mining are generally made by provincial governments and territorial governments, with some exceptions, such as uranium mining having federal oversight (Natural Resources Canada, 1996). Each province establishes mining codes and requirements of mine sites (BC Ministry of Energy and Mines, 2017). As mines go through permitting and consultation, the federal government oversees Indigenous relations through working groups, which is a group of community members, community leaders, and regulators. The federal government also oversees "*fisheries, fish habitat, and ocean-related activities*", with projects potentially affecting Canada's waterways reviewed by the federal government's Department of Fisheries and Oceans (DFO).

Federal EAs are at times conducted along with provincial EAs if "*in the Minister's opinion, either the carrying out of physical activity may cause adverse environmental effects or public concerns related to those effects may warrant the designation*" (Canadian Environmental Assessment Act, 2012). For mining projects, a project requires a federal EA if it has a high potential for environmental impacts or requires significant consultation with Indigenous communities. The potential risk and impacts of a mine depend on its size, mining method, water use, mine waste management practices as well as the area's mineralization, hydrology, climate, and Indigenous traditional land use.

Understanding and collecting Indigenous traditional knowledge is a key step in an EA process (Canadian Environmental Assessment Act, 2012). Engagement with communities is often through chief and council, but is expanded to town halls, community forums, or larger meetings when EA applications and information becomes more established (Collins, 2015).

2.5 Circular Economy

The circular economy is a concept that aims to maximize the use of materials in society to minimize environmental impacts (Lèbre et al., 2017). There are many different definitions currently, but the some main tenets are that it pushes for closed material cycles, renewable energy, and systems thinking (Kirchherr et al., 2017; Korhonen et al., 2018). It maximizes the use of materials during the materials' entire life-cycles (Geissdoerfer et al., 2017). This requires better construction, design, and recycling practices. As shown in Figure 2-2, the goal of the circular economy is to keep materials in the inner-most circles like "*Reuse*" as much as possible, which require less energy and are more economic (Mihelcic et al., 2003). Only going to the outer circles as options in the inner circles are exhausted. Korhonen et al. (2018) challenges this notion however and pushes for the flows to consider the dimensions of sustainable development—economic, environmental, and social dimensions—and should respect the planet's ecosystem's carrying capacities and reproduction rates.

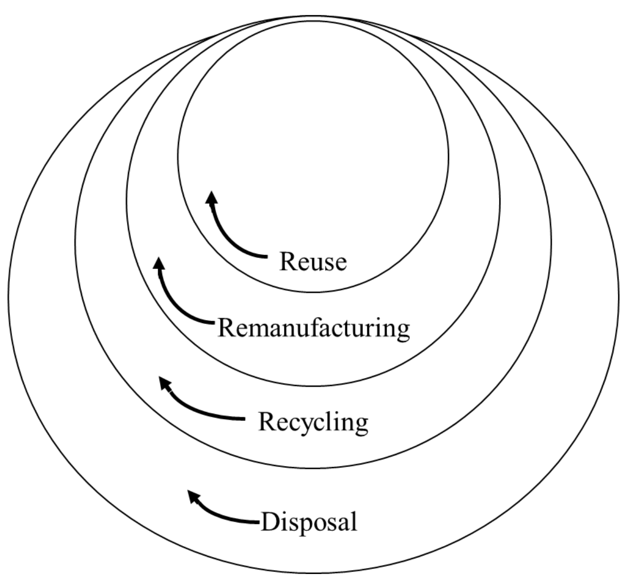

Figure 2-2 Simplified Circular Economy adapted from Mihelcic et al. (2003)

In different forms, the circular economy has become a goal for many nations and has many implications for mining and mineral processing (Korhonen et al., 2018; Pomykała and Tora, 2017). As Lèbre et al. (2017) propose, the circular economy pushes the mining industry to extract at "*acceptable environmental costs*" and "*to minimize the loss of a non-renewable resource*". The issue, as noted by Korhonen et al. (2018), is that the constraints for creating a circular economy are immense. The circular economy, as Korhornen et al. (2018) state, is able to bring the business and policy making communities together for sustainable work, however, it still needs further scientific research to understand the true environmental impacts of many circular practices. System boundaries, energy use, and thermodynamic properties of materials need to be further analyzed for the circular economy. The thermodynamics of materials is an important topic in ecological economics and will be discussed in the next section. By following the goals of a circular economy, mining policies can be better aligned to minimize waste and more sustainable products. The mining industry will need to adapt its practices to minimize its impacts but as stated presented in previous sections, there are considerable challenges that remain.

2.6 Ecological Economics

Ecological economics critiques the notion that economic growth in perpetuity, as followed by our political, legal, and economic systems, is the way to prosperity (Daly and Farley, 2011). They argue that given the ecological thresholds of our planet, unlimited economic growth, which requires the conversion of natural capital to man-made capital, is impossible without severely damaging our planet's life-supporting systems (Brown and Timmerman, 2015; Victor, 2010). Minimal throughput of resources to create a "*steady-state economy"* is a goal of ecological economists, like Daly (1980). However, as discussed by Georgescu-Roegen (1977), entropy laws the second law of thermodynamics of materials must be carefully considered in our use, development, and recycling goals of materials. From the second law of thermodynamics, it is impossible to recycle energy and eventually, all energy will turn to waste heat, and thermal pollution (Boulding, 1966; Daly, 1980; Georgescu-Roegen, 1977). As discussed in entropy, all ordered low entropy resources, like mined-materials, will eventually increase in entropy, break down and become useless (Georgescu-Roegen, 1975). Recycling and circular economic goals attempt to keep a material useful for as long as possible, which is environmentally favourably, but no matter how well our recycling technologies improve, there is a point of diminishing returns, as discussed by Daly (1980). At the point of diminishing returns, the energy required to bring the material back to a useful state will create considerable waste and thermal pollution and will be uneconomic and unsustainable. Thus, some amount of new throughput of materials from mining will always be needed.

Regardless of mineral development methods, a major shift of consumption and life-styles is needed for an "*Ecozoic Age*", as argued for by Berry (1999) and Orr and Brown (2019). The Ecozoic Age, first coined by Berry (1999), is when society will be able to re-establish our connections to nature and develop lifestyles that can symbiotic exist with the planet's ecosystems. The shift to this type of society requires an understanding of our upstream impacts as mineral resources users and how we should limit our resource usage. Thresholds and limitations need to be in place on both global and local scales. Finally, understanding what we need from non-renewable mineral resources is essential. These steps discussed, although extremely complex, are imperative if society to enter a mutually beneficial relationship with nature.

Ecological economists frequently push for analysis that goes beyond the monetary evaluation of natural resources (Kosoy and Corbera, 2010; Smessaert et al., 2020). Arguing that the inherent complexities in ecosystems, that society still does not fully understand, makes it impossible to adequately evaluate the importance of different aspects of an ecosystem (Gowdy, 2011, 1997). From spores to trees and from insects to mammals; the connections and overall health these organisms provide each other is not fully understood.

Another issue is that current economic analysis methods value benefits today as more important than benefits tomorrow because of the time-value of money assumption (Moran et al., 2014). Net-Present Value (NPV) is the main criterion used in mine project evaluation, and incorporates this assumption. NPV discounts both future impacts and benefits, giving more weight to the present time. With mines having at times over thirty years of operation, this can overly discount the cost of environmental mine closure and reclamation on project evaluation. Conversely, ecological economics requires stronger considerations for future generations and the long-term health of ecosystems (Tacconi, 2000).

In all, monetary evaluation brings an anthropocentric and limited analysis of the environment, and a multiple-criteria approach is commonly argued for a more holistic analysis (Knoke et al., 2020; Martinez-Alier, 2001; Martinez-Alier et al., 1998). This study applies these ideas using MCDM processes for decision making.

2.7 Multiple-Criteria Decision Making (MCDM)

The incorporation of multiple-criteria is imperative for analyses to consider environmental and socio-cultural relationship impacts of mining (Smessaert et al., 2020). MCDM is a mature field of study that provides a structured approach to consider multiple criteria and different value systems to then rank alternatives (Linkov et al., 2020). It is also known as multi-criteria decision analysis (MCDA) and is a sub-discipline of operations research. It helps decision makers analyze and consider both conflicting and corresponding criteria for complex decisions. Many different MCDM approaches exist which calculate the rankings of decisions—which are called alternatives in MCDM approaches—in different ways (Amirshenava and Osanloo, 2018; Behzadian et al., 2012; Haralambopoulos and Polatidis, 2003). It has been extensively used for numerous applications in business, policy, economics, and portfolio management, but not well-employed to some sustainability issues in the mining industry (Govindan, 2015; Sitorus et al., 2019). Specific applications used by the mining industry and sustainability applications are discussed in Chapters 3, 4, 5, and 6. There can be challenges with MCDMs when dealing with the uncertainty of inputs (Bonissone, 2008). To improve on this, MCDM researchers can use fuzzy sets for value functions or alternative performance, for which there are numerous examples of including Nuong et al. (2012) and Kusi-Sarpong et al. (2015).

2.8 Incorporating Indigenous Communities into Decision Making

This research wants to briefly note some essential considerations regarding the incorporation, collaboration, and inclusion of Indigenous communities in decision making. All Indigenous communities are unique with their own wants, needs, and values (Boiral et al., 2020). All too often diverse Indigenous communities are lumped into one group by Eurocentric powers, without considering the heterogeneity of Indigenous values both between and even within a community (Menzies, 2006). For a decision regarding the environmental impacts of a development project, often several Indigenous communities are potentially impacted and need to be collaborated with (Collins and Kumral, 2021). It is essential that decision making does not assume what is needed by an Indigenous community or bring a paternalistic approach. Indigenous communities need to be collaborated with directly to ensure project goals and practices are aligned to help their communities flourish (MacInnes et al., 2017).

This research does discuss the incorporation of Indigenous value systems into decision making through MCDM processes. However, this research does not make any assumptions of what those values exactly are for Indigenous communities. Instead, this thesis develops a method that is open and flexible to any set of values of Indigenous communities.

2.9 Game Theory for Decision Making in the Mining Industry

The issue for many decision making processes is that they do not fully consider the cooperation and/or competitive implications of two or more groups making decisions (Collins and Kumral, 2020a). Game theory provides a method to incorporate cooperation or competition implications (Albiac et al., 2008). It is a framework to analyze the most likely outcomes given predicted payoffs of the player's strategies (Sanchez-Soriano, 2013). In a game theoretic approach, many assumptions are for how the game will take place. For example, if it will be cooperative, non-cooperative, what the players know, or do not know, if the players make their choices one at a time, or if it is simultaneous (Matsumoto and Szidarovszky, 2015). It can be difficult to use game theory to consistently predict the outcomes of player interaction, but the game theory can at the very least create a structure to analyze the situation for policy, engineering, and economic decisions (Binmore, 2007; Camerer, 2003).

A more detailed analysis of game theory applications will be provided throughout Chapters 4, 5, and 6. But in general, there is a considerable body of literature on game theory applications and numerous in the environmental sustainability space. Applications focus on transboundary pollution and sharing of environmental resources to determine abatement costs, liabilities, and incentives (Collins and Kumral, 2020a). There are very few applications in the mining industry, but these applications are discussed in detail in Chapter 4.

This study incorporates multiple-criteria into a game theoretic approach. This, again, is not common, as game theory typically uses a single payoff criterion such as dollars, jail time (as in the prisoner's dilemma), or an amount of a resource (Benyoucef et al., 2014). As will be discussed in Chapter 4, in the limited examples incorporating multi-criteria into game theory, there is no standard approach. Teachings from MCDM literature can provide a means to take different criteria and value systems to develop a payoff, but as mentioned, there are countless ways to do this calculation. What this dictates, is that game theory and MCDM approaches need to be tailored to the specific applications which will have their own unique assumptions on conflict/cooperation and how the game will be played. This research aims to add to the game theory literature by developing game theoretic approaches with multi-criteria for mining specific applications.

Chapter 3 - Environmental Sustainability, Decision-Making, And Management For Mineral Development In The Canadian Arctic

3.1 Abstract

The Canadian Arctic is a complex and fragile region which is currently experiencing unprecedented environmental degradation due to climate change. The effects of climate change on the Canadian Arctic is just one example where we're seeing the decline of ecosystems and socio-culture-environmental traditions. Mineral development in this already fragile ecosystem is indeed a contentious and high-risk endeavour. However, mining is currently one of the few industries and economic development opportunities in the Canadian Arctic, which is one of the poorest regions in Canada. Unfortunately, mining struggles to achieve environmental sustainability due to mineral development's inherent trade-off of short-term economic gains for long-term environmental impacts. Local communities are usually left with trying to find this balance. This paper analyzes how we can apply decision-making techniques and environmental management tools for the Canadian Arctic's mining industry to promote better environmental sustainability, understanding of environmental-economic trade-offs, and community involvement. Specific decision-making methodologies and management tools are analyzed to develop, discuss, and explore their application for the Canadian Arctic. This paper concludes with a framework that brings together the analyzed methods and Arctic specificities; to prioritize environmental issues and to ensure long-term thriving communities in the Arctic.

3.2 Introduction

In the wake of climate change, and in a fragile ecosystem like the Canadian Arctic, reducing environmental impacts poses arguably the greatest challenge for mineral development (Moran et al., 2014; Mudd, 2010; Odell et al., 2018). The mining industry continues to become more environmentally efficient; however, the overall environmental strain from green-house gases (GHG), water use, mine waste, and increasing mine footprints continues to increase (Bardi, 2013; Northey et al., 2016; Tost et al., 2018b). This growth is in large part due to the need for larger mines to accommodate our society's growing demand of metals, the decreasing grades of orebodies, and to capitalize on economies of scale (Mudd, 2010, 2007; Sverdrup et al., 2014). The Canadian Arctic is an interesting example of all of this. Its mines need to be large enough to bear the enormous risks associated with developing these remote operations. There are many techniques and frameworks to manage, minimize, and prioritize the environmental impacts associated with mineral development. However, it is unclear how to apply the frameworks to a specific region or project. Furthermore, as this paper will show, there is an unfortunate lack of Arctic specific research regarding environmental decision-making and analysis systems for the mining industry. To support the Canadian Arctic, this research's goal is to provide communities, policymakers, and proponents with an analysis of the available tools for environmental management and decision-making in the mining industry, and to discuss how they can be adapted for the Canadian Arctic. Synthesizing these findings, this paper then proposes a framework to organize and prioritize environmental issues associated with mining in the Arctic.

Environmental sustainability makes up only one of the three pillars of sustainability, the other two being social and economic. However, it is arguably the most difficult, or even unattainable for the mining industry to achieve due to the inherent nature of non-renewable resource extraction and the long-term changes it causes to an ecosystem (Worrall et al., 2009). This paper acknowledges the importance of both social and economic welfare for communities. However, it argues that strong environmental sustainability brings overall sustainability; and needs to be a central focus of the mining industry. Strong environmental sustainability brings economic opportunities and social sustainability through human-environmental interactions such as hunting, fishing, forestry, access to freshwater, outdoor recreational activities, and agriculture (Costanza et al., 2015). Conversely, if the environmental management practices cause severe environmental impacts, the social and economic prosperity of said community will be fundamentally disadvantaged due to the degradation of the previously mentioned human-environmental interactions (Filho et al., 2019).

Given the immense environmental impacts caused by mining and the current health of our planet's ecosystems, one must reflect if mining is reasonable in a sensitive area like the Canadian Arctic. Mineral development and our society's demand for metals stem from our capitalistic-based society, institutions, policies, and corporations that strive for economic growth. Ecological economists argue for the incorporation of our planet's ecological limits for our economic analyses and policies (Costanza et al., 2015; Rockström et al., 2009). However, it is very difficult to understand what our relationship with metals and mining would look like if we are to respect the environmental capacity of our planet (Vela-Almeida et al., 2015). Even with a minimal economic throughput as argued by ecological economists like Herman Daly, our requirement for metals will remain (Daly, 1980). Furthermore, as we push towards green technologies such as lithium–ion batteries, wind turbines, and solar panels, our demand for metals will remain (Bardi, 2013). Certain metals will undeniably have more utility and durability for society if we are to focus on our planet's ecological health rather than economic growth. This dilemma contains many ethical and philosophical dimensions. This research argues that: aligning our environmental management methods to maximize our environmental sustainability and protect our most vulnerable communities is essential for any future policies. The aim of this paper is then to delineate a framework regarding how operations will be performed if mining is conducted. Whether mining is needed in the Arctic is not the scope of this paper, but that the decision should be made alongside the local communities with a transparent and collaborative approach.

The next section will present the methods used for this analysis; followed by an overview of the Canadian Arctic. This paper will then provide an analysis of environmental indicators, management tools, decision-making techniques and frameworks used by the mining industry to understand what can be potentially applied for the Canadian Arctic. Finally, a framework is introduced for the Canadian Arctic on how to synthesize and apply the tools and techniques currently being used by the mining industry for environmental management and decision-making.

3.3 Methods and Materials

A literature review was conducted to compare methodologies of environmental decision-making, environmental management, and sustainability in the mining industry. In addition, to establish a theoretical framework, and to look for gaps for how to prioritize environmental sustainability in the Canadian Arctic (Denzin and Lincoln, 2018). This search was conducted over the winter of 2018–2019. It accessed the McGill University Library Database, Scopus, Web of Science, and

Google Scholar databases to find articles over the last 20 years (2000–2019). The following search strings were used:

‘Environmental Decision Making’ AND ‘Mining’

‘Environmental Sustainability’ AND ‘Mining’

‘Environmental Management’ AND ‘Mining’

From these searches, the abstracts of 157 articles were reviewed. The goal was to find articles that had used or discussed a decision-making process regarding the environment within the mining and metals industry. From that review, it was found that many articles did not explicitly have an environmental decision-making process but made environmental prioritization decisions based on environmental indicator selection or risk management. These types of articles were included in the final analysis. Out of the abstract review, 41 articles were selected to be further analyzed. Information from these articles was summarized and notes were taken in an Excel spreadsheet to organize articles based on what they were analyzing, the methods used, and the level of analysis. The level of analysis ranged from a mine itself, a subset of a mine, a mining region, a commodity, or the overall global mining industry. A subset of a mine was defined as when the analysis assesses an area within a mining operation such as a tailings dam, waste rock pile or water management system. A brief write-up and more in-depth analysis for each analyzed article is presented in the results section depending on its applicability for the main research questions.

3.4 Overview of the Canadian Arctic

The Canadian Arctic, which includes areas in Nunavut, Yukon, the Northwest Territories, Quebec, and Labrador, is a complex region for mineral development, where one must carefully consider the harsh environmental conditions and lack of nearby resources. The unpredictability of permafrost, shipping routes, equipment availability, material availability, maintenance requirements, and general logistics makes mining in the Arctic a high risk and expensive endeavour (Dicks et al., 2013; Szymanski et al., 2003). In addition, climate change is increasing the operational risks in the Arctic. For these mines to be financially profitable, they need to be large tonnage operations to capitalize on economies of scale. Building a mine now requires almost a billion dollars as seen in the Mary River Mine, Meadowbank Mine, and Hope Bay Mine (Agnico Eagle Mines Limited, 2017a; Baffinland Iron Mines Corporation, 2011; TMAC Resources, 2015). These large operations evidently have larger environmental impacts and more robust environmental management plans are needed to manage these sites. Unfortunately, large metal mines in the Arctic have a very poor record of environmental performance. Major metal mining projects such as Faro, Wolverine, Cantung, and Giant Mine opened in the 20th century but were plagued with environmental legacy issues (Faro Mine Remediation Project, 2018; Keeling and Sandlos, 2015; Sandlos and Keeling, 2016; Yukon Minerals Advisory Board, 2017). The Giant and Faro Mine as mentioned are now closed and are both billion dollar environmental liabilities (Barde, 2017; Fawcett et al., 2015; Sandlos and Keeling, 2016).

The Indigenous communities in the Arctic are some of the most vulnerable communities in Canada. They are predominantly Inuit but the regional centres of Yellowknife and Whitehorse have many First Nations, Metis, and non-Indigenous communities (Statistics Canada, 2016b). It is essential that they be considered more than just stakeholders; they are rightsholders with the right to say what occurs on their traditional territories (Kuokkanen, 2019; O’Faircheallaigh and Corbett, 2005). A lack of social and health resources, food insecurity, and living with the long-term devastation of Canada’s residential school systems are some of the many issues found in these communities (Beaumier et al., 2017; Keeling and Sandlos, 2015; The Truth and Reconciliation Commission of Canada, 2015b). Partnerships with Indigenous communities in the Arctic are paramount to ensure that mineral development adequately benefits the community in perpetuity (Keeling and Sandlos, 2015). The community is usually left with a difficult choice of balancing the economic opportunities provided by the mine with the potential environmental impacts to their land and animal populations which they still rely on for food. The environment can also have significant value in terms of cultural, ethical, and aesthetic features which are not easily accounted for during standard economic cost-based analyses (Kosoy and Corbera, 2010; Vela-Almeida et al., 2015). In addition, personal environmental values are a complex aspect of decision-making, as individuals and communities can value the environment in at times conflicting ways (Martinez-Alier et al., 1998). Indigenous communities in the Arctic need to be fully integrated into any environmental management or development decisions.

In Canada, environmental management and community consultation usually occurs at the permitting stage of a mine or during an Environmental Assessment (EA) process. These EA processes are usually conducted by the regional governments with the support of Federal organizations such as Natural Resources Canada, Department of Fisheries and Oceans, and Impact Assessment Agency of Canada. During these permitting and assessment stages, impact benefit agreements are established with local communities (Canadian Environmental Assessment Act, 2012). Indigenous traditional knowledge studies have relatively recently been incorporated into environmental, closure, and reclamation planning to align the post-closure land use to the wants, needs, and values of the community (Ellis, 2005; Wiles et al., 1999). These documents help give a voice to the wants, needs, and values of the local communities (Menzies, 2006).

The Canadian Arctic has very little infrastructure and climate change is causing further issues to logistics. Shipping materials, equipment, and personnel to site are extremely expensive and is conducted by either plane or winter ice roads. One of the vital ice roads begins at Yellowknife and services, Gahcho Kue, Diavik, Ekati, and many other exploration sites. It ends at the abandoned Jericho Mine 600 km from Yellowknife (JVTC, 2019). It is only open on average 67 days a year between February and March, but with warmer winters the ice road season is shortening (Perrin et al., 2015). All other times of the year, materials must be brought in by plane. Travel by plane in the harsh environment of the Arctic can also be unpredictable. Workers and consumables can be delayed in and out of site due to visibility being adequate for the pilots. Furthermore, with a lack of infrastructure, the mines in the Arctic predominantly powered by burning of diesel fuel. Diesel fuel therefore is one of the main consumables that is shipped to the site (Perrin et al., 2015). Along with financial costs associated with shipping thousands of litres of diesel fuel to site every year, there are the environmental costs of releasing GHGs from the burning of diesel. Additionally, climate change is causing increasing mobility of icebergs which makes shipping more challenging (Barber et al., 2014; Dicks et al., 2013). Finally, coastal erosion is increasing as land-fast sea ice and frozen ground near the coast melts away. This puts coastal villages and coastal infrastructure at greater risk of floods. If mining or development increases, more Arctic ports will be needed which will have to consider these challenges.

Another major challenge in the Arctic for mining and construction is the effects of climate change on permafrost (Collins and Kumral, 2019). Warmer winters and summers have caused permafrost layers to decrease which has created several new challenges for the Arctic. As mines and their related infrastructure are designed to consider this layer of permanently frozen ground, the heterogeneity caused by less permafrost has created a much more complex surface to build on (Dicks et al., 2013). This has caused costs to increase and design to become much complicated for ground control, waste management, and rock fragmentation. With permafrost unpredictability caused by climate change, it is unclear if the landscape of the Arctic will be a suitable place to build for the next 100 years.

The post-closure state of mines is a major concern for mineral development in the Canadian Arctic (Keeling and Sandlos, 2015; Lima et al., 2016; Worrall et al., 2009). Unfortunately, like operating a mine, mine closure and reclamation in remote locations like the Canadian Arctic are much more expensive due to the shortage of skilled labour, costs of materials, and limited access to site (Faro Mine Remediation Project, 2018; The Conference Board of Canada, 2013; The Mining Association of Canada, 2017). Robust closure practices are paramount for environmental sustainability as it ensures the mine site's physical stability (e.g. waste rock piles, tailings dams) and chemical stability (e.g. acid rock drainage, metal leaching, water quality). In addition, it protects public safety, environmental ecosystems, and aligns the long-term land use of the site for the communities (Henry et al., 2012; Laurence, 2006). For best-practices, the Arctic needs closure and reclamation planning to be collaborative and inclusive of all vulnerable stakeholders to ensure the final land use is useful for the community (Collins, 2015). Progressive reclamation, which is reclamation that is carried out during the mine life, is often promoted to reduce closure costs, better manage the environmental liability of a mine, and to ensure the mining company pays for reclamation (Bowman et al., 1998). However, depending on the mining method, progressive reclamation may not be possible. Nonetheless, progressive reclamation provides an opportunity to understand how the area will react to reclamation which can lead to better closure plan updates as mining progresses (Bowman et al., 1998; Environment Canada, 2013; The World Bank, 2010).

As outlined, the Canadian Arctic is a place of great challenges for the mining industry in the wake of climate change. Communities need to be close partners and involved in the environmental management of the site. Unfortunately, as the operational risks due to climate change continue to increase, for financial profitability these mines will have to be larger-scale operations which have much more significant environmental impacts. This needs to be understood by the community throughout all stages of the mine life and during all environmental decision-making processes.

Table 3-1 lists the operating properties in 2018 in the Canadian North and Table 3-2 presents mines at the development or advanced exploration stages. Information was tabulated using the provincial government websites, company news releases, and materials from the territory governments at the Prospectors & Developers Association (PDAC) 2019 conference.

Table 3-1 Operating Mines in Northern Canada during 2018 (The Mining Association of Canada, 2017)

Region	Operating Mine	Company	Commodity
Yukon	Minto	Capstone	Cu, Ag, Au
Northwest Territories	Diavik	Rio Tinto	Diamonds
	Ekati	Dominion Diamond Corporation	Diamonds
	Gahcho Kue	De Beers & Mountain Province Diamonds	Diamonds
Nunavut	Meadow Bank	Agnico-Eagle	Au
	Mary River	Baffinland	Fe
	Hope Bay	TMAC Resources	Au

Table 3-2 Mines in Development or Advanced Exploration in Northern Canada 2019

Region	Property	Company	Commodity
Yukon	Kudz ze Kayah	BMC Minerals	Cu, Pb, Zn, Au, Ag
	Wellgreen	Wellgreen Platinum Ltd.	Rare Earth Metals
	Eagle Gold	Victoria Gold Corporation	Au
	Coffee Creek	Goldcorp	Au
	Casino Mine	Casino Mining Corp.	Cu, Au, Mb
	Keno Hill Silver Mines	Alexco Resources	Ag, Pb, Zn
Northwest Territory	NICO Mine	Fortune Minerals Limited	Cobalt
	Prairie Creek	Canadian Zinc	Zn, Pb, Ag
	Pine Point Mine	Osisko Minerals	Pb, Zn
	Nechalcho	Avalon Minerals	Rare earth metals
Nunavut	Meladine Mine	Agnico-Eagle	Au
	Backriver	Sabina Gold	Au
	Amaruq	Agnico Eagle	Au
	Kiggavik	Orano Canada Inc	Uranium

3.5 Sustainability Reporting for Mines of the Canadian Arctic

This section presents the results from analyzing environmental sustainability reporting of Canada's Arctic and Sub-Arctic mining operations in the Canadian North in 2018. Most companies had their sustainability information within their sustainability report but as shown in Table 3-3, some company's information was either out of date or scattered in other documents. Findings for each operation are discussed below. Most companies use both GRI standards for sustainability reporting and ISO 14001 for environmental management.

Both the Minto and Meadowbank mines highlight the significant use of diesel fuel for energy, leading to high GHG emissions. Meadowbank accounts for 63% of the total diesel fuel used by Agnico Eagle while the Minto mine has an energy intensity of ~.37 gigajoules/tonnes processed and a GHG intensity of ~.02 carbon equivalent tonnes/tonnes processed (The exact figures were not provided and were read off the company's bar graphs) (Agnico Eagle Mines Limited, 2017a, 2017b; Capstone Mining Corp, 2017). These are the highest and second highest respectively within Capstone mining's portfolio. Diavik highlights their small wind farm as a means to mitigate their use of diesel energy and production of GHG (Rio Tinto, 2017). Ekati highlighted new energy reduction plans by improving the compressed air, outdoor lighting, water pumping, and main camp power systems (Dominion Diamond Corporation, 2016; Dominion Diamond Mines, 2017).

Closure, reclamation, and progressive reclamation are commonly discussed by the companies. Ekati discusses progressive reclamation work being conducted on the Old Camp pad, Panda, Koala, and Koala North pits. In addition, underground prep for flooding, ongoing revegetation, and topsoil salvage was mentioned. (Dominion Diamond Mines, 2017). At the Minto mine, they discuss working on cover placement and the contouring of several mine waste facilities (Capstone Mining Corp, 2017). For Mary River, ongoing environmental work was described on their waste rock facility to ensure the water quality meets regulatory guidelines (Baffinland, 2017).

As noted, many of the companies disclose their environmental performance through the GRI reporting standard which are linked to the UN sustainable development goals. The companies, although following GRI reporting, discuss their contributions to the sustainable development goals in different ways. Gahcho Kue, outlines their contributions through their own value chain assessment (De Beers Group, 2019). They discuss achieving the environmental sustainable development goals through protecting biodiversity, reducing emissions, managing risks, and anticipating climate change (De Beers Group, 2019, 2018, 2017). Mary River, in their annual report for the Nunavut Impact Review Board reviewed GHG emissions, water quality, air quality, noise, and vegetation (Baffinland, 2017). Meadowbank uses indicators in the categories of: materials, energy, water, biodiversity, compliance, emissions, effluents and waste. Rio Tinto and the Diavik mine emphasize the importance of Caribou, water quality, fish habitat, community, and progressive reclamation (Rio Tinto, 2019, 2018). However, most of the data is presented at a company level and not differentiated by mine as seen at Diavik, Gahcho Kue and Mary River. Meadowbank, Minto Mine, Ekati have some information in regards to energy, water, and land use on a mine level.

Table 3-3 Summary of Sustainability Reporting for Arctic and sub-Arctic Operating Mines in 2018

Region	Operating Mine	Commodity	Location of Sustainability Reporting	Methods Used
Yukon	Minto	Cu, Ag, Au	Sustainability report	GRI Standards ISO 19011 (Energy) ISO 31000 (Risk)
Northwest Territories	Diavik	Diamonds	Company level sustainability reports and mine specific report.	GRI Standards ISO 14001 (EMS) ISO 14040 (LCA)
	Ekati	Diamonds	No current sustainability report. 2016 report as Dominion Diamond Corp. and website was analyzed.	ISO 14001 (EMS)
	Gahcho Kue	Diamonds	No sustainability report. Lots of documentation at company level found on website.	GRI Standards ISO 14001 (EMS)
Nunavut	Meadowbank	Au	Sustainability report	GRI Standards ISO 14001 (EMS)
	Mary River	Fe	Details on mine's website. Sustainability report from parent company	GRI Standards ISO 14001 (EMS)
	Hope Bay	Au	Details on website	Not found.

Common within all companies is discussing the importance of consulting with stakeholders and rightsholders, especially the local Indigenous communities. However, it is difficult to ascertain the results of their collaboration. How the collaboration processes are carried out is sometimes highlighted along with the established company-community environmental management working group (Baffinland, 2017). As noted by Azapagic (2004) and Boiral & Henri (2017) many companies use a variety of reporting formats and sustainability indicators, this was also noted in this appraisal of the reports. This makes it very difficult to make cross-company comparisons and in general gauge how companies are performing. As sustainability requires a location specific definition, there are few specific requirements by regulators for what companies need to disclose in sustainability reporting. Robust EMS systems were present in the mining operations, however, again, it was difficult to ascertain what success they were achieving.

3.6 Environmental Indicators in the Mining Industry for the Arctic

This section provides an analysis of the research currently being conducted on environmental indicators in the mining industry and concludes with what can be applied for the Arctic. In general, there is already crucial research concerning what is an appropriate indicator of environmental sustainability for the mining industry (Azapagic, 2004; Hilson and Basu, 2003; Li et al., 2010). However, it can be very difficult to value, compare, and contrast various features of the environment between stakeholder groups that benefit from the environment in different ways. Some argue that the environment and ecosystems cannot actually fully be valued, especially using monetization, due to the extremely complex relationships within ecosystems (Kosoy and Corbera, 2010). However, the questions of: What exactly do you measure? How do you measure it? What value does it have? Are all subjective questions and require significant discussion when determining which indicators to be used.

Site specificity and community values are the key factors when deciding which indicators are appropriate (Ranängen and Lindman, 2017). Ensuring indicators are applicable and understood must stem from collaboration and involvement with stakeholder groups. This ensures what is being measured helps to uphold the wants and needs of the impacted communities (Kamenopoulos et al., 2016). Frameworks such as the Global Reporting Initiative (GRI), which provide numerous indicators, are commonly used by mining companies (Azapagic, 2004).

Environmental indicators for mining typically cover greenhouse gas emissions, energy use, water quality, water discharge, soil, air, dust, noise, reclamation practices, biodiversity conservation, and flora and fauna health (Global Reporting Initiative, 2016).

This study conducted an analysis on environmental sustainability research in mining and found several articles focussing on how to select environmental indicators. Environmental indicators are required for decision-making and environmental management tools. Additionally, decision-making methods are needed for selecting indicators. Multi-criteria decision-making (MCDM) approaches were seen in Chen et al. (2015), Kommadath et al. (2012), Nuong et al. (2017), and Kamenopoulos et al. (2018) for indicator selection. Further details on MCDM approaches will be discussed in Section 3.6. Most articles looked at indicators on a more general level as seen in Kamenopoulos et al. (2018), Nuong et al. (2017), Kommadath et al. (2012), Worrall et al. (2009), Azapagic (2004), and Hilson and Basu (2003). Kamenopoulos et al. (2018), proposed a hybrid decision support system (DSS) framework, that used MCDM and multi-attribute utility theory (MAUT) to select indicators and support the sustainability evaluation of mining projects. Worrall et al. (2009) assessed previous work in sustainable development in the mining industry and developed sustainability criteria and an indicator framework for assessing mine legacy lands based on the three pillars of sustainability. Stemming from the Mining, Minerals, and Sustainable Development (MMSD) project, Azapagic (2004) conducted a review of sustainability for the mining industry and developed a framework to select sector-specific sustainability indicators. Finally, Hilson and Basu (2003) shed light on the difficulty in finding a suitable definition for sustainable development and then selecting appropriate indicators to model environmental performance (Hilson and Basu, 2003).

Unfortunately, few articles provided a discussion on a site-specific level. Ranängen and Lindman (2017) provided a regional-based analysis by examining the Nordic Mining Industry's sustainability practices (Norway, Sweden, and Finland) in order to develop guidelines and select indicators. They reviewed criteria and indicators such as corporate governance, fair operating practices, economic aspects, human rights, labour practices, society, and the environment (Ranängen and Lindman, 2017). Kamenopoulos et al. (2016) introduced and developed indicators for the rare earth element mining industry stemming from GRI, IISD, and the United Nations' Sustainable development goals (Global Reporting Initiative, 2016; IISD, 2007; United Nations, 2015a). Finally, Chen et al. (2015), looked at sustainable development indicators in the construction minerals industry in China.

For the Canadian Arctic, Azapagic's (2004) framework on sustainable development indicators for the mining industry which follows the GRI standards, provides a robust starting point to propose indicators. Azapagic (2004) proposes numerous categories for environmental indicators such as land use, materials, water, energy, closure & rehabilitation, biodiversity, air emissions, effluents, solid waste, nuisance, compliance & voluntary activities, transport & logistics, suppliers & contractors, and products. All these indicator categories are applicable for the Canadian Arctic, but due to the remoteness and harsh conditions of the Canadian Arctic, indicators concerning usage of materials, energy, and logistics will be especially pertinent, as it is extremely difficult and expensive to bring materials to site. The air emissions of GHG will also be relatively high for the mining industry due to the use of diesel generators for power and the long transportation distance. Furthermore, as other mines in the region have such a poor history of closure performance, robust closure & rehabilitation indicators to manage and track the mine's environmental liability are imperative. Finally, as discussed, building on permafrost is becoming more and more unpredictable due to climate change. Tracking how permafrost is changing year to year and developing permafrost management plans is needed.

3.7 Review of Environmental Decision-making and Environmental Management Tools in the Mining Industry

This section provides an overview of articles on environmental decision-making and environmental management tools in the mining industry. In-depth details on how to develop each of the methods or tools are not provided but readers are encouraged to analyze the referenced material. A few important examples from the articles are briefly discussed to present their potential application. Firstly, this section will discuss environmental decision-making methods followed by environmental management tools.

3.7.1 Environmental decision-making methods

For environmental decision-making, Multi-criteria Decision Methods (MCDM) were discussed extensively. MCDM, also known as multi-criteria decision analysis (MCDA), is a multi-dimensional decision-making framework that organizes and develops criteria to help structure solve complex problems (Govindan, 2015; Zopounidis and Doumpos, 2017). These methods are widely used in environmental decision making.

There are several types of MCDM techniques including Analytical Hierarchy Process (AHP), Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE), VlseKriterijuska optimizacija I komoro misno resenje (VIKOR), Elimination et choix traduisant la realit (ELECTRE), weighted aggregated sum product assessment (WASPAS), and Technique for order of preference by similarity to ideal solution (TOPSIS) (Sitorus et al., 2019). These techniques differ in the ways they compare and evaluate results. They also can vary in how they considered stakeholders. In most articles, the mine's stakeholders were used as the analyzed group. However, in several articles, stakeholders were not used, instead a group of experts (Govindan, 2015; Misthos et al., 2017; Shen et al., 2015). AHP and TOPSIS were the only method MCDM methods that were found in this analysis. Although TOPSIS was only found once, it was used by Kusi-Sarpong et al. (2015) to study the supply chain of the mining industry.

AHP was the most commonly used MCDM technique in the analyzed literature. AHP is a process to understand pairwise comparisons of criteria to determine preferences of a group with a ratio scale (Saaty, 1987). Freitas and Magrini (2013) assessed how to consider water in a dam at a mining complex while incorporating environmental, economic and company reputational indicators. Si et al. (2010) used an MCDM and AHP framework to analyze environmental sustainability of coal mining in the Qijang, Western China. Shen et al. (2015) used AHP to explore competitive priorities in the green supply chain management (GSCM) of mining companies to improve ecological performance. Finally, Sivakumar et al. (2015) analyzed vendor selection in the mining industry using AHP. Further reference on MCDM and AHP method can be found in Saaty (1987).

In addition to the different types of MCDM pro-cesses, like AHP, Fuzzy Logic and Spatial data were found to support an MCDM process. The use of Fuzzy logic was found in several articles to treat for vagueness and imprecise information when working with definitions of sustainability and how stakeholders select environmental indicators (Kommadath et al. 2012; Nuong et al. 2012, 2017). Finally, spatial data from GIS were found in several articles to have specific data for the distinct areas of a mine site (e.g. open pits, waste rock piles, and tailings dams) (Pavloudakis et al. 2009; Kodir et al. 2017).

This analysis provided a varied number and at times disparate group of articles. For example, Vela-Almeida et al. (2015) argued for strong sustainability through recognizing our planet's biophysical constraints in the analysis of mineral extraction. As argued, mining activities should depend on an investigation of the biophysical effects of mining activities on the local area. Additionally, to ensure sustainability of socio-ecological systems, they emphasize social deliberation is required for extraction decisions. They used a stock-flow/fund-service model based in ecosystem services as promoted by the ecological economist, Georgescu-Roegen (1971). Asamoah et al. (2017) used an emergy analysis to analyze the sustainability of small-scale artisanal mines in Ghana. Emergy is the measure of both direct and indirect energy to make a product or a service. Hasanuzzaman et al. (2018) used a Bradley–Terry model-based approach to examine the driving factors for sustainable coal-mining environment. Mpofu et al. (2017) reviewed the implications of using the precautionary principle for environmental management of acid rock drainage in South Africa. Finally, Grech et al.(2016) discussed the implications and importance of assessing cumulative impacts of the coal industry in Australia into an environmental decision-making process.

3.7.2 Environmental management tools

Life-cycle analysis (LCA), Environmental Management System (EMS), and Environmental Footprint analysis were found to be the main environmental management tools used by the mining industry. Each of these tools and their application will be introduced in this section.

A life-cycle analysis (LCA) is a holistic assessment of the environmental impacts of each step, input, or output of a process which can include transportation, distribution, extraction, maintenance (Jin and High 2004; Awuah-Offei and Adekpedjou 2011; Olivier et al. 2016; Hauschild et al. 2018). An LCA can give a robust high-level assessment of the environmental impacts of mining which can be used to support a decision-making process (Myllyviita et al. 2017). Further reference on LCA can be found with Hauschild et al. (2018) or Olivier et al. (2016). As found in this review for mining, these LCAs were applied at the ‘cradle to gate’ midpoint and not just from ‘cradle to grave’ as is common in an LCA (Pettersen and Song 2017; Masindi et al. 2018). However, an LCA as discussed by Kommadath et al. (2012) has some major weaknesses. It can be an extremely complex analysis, requiring a significant amount of time and resources to analyze the large amount of data. Additionally, it does not provide any means for trade-offs of different environmental impacts and results can vary considerably depending on the assumptions used.

Most of the articles found on LCA and the mining industry were high-level evaluations of the mining sector or a mining region. Yellishetty et al. (2009) examined some of the key issues with applying LCA to the mining industry. They specifically looked at land use impacts, abiotic resource depletion, how to apply open-loop recycling, and how to include the temporal sensitivities of LCA. Issues were found to be related to data quality and how an LCA under different assumptions can provide drastically different results. Awuah-Offei and Adekpedjou (2011) argued for future research to concentrate on developing mining specific LCA framework that included: ‘global warming potential, ozone depletion potential, human toxicity potential, freshwater aquatic ecotoxicity potential, acidification potential, eutrophication potential, land use impacts, and energy-use impacts’ as well as a way to consider how these impacts change throughout the mine life (Awuah-Offei and Adekpedjou 2011).

With a regional focus, both Balanay and Halog (2017) and Pettersen and Song (2017) investigated LCAs in the Philippines and the Arctic, respectively. Balanay and Halog (2017) discussed the potential of using LCA when working towards a circular economy. Pettersen and

Song (2017) analyzed the potential for LCAs in the Arctic (Pettersen and Song 2017). They analyzed a copper mine in Norway to highlight the Arctic specific considerations when conducting an LCA. These included: seasonality, cold climate, precipitation, and arctic marine life (Pettersen and Song 2017). Masindi et al. (2018) was the only article found that specifically analyzed an aspect of a mine and was applied across a region. Using an LCA methodology, they analyzed acid mine drainage treatment in South Africa to understand its associated environmental impacts of CO_2 emissions and environmental footprint.

Another important tool to discuss is the environmental management system (EMS). An EMS establishes procedures and responsibilities to ensure compliance with regulations, company policies, and community agreements (Hilson and Nayee 2002). It helps support and structure a decision-making process by providing the potential actions to achieve environmental compliance in various scenarios. As shown in this analysis, implementing an EMS is a common and important practice for the mining industry; however, some operations still do not have adequate environmental systems in place (Baumbach et al. 2013; Northey et al. 2013).

The intricacies of implementing an EMS for a mining site, specifically the ISO 14001 standard, were discussed in several articles (Newbold 2006; Donaldson et al. 2008; Botta et al. 2009; Baumbach et al. 2013; Jia et al. 2015). Many multi-national companies have adopted an ISO 14001 standard for their operations. ISO 14001 is a general framework that defines criteria for environmental management to improve overall environmental performance and to follow government regulations. However, as Botta et al. (2009) stress, there is a lack of sector-specific mining EMS guidelines. Many of the articles on EMS's analyzed regions or mines. Unfortunately, it is difficult to conclude at what level is best for an EMS (e.g. mine, region, country, continent). To consider cumulative impacts of mining, EMS could be successfully implemented on an overarching scale without limits of borders or jurisdictions. Environmental capacities of ecosystems could be the focus rather than regional regulations. Further international examples were found by Baumbach et al. (2013) in Brazil, Ellis et al. (2017) in New Zealand, and Nikolić et al. (2016) in Serbia.

A few studies reviewed the implications of using ecological and environmental footprint with mining operations. Ecological footprint is a specific indicator developed by Wackernagel and Rees (1996) to assess performance in environmental sustainability. Sinha et al. (2017) discussed using ecological footprint as an indicator of a mine site's overall environmental degradation. They investigated the air and soil quality of a coal mine in the Raniganj coal mining district of West Bengal, India. Northey et al. (2013) developed their own environmental footprint indicator that accounted for energy usage, GHG emissions, and water consumption reported in sustainability reports of copper mining companies. Finally, Northey et al. (2016) examined using only water for a footprint calculation of a mine site. These articles found ecological footprint calculations to be robust methods to track a wide range of mining impacts. Similar to an LCA, environmental footprinting could be used to support a decision-making process. However, they found there was a lack of consistent or appropriate data to provide a full industry analysis, or to compare operations (Northey et al. 2013, 2016; Sinha et al. 2017).

3.7.3 Summary and correlation between decision-making tools and methods

As seen in 3-4, the articles are organized based on the level of analysis (subset of a mine, mine level, commodity, region, or the entire mining industry). Regarding the level of analysis, most of the articles either explored the mining industry (46%) or were focused on a region (39%). Some regional-based articles that focused on commodities were categorized as regional (and not commodity) for this study.

The articles fell within one of the major methods described (e.g. AHP, Fuzzy Logic, LCA, EMS). However, there were articles such as Nuong et al. (2017), Chen et al. (2015), and

Table 3-4 Article review summary based on method and analysis level

method \ level	Mine subset	Mine level	Commodity	Region	Mining industry	Total
MCDM-AHP	1			1	2	4
MCDM-Fuzzy Logic			1		5	6
MCDM-Spatial Data				2		2
LCA				3	4	7
Indicators			1	1	4	6
EMS			1	5	2	8
Footprinting			1	1	1	3
Stock flow/fund					1	1
Emergy Analysis				1		1
Bradley–Terry Model				1		1
Precautionary Principal		1				1
Cumulative impacts				1		1
Total	1	1	4	16	19	41

Kommadath et al. (2012), that used both fuzzy logic and indicator selection. Nuong et al. (2012) used both AHP and fuzzy logic. To summarize, Figure 3-1 presents the relationship between decision-making techniques (green), supporting tools (blue). The main decision-making method found was MCDM with the supporting tools being LCAs, EMSs and Indicator selection. Fuzzy logic and spatial data were found to support an MCDM process. The green checkered circles represent the techniques that were not found in this review but are common in general MCDM literature. Methods that only appeared once in the analysis are not included in Figure 3-1 but are included in Table 3-4. Examples of decision-making outputs are given at the bottom of Figure 3-1 in the red box. Unfortunately, none of the MCDM methods found analyzed the operation phase or mine level. From the examination of environmental tools and decision-making methods currently being used by the mining industry, it is apparent that methods need to be adapted to the Arctic's environment and communities.

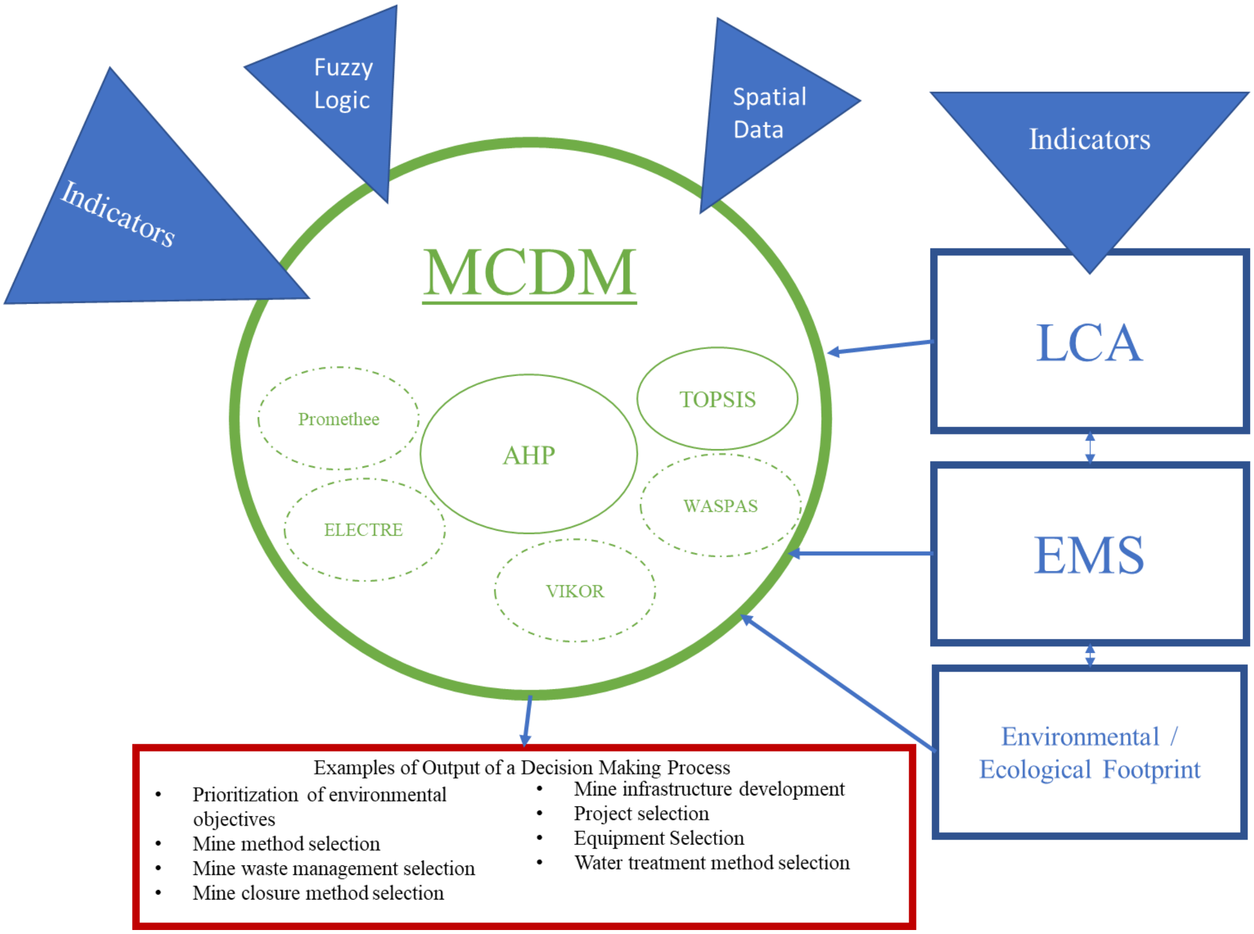

Figure 3-1 Relationship between Decision Making Techniques and Tools

3.8 Discussion – Proposed Environmental Planning Framework for the Canadian Arctic

As demonstrated, there are numerous methods and tools used for making decisions and managing environmental sustainability in the mining industry, all with their own merits and limitations. Synthesizing this study's analysis, Figure 3-2 brings together all the methods and tools analyzed in this paper to help organize and prioritize environmental issues associated with mining in the Arctic. A discussion for each step on how to consider both the intricacies of the Canadian Arctic, and the methods and tools for environmental management is provided. This described framework, simply named 'Environmental Sustainability Planning Framework', can provide guidance to compare options in the Canadian Arctic for energy management, mine waste management, post-closure land use, mine design methods, water treatment methods, and wild life management for mineral development properties. The method supports environmental decision making and incorporates environmental management tools, while weighing local and global environmental impacts of mining, environmental baseline assessments of the area, stakeholders' and rightsholders' values. This proposed method strives to be more transparent with applying the human-value-component to environmental sustainability, can be used at any stage of amine life, and provides a more holistic understanding of a project and region. Along with environmental sustainability, this framework aims to find opportunities for shared value between the community and proponent, social responsibility, and if appropriate, a social license to operate.

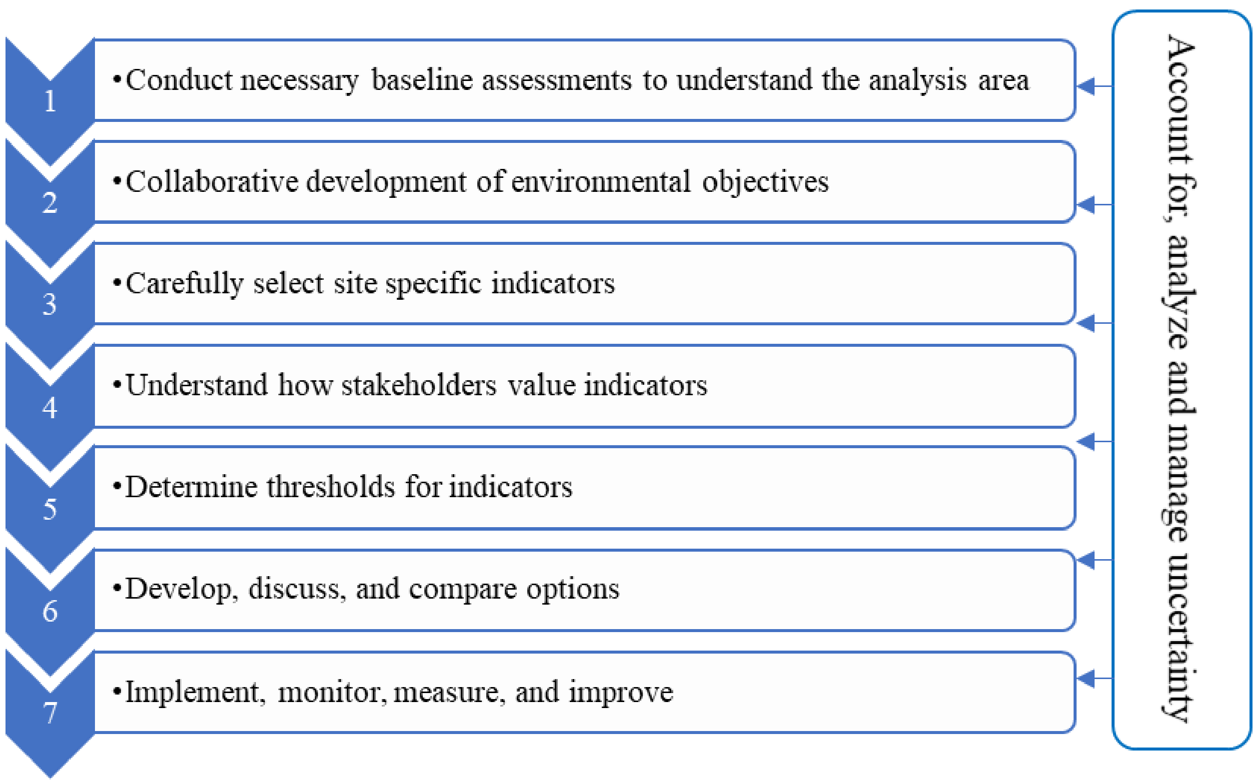

Figure 3-2 Environmental Sustainability Planning Framework

1. Conduct necessary baseline assessments to understand the analysis area

The site's baseline environmental data for climate, hydrology, mineralogy, wildlife, and local ecosystems need to be very well understood. Soil sampling, wildlife studies, water sampling, air quality, traditional knowledge studies, acid rock drainage, and metal leaching potential, must be conducted. From this, the capacity of the environment for effluents can be estimated. As discussed in the articles, mining in the Arctic would benefit from an LCA type assessment to provide a thorough understanding of the potential environmental impacts and to assist with decision-making related to site impacts. Unfortunately, LCA is not commonly used by the mining industry and an LCA process that is specific for the Canadian Arctic's environment needs to be developed (Yellishetty et al. 2009; Pettersen and Song 2017). Consensus for a LCA has not been reached on how to contend with the differences in temporal boundaries of the analysis, recycling of the output and input materials, units of measurement for impacts, how to incorporate land-use impacts, and global resource depletion (Yellishetty et al. 2009; Awuah-Offei and Adekpedjou 2011; Pettersen and Song 2017). Even though LCA methods need to continue to develop for the mining industry, an LCA tracks the necessary information for setting up amore holistic and robust analysis. Using an LCA to track and understand the relatively high GHG emissions of mining in the Canadian Arctic could be a useful application. Additionally, to track and understand the environmental impacts from the complex logistics and maintenance associated with operating remote mine sites.

2. Collaborative development of environmental objectives

Objectives could be used to maximize mine profitability, minimize environmental impacts, and to increase sustainable development. Although commonly used by proponents to evaluate projects, the opinion of the authors is that former of the three objectives does not provide society with the long-term benefits required; even when including externalities of environmental damage. It is impossible to fully value the environment in terms of dollars; it needs special considerations and a more qualitative integrated assessment (Daly 1980; Kosoy and Corbera 2010; Vela-Almeida et al. 2015). In the context of the Canadian Arctic, with limited economic opportunities, mineral development is one of a very select number of drivers for economic growth and job creation. Promoting environmental sustainability, which can be limiting to economic growth, is paramount to protecting the Arctic's fragile ecosystems. A multi-objective optimization problem, where maximizing an agreed upon definition of environmental sustainability and efficiency of a mine could be a way of organizing, understanding, and managing this trade-off. However, determining what exactly sustainable development is for each situation needs to be carefully discussed as it can be mean very different things for different communities and mining sites. The specific objective regarding the Canadian Arctic is to minimize the effect of climate change, adapt mining operations to the conditions of the Arctic, and find the best mining practices.

3. Carefully select site specific indicators

Indicators need to be selected and developed for the specific site, decision, and community. Every mine is unique in terms of environmental impacts due to the region's climate, geology, hydrogeology, mineralogy, local ecosystems, and associated mining methods. The indicators need to be understood, developed, and selected by the site's stakeholders and rightsholders for the specific site. Additionally, the indicators must be applicable and measurable for the objectives previously developed by the stakeholders. Environmental indicators should encompass the categories of water, soil, air, effluents, biodiversity, energy, emissions, ecosystem health, cultural heritage preservation, and mine closure (Azapagic 2004). For the Canadian

Arctic, where energy is predominantly derived from diesel generators, management of GHG emissions and energy is crucial. Operationally, an important consideration for many Arctic operations is how to deal with the decreasing permafrost layer. This is causing a much more complex and heterogeneous surface to build on for both the mine and its related infrastructure. Indicators for permafrost management, and permafrost management plans need to be incorporated.

4. Understand how stakeholders value indicators

After selecting the indicators in Step 3, understanding how stakeholders compare or value each indicator needs to be determined. With the support of technical experts, this comparison needs be from the region's stakeholders and rights-holding Indigenous communities. These communities are not homogenous and can value the environment in very different ways (Menzies 2006). Each community needs to be analyzed separately. Determining how communities compare the importance of water quality versus air quality or wildlife habitat versus greenhouse gas emissions can be very difficult and requires a strong level of trust and respect (Martinez-Alier et al. 1998; Cottier and Panizzon 2005). This information and discussion can perhaps be gleaned through conducting collaborative traditional knowledge studies (Ellis 2005). MCDM methods can be an important tool to structure, compare, and review environmental features and services of an area for stakeholder groups (Kamenopoulos et al. 2018). It can provide clarity for the complex and intricate nature of environmental trade-offs. Establishing trust through collaborative working groups and partnerships is paramount to understand the values, wants, and needs of the local communities.

5. Determine the thresholds for the indicators

Related to indicator valuation in Step 4, the acceptable values and thresholds for the selected indicators need to be examined. For example, threshold values for effluent discharge rates, GHG emissions, mine footprint, soil quality, water use, air quality, permafrost, noise, and wildlife impacts need to be established. Solely following local regulations may not be adequate or accepted by stakeholders and rightsholders. The limits for the indicators need to be anchored in both baseline data and stakeholders' values as developed in previous steps. However, as ecosystems continue to change due to climate change, it is difficult to determine what will be the new standard and what is possible to achieve for environmental technologies. As demonstrated in the analyzed articles and commonly used in Northern Canadian operations, EMSs are vital to ensure operations operate within the agreed upon conditions. EMS systems in the Canadian Arctic are used to minimize GHG emissions through managing transportation of materials as well as energy production from diesel generators. It is difficult to say when new environmental regulations will become more stringent but as more and more studies from researchers and global institutes like the United Nations show biodiversity loss, chemical pollution, ozone depletion, climate change, and water contamination, stricter environmental regulations are imminent (Rockström et al. 2009; United Nations Environment Program 2019).

6. Develop, discuss, and compare options

To achieve the accepted values for the indicators, and depending on the analyzed problem, options for energy management, material transportation, waste management, mine design, reclamation, post land use, water management, and wildlife management need to be developed. These options could be a specific work to be conducted, a management system to be put in place, or a design to be created. The final step of an MCDM for the decision-making group is to compare the potential options with the criteria developed. It provides a structured approach for reviewing decision options and alternatives. It is difficult to say which exact MCDM method is the most appropriate for the mining industry of the Canadian Arctic. In addition, deciding whether to incorporate fuzzy logic, spatial data, or any of the other decision-making techniques discussed in this article. What is paramount is to provide a clear, open, and flexible platform to collaborate and discuss the different options. It needs to be an iterative process, that incorporates new information, as the area changes over the mine life.

7. Implement, monitor, measure and improve

After selecting an option (a plan, design, or work) with the agreed upon indicators, a system to track, monitor, and improve, needs to be implemented to ensure standards are continually achieved. EMSs that follow the ISO 14001 standard are commonly implemented to ensure compliance with regulations and community agreements.

8. Account for, analyze, and manage uncertainty

Even with using the agreed upon indicators and methods, estimating the success of each management options has inherent uncertainty. This is listed as Step 8 but as seen in Figure 3-2, uncertainty needs to be understood and managed at all stages of the decision process. The uncertainty stems from estimations made in mineralogy, geology, climatology, ecology, and hydrology of the area. In addition, uncertainty can come from how communities view sustainable development success and the ability to model their views. Fuzzy logic was introduced into MCDM approaches to consider the uncertainties in applying different views and definitions of sustainable development (Kommadath et al. 2012). Significant areas of uncertainty for working in the Canadian Arctic are the depth of permafrost, the availability of transportation routes (air, road, and sea), snowfall, precipitation, wildlife interactions, and availability of materials.

3.9 Conclusion

The unique and remote environment of the Canadian Arctic provides numerous technical difficulties when planning for environmental sustainability. Operating mines in the Canadian Arctic produce significant amounts of GHGs. Materials and labour are extremely expensive; needing to be transported long distances by air, boat, or ice roads. Changes in the permafrost layer from climate change are creating uncertain challenges for construction and development. To align our use of metals and metal consumption for long-term sustainability, we need decision-making methods that are collaborative, inclusive, project specific, holistic, and can consider impacts on both a local and global scale. The Arctic is an opportunity to align the metals and mining industry sustainably into the future.

The future of the Arctic will depend on the impacts we see from climate change and if we are able to adapt. On the one hand, some claim that climate change will bring opportunities for new sea routes and will lead to more resource development opportunities. However, it will also bring unpredictability to seasonal ice roads' availability, permafrost, precipitation, extreme weather, iceberg risks on sea shipping, and overall costs. Climate change will lead to even more environmental impacts on an already fragile and sensitive ecosystem. Going forward, ensuring sustainability for our Arctic communities and their environment, through collaborative and open decision-making methods, is paramount. Decision-making methods for mining in the Canadian Arctic will need to focus on protecting community–environment interactions, incorporating community values, and ensuring operations are run in an efficient manner. In the presence of climate change and global environmental degradation, mining methods, environmental technologies, and humankind’s relationship with metals are due for a major overhaul. Research in the mining industry will need to focus on developing new mining methods that minimize environmental impacts through reducing the mine’s footprint, and energy, water, and chemical inputs.

3.10 Next Steps

This section provided an analysis of environmental sustainability focused decision making methods for the mining industry and proposed a new process to combine these findings. The challenges found in this analysis, in terms of incorporating multi-stakeholder preferences, are further analyzed in the next section using game theory. As will be discussed, game theory can provide a structured approach to incorporate and predict outcomes of stakeholders under cooperation or competition. The findings from this section feed into the next section’s analysis and development of potential games for the mining industry.

Chapter 4 - Game Theory for Analyzing and Improving Environmental Management in the Mining Industry

4.1 Abstract

The interactions, negotiations and decision-making involved in environmental sustainability in the mining industry are intricate and multi-faceted. Negotiations between communities, companies, governments, and countless other stakeholders occur predominantly during the permitting stage where potential impacts are estimated, management plans are established, site remediation is planned, and the sharing of benefits is discussed. Game theory is a structured tool that can investigate the interactions between two or more players to understand their actions under given conditions. There are many applications of game theory in economics, environmental economics, business, policy, and sciences; however, there are limited examples of applications in the mining industry. With a multi-criteria approach, this research develops five games to explore game theory for the mining industry. The games are developed to investigate scenarios that maximize both overall sustainability and environmental sustainability. A discussion is provided on the challenges of incorporating multi-criteria as well as the general issues with modelling environmental management problems with game theory for the mining industry. Finally, this paper concludes by providing future direction for further research and mineral policy.

4.2 Introduction

Today, society is faced with countless multi-faceted decisions on how to protect the environment while building just, equitable, and prosperous communities. Mined natural resources continue to be the driving force behind growth and development yet, their overuse has undoubtedly created the planet's current environmental distress (Ayres, 2016; Brown and Timmerman, 2015; Daly and Farley, 2010). On one hand, mined minerals are required for greener technologies such as wind power, solar power, and electric vehicles. On the other, some of the largest polluters in the world are mining companies (Heede, 2014, 2019). Decision-making for mineral development requires complex trade-offs with an understanding of the gains and losses of the numerous stakeholders affected by mineral development. Game theory is a method, developed in the 20th and 21st centuries, to investigate the interactions between groups, individuals, or "*players*". Its applications include modelling of environmental economic strategies to direct policy towards efficient outcomes for society on both local and international scales. However, mining, mineral development, and mineral economics, even though at the forefront of environmental decisions, have not been modeled using game theory on a meaningful level. With an ecological sustainability focus, this paper's goal is to explore how game theory can be used to understand the potential interactions and decision-making of players (e.g., mining companies, governments, communities, stakeholders, and the environment) in the global mining industry. Potential games are presented along with an analysis of how these games could be modeled using a multi-criteria approach to bring a more holistic and realistic consideration of ecological health.

Conventional economic and monetary based approaches typically are unable to provide a full estimate of the intricacies of the environment (Daly, 2007; Tacconi, 2000). Standard economic productive use typically values land in terms of farming, forestry, residential development, and resource development, but can fail to fully value areas that have cultural importance associated with stories, events, or ceremonies, as they can have an intrinsic value to certain groups (Gowdy, 1997; Kosoy and Corbera, 2010; Menzies, 2006; Vela-Almeida et al., 2015). Furthermore, personal values add complexity for decision-making, as groups or individuals can value the environment in conflicting ways (Martinez-Alier et al., 1998). A multi-criteria approach is presented in this work, where payoff evaluation goes beyond traditional economic approaches and includes environmental indicators that are developed or selected alongside the affected groups. The value-based decisions needed for developing and comparing criteria should be evaluated alongside the local community and project's stakeholders to understand the specific socio-cultural, economic, and environmental relationships (Collins and Kumral, 2020). For the use of multi-criteria and game theory, this article uses the mining industry as an example, but this method is also relevant to other environmental management issues outside of the mining industry. In addition to exploring game theory and the mining industry, this article provides a discussion into the potential use of multi-criteria with game theory.

Game theory can help present a simplified version of a problem to explore how two or more parties interact and make decisions (Bauso, 2016). There are countless types of games, each with different assumptions. Simplified or idealized games such as the prisoner's dilemma introduce concepts such as the Nash equilibrium, cooperation, zero-sum games, symmetric games, infinite games, simultaneous games, and complete/incomplete information that are applicable to more complicated real-world examples (Webster, 2009). To create a game, assumptions must be made on the type of game, the players' strategies, as well as the payoffs and losses for the decisions of each party (Benchekroun and Van Long, 2014). With a focus on reducing the environmental impacts of metals and minerals usage, this paper's contribution and originality is to investigate how game theory could be applied to environmental sustainability issues in the mining industry on both a local and global scale. This article will demonstrate that game theory can be used to understand the intricacies of the wins, losses, and value trade-offs of decisions to align research and development for more sustainable outcomes. Furthermore, that game theory can help develop mineral policy that strives for improved sustainability through understanding the behaviours and values of stakeholders.

The following section will present the methods used to develop the potential games. This paper will then introduce the concept of game theory, discuss previous applications, and finally important considerations when developing games for the mining industry. The essential components of a game: players, strategies, and payoffs, will be discussed throughout the proceeding sections. The potential games are presented in Section 4.6, followed by an investigation of the challenges in constructing these games using a multi-criteria approach.

4.3 Methods

A critical analysis was conducted on game theory and its potential application for environmental management issues in the mining industry. Comparing methodologies of game theory used in the mining industry was carried out to explore gaps and analyze opportunities for the application of game theory with environmental sustainability, mineral development, and policy. Firstly, an analysis of game theory was accomplished through the literature on its application within environmental economics, environmental policy, and engineering. Secondly, an analysis was conducted to investigate game theory's application on mineral development issues. Finally, an investigation on how multi-criteria can be incorporated into game theory was carried out.

Potential applications, which focused on sustainability, were developed based on the gaps found in the literature and the authors' previous experience on this topic. These are presented in Section 4.4 as scenarios with various players, payoffs, and assumptions. Section 4.7 then discusses the challenges for the application of game theory and multi-criteria for the environmentally focused scenarios and games presented in Section 4.6.

To understand current applications of game theory, the key words of "*Game theory*", "*Mining*", "*Minerals*", "*Metals*", "*Multi-Criteria*" and "*Environmental Sustainability*" were used individually and in combination to search McGill's University Library Database, Scopus, Web of Science, and Google Scholar Databases for articles over the last 20 years (2000–2019). This by no means was to suppose to be an exhaustive literature review of environmental sustainability and game theory, but rather to ensure a thorough understanding for potential application in the mining industry. From these searches forty-three articles and eight textbooks were reviewed. The next section will present the analysis of the articles found on game theory and its application for mining. It will also be the basis of this paper's main contribution, which is the development of potential games for environmental management in the mining industry.

4.4 Game Theory Analysis and Applications

Game theory is a method to model and analyze the strategic relationships, situations, and interactions between players to understand the most likely or best outcomes (Matsumoto and Szidarovszky, 2015). Game theory was originally grounded in the field of economics by von Neumann and Morgenstern (1944) and further developed by John Nash (1950) and Lloyd Shapley (1953). Today there are numerous applications in public policy, economics, law, business, decision-making, computer science, engineering and, as will be presented in the next section on environmental decision-making (Dinar et al., 2008).

To provide a general overview, Bauso (2016) discusses that to set-up a game, two important distinctions are needed: non-cooperative vs. cooperative and simultaneous vs. sequential. Cooperative games are when the players are looking for a joint action which works for the entire group. Players have a pre-play communication stage and side-payments depend on if the utility of the outcomes is transferable. Non-cooperative games are when every player is looking to maximize their own payoff and make decisions based on what they know about the other players. Regarding simultaneous and sequential games, simultaneous games are simply when players make decisions at the same time. For sequential games, an order must be established; each stage information is collected based on previous decisions; the player must make their decision based on the games' "*state*"; and finally, the strategy is selected for the duration of the game. In cooperative, non-cooperative, simultaneous, and sequential games, different players can have unassociated strategies, which can create unique outcomes. A special outcome, called the Nash equilibrium, occurs when no player can be better off from deviating from the current outcome (Hanley and Folmer, 1998; Webster, 2009).

In terms of cooperative vs. non-cooperative games for environmental management, society is at a point where we need to create cooperative solutions (Henckens et al., 2018). Environmental degradation, greenhouse effect and climate change are global problems which require transboundary agreements. Unfortunately, many countries try to capitalize on free-riding of well-performing countries (Hanley and Folmer, 1998) and thus agreements like the Paris Climate Change Agreement have failed to reach their emission reduction targets (Ratha, 2019). Environmental management is best done cooperatively, yet realistically and internationally it is done competitively. The next section will further discuss environmental sustainability and management applications which are analyzed using game theory.

4.4.1 Overview of environmental sustainability applications

There is considerable literature on game theory's application within environmental management for policy, business, and economics. Game theory has been used to analyze the management of fisheries, greenhouse gas emissions, transboundary pollution, and water management to determine potential abatement costs, liabilities, and incentive programs (Dinar et al., 2008; Webster, 2009). This section does not attempt an all-encompassing review of game theory's application in environmental management but brings a high-level overview to provide a base to develop games for the mining industry.

Game theory can be used to model the complex relationships be-tween parties or stakeholders who are affected by environmental impacts (e.g. climate change, natural resource degradation, etc.) on both a local and global level (Ostrom et al., 1994; Wood, 2011). As models become more complicated, methods from computer science or software can be used to calculate equilibriums and potential outcomes (Mckelvey et al., 2016). On a local level, game theory can analyze regional use and management of common-pool resources. Common pool resources and the concept of "*tragedy of the commons*" as first discussed by Hardin (1968), is when a resource, like water or grazing land, is exploited by its users who are trying to maximize their benefits. This unfortunately can cause the shared resource to collapse. Ostrom (1990) furthered this discussion by investigating how communities manage their local common-pool resource and how success can be found in local self-governance. Stemming from this, game theory can analyze cooperation as well as competition with managing of common-pool resources (on both a local and international level) in research such as Ostrom et al. (1994), Lee (2012), Swart and Zevenberg (2018) and with further examples in Dinar et al. (2008) and Carraro and Filar (1995).

On a global level, game theory lends itself well to analyzing the interactions of countries for environmental and pollution management, as shown in Benchekroun and Van Long (2014) and Haurie and Zaccour (1995). Climate change and carbon emission management strategies are often modeled on a government level as discussed in Carfi and Schiliro (2013), Kaitala and Pohjola (1995), and Wood (2011), but also, Kruitwagen et al, (2017) with the modelling of investors and companies. The exploration of cooperation, non-cooperation, and bargaining are at the core of these types of analyses. In these games, asymmetries in environmental damages, technical capacity, and emission abatement costs play a major role in designing cooperative environmental agreements for reducing the scale of global environmental impacts (Frisvold and Emerick, 2008; Haurie and Zaccour, 1995; Kaitala and Pohjola, 1995). Unfortunately, on an international level, games are more often competitive in nature, caused by the influence of freeriding nations, and nations potentially being worse-off economically due to stricter environmental policies (Dinar et al., 2008).

To ensure fairness and promote cooperation, game theory can help to redistribute the gains through possible side-payments. These side payments can be established for example by ensuring the marginal cost (or gains) of each user is distributed fairly (e.g., Shapley Value), through Nash bargaining, or by establishing cost-sharing rules (e.g., taxes, permits, fines, or subsidies), (Dinar et al., 2008). There are countless applications, variations, and examples of these types of games in the literature. The next section analyzes the current application of game theory and the mining industry to understand possible crossover applications.

4.4.2 Mining applications

Only thirteen articles were found which used game theory with a mining based problem. Major discussion points in the articles were on how to account for uncertainty, incomplete information, and on solving several objectives simultaneously. Three publications focused on safety and evolutionary game theory. Liu et al. (2019) modeled a multi-player game focussing on safety regulations and penalties, while Lu et al. (2018) more generally analyzed the behaviors of the players and strategies. Yu et al. (2019) looked at the asymmetric aspect of safety between workers and safety managers, encouraging dynamic incentive programs.

Using game theory, several publications focused on how to achieve best practices between mining companies and the regulators. Kaluski (2011), reviewed how a model could be used to plan and manage the required materials for a coal mining operation. Wang (2019), used an evolutionary game model to analyze why offshore mining companies perform poorly environmentally, and what role the government should take to encourage environmental protection. Podimata and Yannopoulos (2016), analyzed the decisions of companies and regulators for riverbed mining to maximize profitability and ensure environmental risks and impacts are minimized. In this game, the government profits from extraction but can levy fines, penalties, and exclusions to the companies if they extract more than what the river can provide. Finally, Sinha et al. (2013) used environmental economics to find a balance between profit maximization, taxes, and reduction of welfare from environment pollution in a Stackelberg game where the regulator was the "*leader*" and the mining company was the "*follower*".

A couple articles explored the interaction between mining companies and water management. Figueroa (2013) analyzed the conflicts between mining companies and communities using a Bayesian approach to incomplete information between players. To understand a variety of possible solutions, Szidarovszky et al. (1984) used game theory with a multi-objective problem of considering mining costs, the water supply of an aquifer, and environmental protection.

Several articles took unique approaches to using game theory and mining. Krzak (2013, 2014) used a pseudo-player "*nature*" to account for the uncertainties of the location and mineral deposit. This was used to understand the development potential of an orebody. In Krzak (2014), he explored Bayesian games additionally to account for the incomplete information when using game theory. Cole et al, (2014), takes a more economic approach to game theory and touches on the interactions and conflicts with mining in the context of the Arctic. He discussed game theory on a more general sense to understand if the bargaining parties can reach an acceptable outcome. This was discussed both at an international level with Arctic countries but also at a local level with stakeholders and communities. Finally, Boyce, 1997 analyzed why mine's joint venture partners failed to create a successful business relationship. Articles such as Han et al. (2015) which explore policies around specific commodities (e.g., Rare earth metals) are not included in this analysis but provide an interesting review of how countries can determine tax rates or levels of production.

4.4.3 Multi-criteria analysis and game theory

Multi-criteria and game theory can be integrated through multiple methodological schemes (Deng et al., 2014). The integration of multi-criteria and game theory is often through multi-criteria decision making (MCDM), also known as, multi-criteria decisions analysis (MCDA) (Benyoucef et al., 2014). For an MCDM process a variety of criteria and indicators can be integrated for trade-offs between alternatives (Govindan, 2015; Zopounidis and Doumpos, 2017). Multiple types of MCDM methods exist such as Analytical Hierarchy Process (AHP), PROMETHEE, VIKOR, ELECTRE, WASPAS, and TOPSIS (Sitorus et al., 2019). These techniques differ in how they compare and evaluate preferences of indicators and criteria. A key challenge in the practical application of game theory is to attach a payoff value associated with a strategy of a player. MCDM approaches could be used to determine these payoffs. As mentioned, it is extremely difficult to value the environment due to its cultural, ethical, and aesthetic dimensions which can be different for different players (Gowdy, 1997; Vela-Almeida et al., 2015). MCDM techniques can be used for valuing, ranking, and classifying indicators or actions for decision-making (Deng et al., 2014). As is common in MCDM, a questionnaire or a focus group could be developed to determine the values for a player's strategy profile for a specific project (Zopounidis and Doumpos, 2017).

Game theory is also noted to aid MCDM techniques as MCDM alone does not consider the competitive environment of decision makers (Chen et al., 2013; Deng et al., 2014). This is demonstrated when game theory is used to investigate strategies of the participants in an MCDM, as discussed in Aplak and Sogut (2013), Chen et al. (2013), Debnath et al. (2018), and Hashemkhani Zolfani et al. (2015). On a general level, they establish games from the fact that MCDMs are simply when participants are making simultaneous decisions. From this, one can take criteria and alternatives within MCDM as the strategies of the players to be analyzed with game theory (Debnath et al., 2018). The detailed methodologies in this research field vary considerably with the choices of how to include or not include fuzzy sets, Monte Carlo simulations, and uncertainty analyses (Madani and Lund, 2011; Medineckiene et al., 2011; Wu et al., 2018).

The combination of game theory and MCDM can be found in many applications such as dwelling selection by Medineckiene et al. (2011), water resource systems by Madani and Lund

(2011), energy management by Wu et al. (2018), and Aplak and Sogut (2013), market volatility in the tea industry by Debnath et al. (2018), and risk management of urban tunnels by Nikkhah et al. (2019). On the other hand, many of the examples of MCDM and game theory are presented as general mathematical processes without an application to a specific industry (Aplak and Türkbey, 2013; Chen et al., 2013; Deng et al., 2014; Wolny, 2008).

A few examples exist in the mining industry, as discussed in Section 4.4.2, Sinha et al. (2013) and Szidarovszky et al. (1984) both used multi-criteria analyses to balance mining and environmental damages but with very different problems and game structures. The articles developed methods to incorporate preferences of the users to compare the various objectives and criteria.

As discussed in this section, there are many ways to incorporate a multi-criteria analysis with game theory. This research argues for the general use of multi-criteria to provide a more pluralistic analysis but does not argue for how multi-criteria should exactly be incorporated. However, as an example this research discusses the use of multi-criteria through the incorporation of payoff functions, as will be discussed at the beginning of Section 4.6. An essential goal for this work is to promote multi-criteria analysis with game theory to integrate incommensurable criteria and values, as discussed by Wolny (2008). With this section's analysis, and with the development of potential games and players, this research aims to provide an appreciation of the opportunities that exist in using multi-criteria and game theory to solve complex problems in the mining industry.

4.5 Potential Players

Countless groups, communities, industries, and governments are directly involved, influenced, and impacted by mineral development. To determine the types of games for environmental management in the mining industry, the potential players need to be introduced and discussed. This section introduces some of the key players who are commonly included in environmental impact assessments for mineral development properties (Azapagic, 2004; Viveros, 2016). Their key drivers and some important assumptions are outlined for game theory analysis. This not an exhaustive list of stakeholders or players who are affected from the mining industry. The goal of this section is to provide an appreciation for the type of thinking that needs to be conducted to implement an affected group into a game theory model.

4.5.1 Mining company

As a business, a mining company's goals are to maximize their profits while following regulations and upkeeping their reputation. Mining companies and regulators have partnered to create numerous sustainable development initiatives, such as the International Council on Mining and Metals (ICMM, 2015), the Mining Association of Canada's (MAC) Towards Sustainable Mining (The Mining Association of Canada, 2004), and Australia's Leading Practice Guides (Australian Government, 2011); however, a company exists primarily to grow economically and is not altruistic. A mining company must perform to the level of regulations but in regions of lower regulations mining companies at times follow global best practices as recommended by the previously mentioned mining sustainable development initiatives. Environmental performance requirements can also stem from agreements with local stakeholders and communities (Gibson and O'Faircheallaigh, 2015).

4.5.2 Government agencies or representatives

Government mandates depend on the political party in power but are generally attempting to maximize the well-being of society or a nation through shared economic growth, social services, health services, infrastructure, and education (Bara and Pennington, 2009). Mineral development can provide governments with taxes and help spur economic development. Environmental regulations are established by government agencies but can greatly vary from country to country or even from region to region. Governments can impose tariffs, penalties, or rewards to ensure regulatory compliance is met; this is commonly analyzed by game theory (Dinar et al., 2008). When mines go bankrupt, governments are often left with managing the environmental risks and the costs for reclamation (Warhurst and Noronha, 2000). It is therefore in the government's best interest to ensure environmental compliance is met and adequate funds are available to reclaim the land if the proponent were to go bankrupt (Peck and Sinding, 2009). In some games, the government is not necessarily a player, but rather the policies implemented by the government are analyzed to see how they affect companies or individuals (Carfi and Schiliro, 2013; Kaitala and Pohjola, 1995; Wood, 2011). On an international level, governments could be looking to compete globally for trade and economic growth opportunities.

4.5.3 Communities

What a community values can vary considerably and depends on their culture, wants, needs, historical context, and region (Babi et al., 2016; Dery Tuokuu et al., 2019; Svobodova et al., 2019; Tacconi, 2000). The mining industry commonly uses the term "*social license to operate*" to describe community acceptance and reaching an agreement to operate in collaboration (Boutilier and Thomson, 2018; Owen and Kemp, 2013). For these agreements, some communities could strongly value environmental sustainability while others are more inclined to value economic development and job creation. Preferences aside, environmental degradation from mining greatly affects local communities over the long-term and must be carefully considered. In a game, their preferences need to be understood to develop a payoff or loss function. Each community is unique, and they need to be consulted and collaborated with for any game in which they are analyzed. All impacted communities should be included and modeled in these games. Local Indigenous communities need special consideration. After generations of cultural genocide by Western societies, Indigenous communities around the world are finally starting to be heard through documents such as the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) in 2007. They are now seen more as rightsholders rather than stakeholders, who require meaningful collaboration for any development and decisions in their territory (UN General Assembly, 2007).

Future generation could theoretically be included but several complex assumptions on values would be required. Questions that would be required to be rectified would be: how much do we want to leave our future generations? How many generations forward should we look? What standard of living do we want for our future generations? These questions vary considerably between individuals and groups. This research aims that through a general multi-criteria process, the overall values of a community would be incorporated, which depending on the community, could or could not include future generations.

4.5.4 Non-governmental organizations

Non-governmental organizations have an important role in influencing mining performance as they can function on a more interjurisdictional level (Filho et al., 2019; Viveros, 2016). Some groups push for better wildlife rights, conservation, clean water, air quality, or community health

(ICMM, 2015). It could be complicated to model their payoffs or losses with game theory as they are dependent on donations, which depend on the values, wants, and needs of their many donors.

4.5.5 Affected businesses

There are both positively and negatively affected businesses alongside mining projects (Azapagic, 2004). Mining projects can be a strain on the local resources, which can negatively impact other industries such as forestry and agriculture but can positively impact many services and suppliers to the mine. Negative externalities from pollution can impact many businesses in the local area which rely on a clean local environment. The terms "*Dutch Disease*" or "*Resource Curse*" are commonly used to describe when the overall economy is actually worse off from resource development (Elbra, 2017). The term Resource Curse relates to a multitude of factors such as an increase in conflicts, corruption, and inequities from resource development, while the term Dutch Disease relates to factors associated with currency appreciation such as spending effect, and labor and resource movement. The opportunities for many local businesses can drastically grow when a mine opens, unfortunately, the economic opportunities created by the mine do not last forever. Careful consideration is needed for ensuring the mining community can transfer the opportunities during the mine-life into non-mining related industries (Warhurst and Noronha, 2000).

4.5.6 Environment

The final player in the mining space is the environment, which can be arguably impossible to model adequately. Ecosystems are extremely complex and can be highly variable in terms of how they function, as well as their sensitivities and vulnerabilities. Additionally, they can be valued diversely between and within stakeholder groups (Ascough et al., 2008; Tacconi, 2000). Nonetheless, thriving ecosystems must be maintained to provide the planet with the fresh water, clean air, fertile land, and food, needed to sustain life. Decision-making methods have generally failed to fully account for the interconnectedness and relationships of ecosystems on both a local and global scale (Gowdy, 1997; Vela-Almeida et al., 2015). A healthy environment still needs to somehow be valued and incorporated into a game even if it is not directly through the values of the communities, companies, NGOs, or governments. The environment is often not directly brought in as a player but impacts of lowering of environmental health are seen within the payoff function of communities (Hanley and Folmer, 1998). The mining methods chosen, and the environmental impacts are closely linked. Different mining methods affect the environment in different ways. For example, open pits and underground caving methods are at times more economically efficient but alter the landscape much more as compared to other methods. Furthermore, choices in mine waste storage, water usage, mineral processing methods, and mine closure can greatly affect the environment (Lottermoser, 2010).

4.6 Potential Games and Scenarios

This section presents five potential games within the mining industry and between the players introduced in Section 4.5. The games are summarized in Table 4-1, which presents their key features, potential players, considerations for multi-criteria, and main references. There could be many iterations and changes to the assumption for these presented games, but the main goal of this section is to provide examples of games that could be analyzed from the mining industry using multi-criteria. Before introducing the games, a high-level discussion of how multi-criteria could be implemented is provided.

As discussed in Section 4.4.3, there are many ways to incorporate multi-criteria. This research argues for games to use environmental or sustainability indicators for the payoff functions to provide a more pluralistic analysis of the environment. These indicators could be incorporated into the payoff functions with the objective of minimizing, maximizing, or establishing a threshold for each indicator. If the objective for the indicator is achieved, then depending on the values of the player, a utility could be provided to the player as seen in Aplak and Türkbey (2013), Sinha et al. (2013), and Szidarovszky et al. (1984). Monte Carlo simulation which uses random sampling to obtain results, is suggested for analyzing the effect of value systems in the analysis as discussed by Madani and Lund (2011). Furthermore, fuzzy information sets could be used to define success and provide full or partial value (see game 2 below). Through the use of various criteria and with an analysis on how value systems affect the results, this research aims to bring a more holistic understanding of the environment when making decisions alongside other actors. In addition, to provide clarity on the personal value trade-offs that are involved in the players' decisions. The specific games are introduced below, with a more focussed discussion of how they could include various criteria.

4.6.1 Game 1: international environmental management and mining

A common application for game theory is exploring environmental management at an international level (Carraro and Filar, 1995). Environmental impacts, management and policy development for mining is a global problem. Impacts of mining are not necessarily localized in a region or country, as the use of water, energy, and land in conjunction with the release of contaminants (e.g. emissions, heavy metals) can have impacts far away from mining regions. Inconsistent regulations across jurisdictions make it challenging to ensure the global mining industry keeps to the highest standards for GHG emissions, water usage, energy usage, mine waste management, and reclamation, while also encouraging economic development. The decision to develop a mining area is a cooperative and simultaneous game where every player is trying to be economically prosperous while ensuring they have healthy ecosystems. The payoffs from the mine's taxes are relatively easy to consider for game 1, as seen in Binmore (2007), Podimata and Yannopoulos (2016) and Figueroa (2013); however, the benefits from healthy ecosystems are not. Implementing environmental performance criteria and indicators into game 1 by adding them as an objective to either minimize or maximize, could provide a more accurate consideration of the environment. For comparison of taxes with environmental indicators, a value indicator is needed, but these can be simply added as variables to investigate sensitivities. As mentioned, Monte Carlo analyses could be implemented to examine how the results change with differing value systems (Madani and Lund, 2011). In practice in an international setting, governments often have been unable to fully account for and prioritize environmental sustainability (Gowdy, 1997). This is evident in our greenhouse gas emissions, where global initiatives have failed to enforce targets and many countries are attempting to act as free riders (Dinar et al., 2008; Hanley and Folmer, 1998).

An important issue with Game 1 is that there are asymmetries between countries for abatement costs and environmental damage (Hanley and Folmer, 1998; Vrieze, 1995). Some countries are worse off than others from the environmental damage caused by mineral activities. An international oversight committee is necessary to ensure mining practices are consistent across jurisdictions. Groups like the ICMM (2015), The Mining Association of Canada, 2004, or the Australian Government's Leading Practice Program (Australian Government, 2011) provide some guidelines for mining practices across jurisdictions but unfortunately often do not have adequate power to ensure best-practices are met across international jurisdictions. Game theory can lend itself to determining the types of payoffs and appropriate penalties to ensure compliance is met by the proponents. Unfortunately, countries can be unamenable to following cooperative environmental agreements as some countries will regress to free riding to avoid potential short-term economic losses.

4.6.2 Game 2: impact benefit agreements (IBA) – companies and communities

In many mining countries such as Canada and Australia, when a project is in permitting, an impact benefit agreement, benefit-sharing agreements, or community sharing agreements are now commonly negotiated between the mining company and local communities (O'Faircheallaigh, 2018). These typically outline the requirements for investment, environmental performance, social sustainability, and economic opportunities for the local community (Craik et al., 2017; Gibson and O'Faircheallaigh, 2015). However these agreements are not necessarily required, but are done in good faith by the mining company. Many factors come into play with the types of benefits the community can receive (Adebay and Werker, 2019). A bargaining type game, as discussed in Cole et al, (2014), could be developed to model this situation between the mining company and the community to determine the types of payoffs or environmental performance required for accepting or denying the mine. If the community rejects the IBA, it could decrease the chance the mine would be permitted, increase the chance for protests or construction delays, and impact the company's reputation. This is a repeated and sequential game which ends if players accept the proposal. The proposal by the company would either satisfy, not satisfy, or something in-between, for different criteria. The payoffs for the criteria would again be based on the values of the players, which could be analyzed using Monte Carlo analysis. However, in this case the notion of satisfy, not-satisfy, or an "*in between*" case could be an opportunity to provide partial utility with the use of fuzzy sets as shown by Aplak and Türkbey (2013) or Medineckiene et al. (2011).

4.6.3 Game 3: cumulative impacts of mining and other users in a region for common-pool resources

A region typically has many users such as mines, farms, residents, and factories who all require the use of local resources (e.g., water, air, and land). However, the cumulative environmental impacts of these users and the carrying capacity of the region is often not well understood. Depending on the region, competition between mining companies and other users exists for water usage, land use, power, materials, and emissions (Kaluski, 2011; Podimata and Yannopoulos, 2016; Szidarovszky et al., 1984). Using game theory to determine thresholds for users, environmental impacts could be capped or heavily taxed in the region. Unfortunately, the thresholds for environmental use of all users can be difficult to determine but generally needs to be based on environmental studies that take into consideration the region's specific environmental carrying capacity. The carrying capacity is typically determined by studies on hydrology, mineralogy, geology, and ecology, for example. These studies can also help determine which criteria are to be implemented into the payoff functions for the game. If a threshold for overall environmental usage is accurately determined, this could be a zero-sum game. Each criteria could have its own threshold or objective for the players' payoff function (Deng et al., 2014). This is a non-cooperative game as each user is competing for permits and resources. As mentioned, the use and management of common-pool resources are extensively discussed and applied by many scholars in game theory (Ostrom et al., 1994). The incorporation of mining users could help explore their relationships with the environment, and how the mining industry should bid on permits (Binmore, 2007).

4.6.4 Game 4: environmental sustainability negotiations between company, community, and government

A company, community, and government are all trying to be prosperous during environmental negotiations. As previously discussed, a company is trying to maximize their profits, upkeep its reputation, and follow regulations. The regulators are trying to fulfill their mandates, which include economic, social, and environmental policies. Finally, the community is trying to maximize their long term well-being and sustainability. As stated, the issue is each group is affected by the game's potential outcomes in different ways (Owen and Kemp, 2013; Tacconi, 2000). For example, local communities are typically more affected by environmental sustainability than both the government and the company (Horowitz et al., 2018). To consider contrasting values, this type of game requires a multi-criteria approach. The use of sustainability indicators must be specifically selected for the project and determined collaboratively with all stakeholders (Azapagic, 2004). As previously outlined, the multi-criteria indicators can have different rules or objectives in the payoff functions (e.g., min, max). Players can attain a certain utility based on their values if the scenario in the game satisfies their wants (see the beginning of this section and Section 4.3.3 for more details).

This type of scenario has many applications for a mineral development area. It could help make decisions for mine planning, mine closure planning, and developing environmental management plans. This is another type of sequential bargaining game, as discussed by Cole et al, (2014), where mining companies provide proposals while governments and communities can reject or accept the project. Depending on the region, some communities may have more power and influence than others. Regulators in times of conflict will have to choose to either side with the community or company. This can also be applied to NGOs, affected businesses, and project stakeholders.

4.6.5 Game 5: a mine and the local environment

The goal of game 5 is to understand the complex relationship between mineral development and the local environment; or how the local environment would react to development. Our environment is a series of relationships between flora, fauna, and different ecosystems to bring the planet life-supporting services such as clean water, air, soil, and food (Brown and Timmerman, 2015; Costanza et al., 2015; Gowdy, 1997). A mine must predict how the environment will react to changes, to ensure regulations are followed. This should be grounded in baseline testing on the local climate, hydrology, mineralogy, wildlife, and general ecosystem health from soil sampling, wildlife studies, water sampling, air quality testing, traditional knowledge studies, acid rock drainage, and metal leaching potential. A mineral development property has many distinct parts which affect the environment in unique ways. Open pits, waste rock piles, underground openings, tailings management facilities, mineral processing facilities, and their related infrastructure have distinct environmental impacts (Bardi, 2013; Lottermoser, 2010). Game 5 models the decision of expanding one or all these areas of a mine site to see how the environment reacts under uncertainty. For this game, one must measure using environmental indicators to ascertain how the environment could react or change from mineral development. The company’s payoff function is based on the wealth it generates from the mine with losses relating to how much closure costs could increase, it is reputational risks, and the potential increase of environmental liabilities. A game using the environment as a player was not found in this analysis, but Krzak (2013, 2014) used a pseudo-player to account for the uncertainties of the region. This is not exactly what is proposed in this game, but implementing the environment in a game, as “*uncertainties*”, could be a useful method. The multi-criteria approach stems from the environmental indicators that could be implemented through the payoff functions, and as described in the previous games.

Table 4-1 Summary of Proposed Games

#	Title	Goal	Highlights	Game Types	Potential Players	Key References	Multi-criteria Considerations
1	International environmental management	Determine how to prioritize environmental management on an international level.	• Aids regulators on mineral development decisions • International compliance • Asymmetric costs and environmental damages • Mineral policy development	• Cooperative • Simultaneous	• Various nations	• Boyce (1997) • Carraro and Filar, (1995) • Figueroa (2013) • Podimata and Yannopoulos (2016) 9.	• Sustainability indicator selection • Values of various nations and if they represent their people. • Analysis area • Monte Carlo for uncertainty • Criteria thresholds, or min and max. • Indicator acceptance • Values and goals could change over time. • Thresholds based on environmental studies and collaboration between players
2	Impact Benefit Agreements	Determine how to successfully share benefit and minimize impacts of a mining company and a community.	• Collaboration with stakeholders • Benefit sharing • Environmental performance agreements	• Bargaining • Repeated • Sequential	• Mining Companies • Stakeholder groups • Communities	• Cole at al., (2014) • Gibson and O'Faircheallaigh, (2018, 2015) • Aplak and Turkbey (2013) • Medineckiene et al. (2011)	
3	Cumulative impacts and common-pool resources	Analyze how different users share resources in a region.	• Sharing of local resources under competition • Regulating users of the environment • Regional focus • Permitting	• Non-cooperative game • Zero-sum	• Mining Companies • Businesses • Users of the environment • Stakeholder groups • Communities	• Kaluski, (2011) • Ostrom, (1994) • Podimata and Yannopoulos, (2016) • Szidarovszky et al., (1984)	
4	Environmental sustainability negotiations	Explore how a mine makes environmental sustainability decisions while considering different stakeholders.	• Negotiations for mineral development • Asymmetric costs and environmental damage	• Bargaining • Repeated • Sequential	• Mining Companies • Regulators • Local Community • Stakeholders	• Azapagic, (2004) • Cole at al. (2014) • Tacconi, (2013)	
5	A mine and the local environment	Investigate how a mine and its environment interact	• Analyzing the relationship between mineral development and ecosystems • Incorporating environmental risk • To aid in decisions for developing areas of a mine site	• Uncertainty • Incomplete information	• Mining company • Local Environment	• Costanza et al., (2015); • Gowdy, (1997) • Krzak (2013, 2014) • Lottermoser, (2010)	

4.7 Analysis and Considerations

From analysing these potential games, a few considerations standout. Firstly, when developing these games, the payoff functions are very complex. Exactly how these are developed will depend on both the specific game, as in Games 1–5 presented above, and the specified players. The environment, community, and the mine can all be unique from project to project with their losses or payoffs valued in at times conflicting ways. This paper's goal was not to provide a single method to develop payoff functions but to provide an appreciation of all the factors involved in doing so. One of the most complex factors to be discussed in this section is the valuation of the environment. As mentioned, the environment or local ecosystem can be valued drastically different based on an individual's background, wants, needs, and position within society (Kenter et al., 2015; Martinez-Alier et al., 1998; Norton, 2017). The environment can bring value from its cultural and aesthetic features, which dollar-based analyses struggle to consider (Daly and Farley, 2011; Vela-Almeida et al., 2015). To account for the complexity of modelling and valuing the environment, a multi-criteria approach using sustainability indicators would create a method to understand the potential environmental impacts of mining.

With game theory, the use of multi-criteria is commonly applied within Multi-Criteria Decision Making (MCDM) as shown in Section 4.3.3 (Sitorus et al., 2019). There are countless applications across different sectors with different methodologies. Unfortunately, as shown in Section 4.4.2 and 4.4.1, there are few examples of mining applications in game theory and with the incorporation of multi-criteria. In these proposed games, a multi-criteria approach like in an MCDM, where indicators and preferences are selected, could be transferable to the development of payoff functions. The steps can include but are not limited to: establishing objectives, selecting indicators, valuing indicators, developing alternatives choices, and selecting an alternative (Chen et al., 2015; Collins and Kumral, 2020; Kamenopoulos et al., 2018 Nuong et al., 2017). In terms of valuing indicators, this research proposes the use of Monte Carlo simulation, to understand the sensitivities of the games to variances in values for the players, as discussed by Madani and Lund (2011). Furthermore, the development and selection of alternatives in MCDM processes could help with the creation of the games by providing a better understanding of each player's best-reply's or strategies.

The indicators used for the multi-criteria payoff functions need to be site-specific and determined alongside the local communities and stakeholders to best understand the area (Azapagic, 2004; Ranangen and Lindman, 2017). In addition, how these indicators are managed needs to be determined, as in if the indicator has a threshold or if the goal is to minimize or maximize its value. Indicators developed by the Global Reporting Initiative (GRI) are commonly used by mining companies for sustainability reporting (Azapagic, 2004; Global Reporting Initiative, 2016). Common environmental indicators used by the mining industry include: greenhouse gas emissions, energy use, water quality, water discharge, soil, air, dust, noise, reclamation practices, biodiversity conservation, and flora and fauna health (Azapagic, 2004). Even by following the previously developed frameworks, the site's community and stakeholders still need to be involved through collaborative decision-making groups to ensure the process is trusted and aligned to the wants and needs of the communities (Collins and Kumral, 2020). Furthermore, to ensure the socio-cultural and economic relationships between the community and the region are properly considered.

The local Indigenous communities are typically more affected by mining's environmental impacts due to their close cultural relationship with their territory (Horowitz et al., 2018). They are more than just stakeholders; they are rightsholders with the right to say what occurs on their traditional territories (O'Faircheallaigh and Corbett, 2005). The development of traditional knowledge studies in countries like Canada can provide an opportunity to collaborate and preserve the wants, needs, and values, of vulnerable Indigenous communities (Menzies, 2006).

Environmental economics can fail to fully appreciate the intricacies of ecosystems for decision-making techniques. Environmental economics can bring a simplistic, Western focused, and anthropocentric view of the environment using monetary valuation (Brown and Timmerman, 2015). Environmental economists argue for monetary valuation as it can provide a transparent and transferable method for making trade-offs (Hanley and Barbier, 2009). Preferences can be measured, and markets can be established for environmental goods to reduce the negative externalities and market failures (Calow, 2015). However, the connections between ecosystems and the global health of the planet can arguably never be fully understood or valued using money. There are countless aspects of the environment that may not have any value to humans but are essential to a healthy ecosystem, which brings the necessary environmental services for sustaining life. Diverging from environmental economists, ecological economics argues for placing humans and our economic systems within the planet's ecosystems and not above it (Daly and Farley, 2010). In other words, ecological economists treat the economy as a sub-system within our planet and the global environment. Considering this, communities must still try to prioritize, analyze, and make decisions with the environment, as conducted in game theory, in order to understand the best outcomes for land use and societal prosperity. Appreciating and incorporating the limits of evaluation models and environmental indicators is imperative to ensure protection of global environmental systems. As previously outlined, the use of multi-criteria brings a more comprehensive and realistic evaluation of the environment rather than environmental economics' reductionistic approach. In the end, the games proposed use the players' values to calculate utility which is then used to make trade-offs with the environment, which is similar to environmental economic methods. However, with the incorporation of Monte Carlo simulation for value functions and with clearly outlining the value trade-offs between multi-criteria indicators, it is hoped that this analysis provides a deeper understanding of the relationships between humans and the health of our planet.

Outside of payoff function development, a consideration to note is game theory assumes players are rational and will make decisions to maximize their benefit with a given set of information. In real life, this is sometimes not the case. For example, it is possible that providing benefits to one player could be the goal of another player. It can be difficult to fully evaluate the wins-and-losses of inter-player relationships. A community trying to maximize what they see as their utility rather than what standard economic processes see as their utility might not be viewed as rational in game theory's economic evaluation processes. Furthermore, in games that repeat for longer periods, as seen in the proposed games in this paper, strategies of the players can change. The strategies can change for numerous reasons such as: new data, changes in technologies, world developments, changes of political parties (or their platforms), and new inter-player agreements.

The level of analysis is another important consideration. Impacts of mining and metals occur both on a global and local scale. When games focus solely on the local boundaries, it does not properly consider the environmental impacts and added cumulative of mining to the greater region or the planet. Games 2–5 could be both international or local games with considerations needed on a local and global scale (Game 1 is evidently an international game). Careful attention must be placed in the non-global games where the environmental impacts affect global ecosystems. For example, when analyzing carbon emissions, energy usage, or any type of use of a limited resource.

A common issue in these games is the fact they are competitive, creating inefficient solutions. In many cases, like in the prisoner's dilemma, a cooperative agreement brings the best outcome and utility for the players. The harsh reality is the best outcomes are not currently achieved globally for environmental management, due to the competitive nature of nations with the global economy. Enforceable global regulations are needed to ensure agreements like the Paris Climate Agreement are followed. This is not impossible, as shown in the international agreement, The Montreal Protocol, which required a percentage reduction of many substances responsible for ozone layer depletion (Frisvold and Emerick, 2008). Forms of cap-and-trade and environmental tax systems are extensively discussed by academics and politicians to try to limit environmental impacts (e.g., carbon emissions) and spur environmental innovation. Unfortunately, these systems are not always suitable, and have not been adequately developed or adopted on a global level (Chang, 2017). Cooperation is essential but it is difficult to achieve. Not all countries are better off for the short term with stricter environmental management regulations (Dinar et al., 2008; Kaitala and Pohjola, 1995). Asymmetries between players can also exist in a technical capacity, abatement costs, knowledge of the game, and reliability of data that push players away from cooperation (Hanley and Folmer, 1998; Vrieze, 1995). Side payments will most likely be required to countries who are unable to maintain their economy under stricter environmental regulations (Benchekroun and Van Long, 2014). However, the use of side payments could create a lack of motivation by the countries receiving them to not want to innovate or alter their environmentally impactful economies. Game theory could be used as a method to compare the success of side payments, cap-and-trade, or environmental tax systems and determine fair levels of regulation between jurisdictions.

A final concern and area of uncertainty with these games is how mining regions will react to climate change. Climate change is currently affecting the planet's ecosystems at an alarming rate and it is difficult to predict how the environment will change over the next 30 years. If communities are to make decisions based on how mining will affect a region's environmental health, one must also understand how the area is changing due to climate change. This is to ensure the region can continue to support environmental services like clean water, air, and soil. Climate change creates a moving target for maintaining environmental health.

4.8 Conclusion

Game theory, as explored, is a structured decision-making tool to analyze numerous scenarios as it can consider and exhibit the complex interactions of many players with unique utilities and values. With a multi-criteria approach, environmentally focused applications in the mining industry can help determine long-term sustainable agreements between stakeholders. Additionally, it can be used to assist in developing and comparing potential outcomes of mineral policies. These mineral policies could outline requirements for effluent discharge, mine ownership, mine closure permits, water permits, emissions, tax rates, and general mining permits. Additionally, with the gamification among government, local communities, mining companies, NGOs, unions, and other private sectors, mining rents can provide resources for poverty alleviation, health, education, transportation infrastructure, and general environmental sustainability. However, as shown, a considerable amount of thought must be conducted in the implementation, development, and selection of data and criteria as well as the asymmetries between players. The games introduced require many assumptions, which could be difficult to recreate in scenarios where information is withheld, players' payoff functions can change, and our understanding of ecosystems can be lacking. Emphasis must be placed on determining outcomes and methods that respect the complexity of nature and its holistic life-supporting systems, rather than reducing it down to dollars. Avoiding a future with plenty of money but a planet void of clean water, air, and soil. Simply, if the mineral reserve does not provide enough value while respecting the ecological thresholds of our planet, then mining should not be allowed. Innovation needs to align mineral development patterns to ensure our ecosystems are protected at each stage of the mining life-cycle. Future work will require the implementation of these games with regional specific data, community values, environmental indicators, and mine operation performance to determine how to best direct policy and decisions for prioritizing collaborative environmental sustainability in the mining industry.

4.9 Next Steps

This section provided an analysis of game theory applications for the mining industry and proposed several potential games for further analysis. The next two sections develop some of these proposed games using a multiple-criteria approach. The next section specifically analyzes impact and benefit agreements using the game theory and multiple-criteria decision making approach first proposed in this section. These approaches are further developed using unknown value functions and a Monte Carlo simulation.

Chapter 5 - Examining Impact and Benefit Agreements in Mineral Extraction using Game Theory and Multiple-Criteria Decision Making

5.1 Abstract

This research takes a novel approach to analyzing impact and benefit agreements (IBA) using multiple-criteria decision making (MCDM) and game theory. Local communities, which are often Indigenous communities, are faced with difficult decisions regarding the trade-offs of impacts vs. benefits from mineral resource development. Analyses of IBAs typically focus on their economic benefits but fail to the consider environmental, socio-cultural, and other sustainability criteria. By not considering these criteria, current methods struggle to predict if an IBA is adequate or if it will be accepted. This research develops a model with MCDM that balances complex sustainability trade-offs for communities during mineral development negotiations. Bargaining positions of companies or impacted communities are also an essential, yet understudied factor in IBA analyses. Game theory is employed to show how bargaining positions can affect the compensation included in an IBA. In all, this research develops a model that can consider different criteria, value systems, and the implications of cooperation or competition to predict if an IBA will be accepted. This study provides recommendations, which can be applied other resource development projects which impact communities. The model shows the importance of flexibility in design, power dynamics in bargaining, cooperation, and knowledge sharing.

5.2 Introduction

The mining industry is at a crossroads. Society's growing demand for minerals continues to push for more mines, but many projects struggle to secure permits due to opposition from impacted Indigenous communities and other stakeholders. The continued growth of the mining industry impacts communities on countless socio-environmental levels, which are not easily accounted for during project evaluation. Impact and benefit agreements (IBAs) were developed to create collaborative solutions to balance the impacts and benefits of mineral development for communities. IBAs are contracts between impacted groups and project proponents that typically outline the benefits the community will receive, in terms of compensation and economic opportunities, as well as the strategies for impact mitigation (Gibson and O'Faircheallaigh, 2015). IBAs formalize company-community partnership with the goal of reducing project delays and disruptions from protests, blockades, or legal opposition (Ali, 2003). The issue is that it is not well understood what exactly should be included in IBAs to balance the impacts vs. benefits of a project (Cascadden et al., 2021). There are several guidelines created for IBAs, e.g., Gibson and O'Faircheallaigh (2015), but there is a critical lack of formalized methods that can incorporate community values and predict if IBAs will be accepted and successful. The main questions of this research are: How can we predict if an IBA will be accepted? What are the main factors for a successful IBA? How can IBAs be better aligned to the wants, needs, and values of communities? And, what are the sustainability challenges with IBAs for mineral development projects? To better understand these questions, this research's goal is to create a new method to analyze IBAs.

This research creates a formalized method using bargaining game theory and multiple-criteria decision analysis (MCDM) to investigate IBAs. Analyses of sustainability focused decision making methods for the mining industry, as seen in Collins and Kumral (2020a, 2020c), showed the need in selecting these two methods. The use of MCDM and game theory can help investigate mineral developments’ trade-offs between economic, social, and environmental indicators. Incorporating bargaining game theory allows this research to explore the implications of how two or more groups interact. While MCDM brings a method to incorporate multiple-criteria and differing value systems to rank alternatives (Liang et al., 2019; Sitorus et al., 2019). These two methods were selected because their strong potential to aide in holistic sustainability assessments that factor in different stakeholders and criteria. Both bargaining game theory and MCDM individually, and especially in combination, are rarely applied to the mining industry, and have never been applied to IBAs. MCDM and bargaining game theory are well-developed fields of study with many applications. This study provides a novel approach to IBA analyses by combining game theory and MCDM. There is no agreed upon method for this combination, which rarely occurs, therefore a strong emphasis on MCDM and game theory methods is needed and is conducted.

Typically, mineral economics and sustainability guides are often employed by the mining industry to guide socio-economic and environmental considerations for IBAs (Collins and Kumral, 2020a). Mineral economics and sustainability guides unfortunately provide too narrow of an analysis. Mineral economics can lack the ability to consider non-market aspects of ecosystems, account for our lack of understanding of ecosystems, and respect differences in values of decision makers (Daly and Farley, 2011). Sustainability guides present numerous important sustainability criteria to consider but do not provide any direction on how to prioritize or trade-off between the sustainability criteria (Eisenmenger et al., 2020). Bargaining game theory and MCDM are used in this study to help bring a more holistic approach to IBA strategies originally based on mineral economics and sustainability guides.

IBAs are often developed between Indigenous communities and development proponents. MCDM and game theory are selected to better consider impacted groups, like Indigenous communities. IBA requirements are constantly morphing depending on the community's needs, the type of development taking place, environmental sensitivities of the area, and the political conditions. As mining continues to push into more remote regions and expands to meet demand, the impacts seen by Indigenous communities will continue to grow as well. IBA negotiations are opportunities to find collaborative solutions into a historically non-collaborative situation. To protect Indigenous communities, it is imperative analysis methods for IBAs are inclusive and can consider different value systems, wants, needs, and cultures.

The next section outlines the methods and applications used in this research. Section 5.4 will introduce, discuss, and glean the relevant literature from IBAs (Section 5.4.1), MCDM (Section 5.4.2) and bargaining game theory (5.4.3). Section 5.5 brings together the findings in Section 5.4 to develop a method to investigate and predict IBA requirements. Section 5.5 and 5.6 analyze the model's assumptions and discuss its persistent complexities and limitations. Finally, Section 5.7 distills the key recommendations from this research.

5.3 Methods and Materials

This research investigated and applied MCDM methods and game theory to inspect IBAs. Literature over the past twenty years was examined for relations between bargaining theory, non-cooperative game theory, sustainability decision making, MCDM, Monte-Carlo simulation, and resource development decisions. McGill's University Library Database, Scopus, Web of Science, and Google Scholar Databases were used for finding journal articles, conference proceedings, and books. Mendeley citation software was used to organize and analyze literature.

Drawing on examples from Nunavut, the IBAs signed by the communities in Nunavut have provided economic opportunities, investment, training, and involvement in environmental negotiations. In the Appendix there is information collected from several IBAs in Nunavut. This was used to inform how to build the model. The main benefits and considerations from these documents, along with NI 43-101 feasibility studies, provided the background information for the base case scenarios. This model however, stayed general to allow the different perspectives from communities that exist in mineral development and IBAs. The authors of this paper did not want to make any assumptions for the values, wants, and needs of Indigenous communities. Indigenous communities should have their own voices heard and incorporated, which requires open and respectful collaboration. This paper focusses on the development of this new method, which is needed at this stage of research.

To synthesize the analysis, a model was developed using Python3 and several software packages. With Python 3 and the packages "*MCDM 1.2*" and "*Nashpy 0.0.20*", a program was written to investigate IBAs. "*TOPSIS*", which is an MCDM, was selected because it is well suited to clearly present trade-offs between criteria, specifically sustainability criteria (Papathanasiou and Ploskas, 2018). To consider unknown weightings of the value functions, Monte-Carlo simulation-based analysis is used. For a more detailed discussion on the developed model please see Section 5.5. Sections 5.4.2 and 5.4.3 will further outline MCDM and Game theory, and distill applicable applications for this research.

5.4 Literature Review

This section first analyzes recent literature on IBAs and describes how this study's model adds to this field. This section then presents the findings used for this study's model from relevant applications of MCDM and bargaining game theory.

5.4.1 Impact and benefit agreements review

IBAs outline the benefits to be shared from a development project with impacted communities. As seen in IBAs from the Mary River (2018), Meliadine (2017) and Meadowbank mines (2017), these benefits can include preferential employment, training, joint venture agreements, compensation, environmental protection, cultural protection, and participation in decisions. This section reviews some key IBA literature for their main findings and specifically how they incorporate multiple-criteria trade-offs into best-practices and decision making.

IBAs are independent contracts with impacted Indigenous nations, communities, or stakeholders. They are also known as benefit-sharing agreements but go by many other names (Gunton and Markey 2021). Depending on the region, they can be required by regulators (Fidler and Hitch, 2007; Galbraith et al., 2007; O'Faircheallaigh, 2021). IBAs are a relatively recent instrument for company-community relations. As noted by Gunton and Markey (2021), IBA are context dependent instruments which are dependent on the community, mine, local environment. They unfortunately stem from a failure of government to ensure impacted communities receive the necessary benefits from a project (Peterson St-Laurent and Billon, 2015). In theory, and in Canada, processes like environmental assessments, socio-economic assessments, and project permitting should assess the impacts of a project. Regulators should then ensure adequate resources are given back to the impacted communities from the mine's taxes and royalties. This scheme is successful for some communities, but many, for example, Indigenous communities, who are typically more impacted by resource development projects, have a history of receiving little to no benefits from both regulators and project owners.

The IBA bargaining process, which is most advanced in Australia and Canada, has both its merits and challenges. Research over the past ten years, such as Bradshaw et al. (2018), Craik et al. (2017), and Papillon and Rodon (2017), have analyzed the current state of IBAs, and what it adds to Indigenous law and consultation requirements. Bradshaw et al. (2018) notes the many questions that remain for IBAs around the variability of negotiations, the governance issues, and if IBAs are benefiting both communities and companies. In terms of governance, Craik et al. (2017) argue IBAs as a type of private governance but require accounting the additional procedural and legitimacy demands. Papillon and Rodon (2017) on the other hand, see proponent led IBAs as a "*truncated version of FPIC [Free Prior and Informed Consent]*", which undermines the FPIC process.

Some scholars argue that EA and IBA negotiations can overlap, and even that IBAs should be a part of the EA process (Gibson and O'Faircheallaigh, 2010). Lukas-Amulung (2009) found that they overlap during the scoping, deliberation, and resolution stage. She proposes that IBA and EAs be coordinated at the beginning stage of a project to improve information sharing and monitoring. It is also argued by scholars such as Bradshaw et al. (2018), St-Laurent and Le Billon (2015), and Caine and Krogman (2010), that power imbalances will continue to be an issue in IBA negotiations.

Cascadden et al. (2021) create a best practice framework for IBAs and discuss success depends on "*the quality of the agreement, the context within which the IBA exists, and the dedication with which the agreement is implemented*." Based on best practices, it provides an overview of the types of criteria to be considered. The criteria, although imperative for an inclusive IBA, does not consider the environmental implications of the mine plan. A mine's impact can vary greatly depending on its mining methods, size, processing methods, and the proximity to environmental features (e.g., lakes, rivers, forests, and sensitive ecosystems). To determine if an IBA is successful, there must be some consideration of what the actual mine plan is. Understanding the mine plan can lead to understanding the total impacts of the mine. A mine plan with more impacts should potentially have a lower chance of being accepted. Using an MCDM with different mine plan scenarios, this research's model can investigate this aspect of IBAs. It can better present the relationship between community values and the environmental impacts of the mine.

Adebayo and Werker (2021) calculate the economic benefits that can be received in terms of financial transfers, jobs, and contracting opportunities. As they note in their paper, through taking an economic perspective solely, essential socio-environmental benefits are not considered. Ecosystem health is an imperative requirement of many communities. By not including environmental criteria for benefit calculations, the trade-offs of environmental impacts versus economic opportunities that communities make are not considered. It is therefore impossible to tell if the mine provides adequate benefits for its impacts. This study adds to this by developing a method which considers the environmental criteria and trade-offs communities make when deciding to accept or reject an IBA.

An IBA can enhance a community through project revenues and protocols for monitoring project impacts. However, it is unclear how successful, in terms of helping communities over the long-term, these IBAs truly are (O'Faircheallaigh, 2020, 2018). O'Faircheallaigh (2018) argues for more systemic analyses of the positive outcomes of IBAs to truly conclude they are positive instruments. O’Faircheallaigh (2020) also finds IBAs do not often realize their potential to be able to monitor projects. Finally, these agreements do have the potential to protect the community’s cultural heritage, but as O’Faircheallaigh (2008) discusses, bargaining positions need to be addressed. This research uses bargaining game theory to analyze these bargaining positions.

A key reference, O’Faircheallaigh (2016), evaluates 45 IBAs across Australia and develops several criteria to evaluate negotiation outcomes. He notes that the aggregation of outcomes in criteria such as—environmental management, cultural heritage protection, rights and interests in land, financial payments, employment and training, business development, and implementation measures—will show if a negotiation is successful or not. He ranks the agreements based on environmental performance and finds that the “*agreements that display strongly positive outcomes in one area tend to be strong in others; weaker agreements tend to be weaker across the board*” (O’Faircheallaigh, 2016). His research brings a quantitative approach for which this paper is also attempting to achieve, however the difference is that this paper develops a method from MCDM, to aggregate the indicators based on a community’s values function. O’Faircheallaigh (2016) only uses environmental criteria to define the IBAs as “*strong*”. Even though he finds that strong environmental performance is linked to strong socio-cultural performance, he ignores that a community may value one criterion over the environment, and deems the IBA as being strong across all criteria regardless.

The incorporation of environmental criteria takes place in O'Faircheallaigh and Corbett (2005) and O’Faircheallaigh (2016). The issues with O'Faircheallaigh and Corbett (2005) and O’Faircheallaigh (2016) is their methods of putting values on to the environmental criteria. From O'Faircheallaigh and Corbett (2005), going from “*Joint decision making on some or all* *environmental management issues*” to “*Indigenous parties have the capacity to act unilaterally to deal with environmental concerns or problems associated with a project*” is worth a score increase of one. Why one? Why not two? The community being impacted should be able to make this judgement on the scoring differences between criteria. MCDM brings this into the analysis by incorporating a value-function for a community.

Peterson St-Laurent and Billon (2015) discuss how IBAs take away from the state’s responsibility towards communities. Cameron and Levitan (2014) also discuss the creation of IBAs is in fact the privatizing of government’s duty to consult. This can lead to limiting access to political and legal systems and creating market-based solutions to community impacts. IBAs exist within an already flawed neoliberal governance system but provide some recourse for communities. Caine and Krogman (2019) show IBAs can help create engagement and benefits, but provisions need to allow transparency and dialogue between communities, companies, and regulators. Benefits need to be shared throughout the community; however, power dynamics within the community and with the proponents need to be considered.

Many IBAs are confidential, which has issues and merits. Confidentiality can prevent other communities from understanding how projects typically affect and benefit communities. When an IBA is confidential, communities cannot learn what is typically included. On the other side, mining companies can take advantage of their experience on previous properties (Caine and Krogman, 2010). Hummel (2019) argues IBAs should be transparent because they resemble public law and have an increasing role in a company’s duty to consult. In Nunavut, Hummel (2019) shows the transparency of IBAs has created opportunities for constructive scrutiny. Some communities prefer IBA confidentiality because it protects them from the Federal Government potentially reducing their support in proportion to how much the IBA is providing (Hummel, 2019). In addition, given each project is unique and has regional specific impacts, it is possible referencing other IBAs would be extraneous and could impact their bargaining positions. Bargaining game theory, which this study presents, can show the implications of confidentiality.

As shown in the literature, the current calculation of benefits of IBAs is inconsistent. Some studies incorporate environmental indicators, some do not, and none of them are able to bring together all sustainability criteria with a community-focused approach of incorporating how communities value criteria. Additionally, the bargaining positions of each group is an essential piece that dictates what is included in an IBAs, but there is a lack of methods to include bargaining positions. To fill these gaps, this study uses MCDM and game theory, which are described in the next two sections.

5.4.2 Multiple-criteria decision making: Trade-offs with TOPSIS

MCDM, also known as multiple-criteria decision analysis, helps structure decisions between alternatives using conflicting or corresponding criteria (Zopounidis and Doumpos, 2017). Different MCDM techniques, such as PROMETHEE, AHP, ELECTRA, VIKOR, COPRAS, ARAS, MOORA, MULTIMOORA and TOPSIS vary with how they calculate trade-offs between criteria and rank alternatives (Sitorus et al., 2019). There are countless applications of MCDMs for sustainability focused decisions, unfortunately there is a critical lack of MCDM applications in the mining industry (Collins and Kumral, 2020a). Some applications of MCDM in the mining industry include Štirbanović et al. (2019) for flotation machine selection, Rahimdel and Noferesti (2020) mined material investement, and Naghadehi et al. (2009) for underground mining method selection. This section will now briefly introduce TOPSIS and present how it is applied to this research.

Originally developed by Hwang and Yoon (1981), the TOPSIS procedure selects the best alternative by having the shortest distance from the positive ideal solution and the farthest distance from the negative-ideal solution (Behzadian et al., 2012; Zavadskas et al., 2016). This allows criteria to be either minimized or maximized. Crucially, attribute values must be numeric, monotonically increasing or decreasing, and have commensurable units (Hwang and Yoon, 1981; Papathanasiou and Ploskas, 2018).

This study selected TOPSIS because it provides a clear approach to dealing with criteria trade-offs in decision making (Savun-Hekimoğlu et al., 2021). As discussed by Zavadskas et al. (2016), TOPSIS does not exclude alternatives based on pre-defined thresholds, which corresponds well to this research's IBA application: maximizing sustainability in mineral development requires trade-offs of different sustainability criteria. TOPSIS is relatively easy to structure for both negative and positive criteria, and is flexible when using both quantitative and qualitative data. This is key for working with stakeholders that use different analysis methods.

The TOPSIS process used in this research is briefly summarized below.

First, a decision matrix with *m* alternatives, $A_1, \ldots, A_m$, and n criteria, $C_1, \ldots, C_n$, needs to be created. These two matrices are evaluated with respect to the other to create the matrix:

$$X = (x_{ij})_{m \times n}$$

A vector for criteria weighting also needs to be created. Let $W = (w_1, \ldots, w_n)$ such that $\sum_{j=1}^{n} w_j = 1$. This research explores situations with unknown criteria functions.

Normalization of the decision matrix is conducted for creating dimensionless criteria. There are several methods for normalization; this study uses vector normalization to produce smoother trade-offs as compared to linear normalization. This is shown in the following equation:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, i = 1, \dots, m, \quad j = 1, \dots, n$$

Using the weights, the normalized weighted values are calculated with:

$$v_{ij} = w_j r_{ij}, \qquad i = 1, \dots, m, \quad j = 1, \dots, n$$

Assumptions are made for the ideal (A^*) and negative solutions (A^-). They are calculated as follows:

$$A^* = \{v_1^*, v_2^*, \dots, v_n^*\} = \left\{\left(\max_j v_{ij} | \ i \in I'\right), \left(\min_j v_{ij} | \ i \in I''\right)\right\}, \ i = 1, \dots, m, \quad j = 1, \dots, n$$

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\} = \left\{\left(\min_j v_{ij} | \ i \in I'\right), \left(\max_j v_{ij} | \ i \in I''\right)\right\}, \ i = 1, \dots, m, \quad j = 1, \dots, n$$

Calculation of the Euclidian distances to the ideal (D_i^*) and anti-ideal solutions (D_i^-) then take place.

$$D_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2}, \quad i = 1, \dots, m, \quad j = 1, \dots, n$$

$$D_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2}, \quad i = 1, \ldots, m, \quad j = 1, \ldots, n$$

Finally, the relative closeness (C^*_i) is calculated for each alternative. The closer to 1, the higher the rank.

$$C_i^* = \frac{D_i^-}{D_i^* + D_i^-} \quad i = 1, \ldots, m$$

There are some drawbacks of the TOPSIS method. The normalized decision matrix is often derived from a narrow gap between the criteria performances. This can at times not show the true dominance of alternatives. In addition, like other MCDM methods, when adding in non-optimal alternatives, or more alternatives, ranking reversal can occur or contradictions in the model. In Section 5.5, this method will be applied to incorporate unknown weighting of values using Monte-Carlo simulation-based analysis.

5.4.3 Game theory for bargaining

Modern game theory, discussed by von Neumann and Morgenstern (1944), investigates how two or more "*players*" interact, compete, or cooperate. Nash (1950a) discussed equilibrium cases where no player would be better off from changing their strategy. This led to Nash (1950b) branching into bargaining theory. Bargaining theory, which this study considers, is a branch of game theory which explores how players divide a surplus of goods (Binmore, 2007; Harsanyi, 1961; Spaniel, 2014; Sutton, 1986). Game theory and bargaining have been applied extensively. (Binmore, 2007). This research uses bargaining game theory and game theory in general to analyze how benefits are shared and how impacts are managed during IBA negotiations. It can provide a framework to investigate what influences how parties divide a resource or a surplus.

Different game assumptions provide different outcomes and insights. Insights from simple games such as the ultimatum game and the Rubinstein bargaining model can provide a base for analyzing real life scenarios. For an ultimatum game there is a proposer and a responder. The proposer decides how much money they want to split with the responder, and the responder decides to accept or reject (Harsanyi, 1961). This is further described below and shown in Figure 5-1.

If, V_1 = the maximum the proposer is willing to share, and V_2 = the minimum the proposer is willing to accept, then surplus (S) will be: $\frac{V_1 - V_2}{V_1}$. For an ultimatum game to take place $S \geq 0$; all other scenarios will be rejected.

Figure 5-1 presents a simple two stage bargaining model based on this ultimatum game. In this figure, *x* denotes the proposed split of surplus, or for this research, the percent the community will receive. The community can either accept or reject the offer. The payoffs, which are in terms of percent surplus, for the proponent are at the bottom of the figure in blue, the payoffs for the community are in yellow. In this ultimatum game, the equilibrium state, which occurs when no player is better off deviating from their strategy, occurs when the offered surplus (x) is as close as possible to, or equal to V_2.

If S_i is the strategy set for player "*i*", where *i* = 1, 2…N. Let $s^* = (s_i^*, s_{-i}^*)$ be a strategy set, where each player has one strategy. s_{-i}^* means the set of all strategies for every player except *i*.

The equilibrium state occurs if for any player altering the strategy is not profitable. That is if, $u_i(s_i^*, s_{-i}^*)\ u_i(s_i^*, s_{-i}^*)\ for\ all\ s_i \in S_i$, and where $u_i(s_i^*, s_{-i}^*)$ is the player's payoff as a function of their strategies.

For a Rubinstein bargaining model, the game has alternating offers over an infinite time horizon. Both players have complete information, meaning they know the options of each player, and delays in the game are costly (Rubinstein, 1982). The discount factor "*d*" of each bargaining stage then plays an important role for the equilibrium calculation. In this game, the first player gets a surplus payoff of $\frac{1}{1+d}$ and the second player gets a surplus of $\frac{d}{1+d}$.

This study focussed on game theory and bargaining in relation to sustainability trade-offs. Some examples include Carraro et al. (2007) and Hemati and Abrishamchi (2020) for water management, Carraro and Sgobbi (2008) for natural resource management, Stranlund (1999) for forestry management, Sauer et al. (2003) pollution reduction, Lennox et al. (2013) for conservation agreements, Caparrós (2016) for international environmental agreements, and Schopf and Voss (2019) for a three-person game over natural resources.

The simple games and the applications in sustainability trade-offs present key factors affecting bargaining positions and outcomes**.** Table 5-1 presents the many factors that influence how the surplus is divided or what "x" is in Figure 5-1. This has been adapted from research previously mentioned such as: Binmore (2007), Harsanyi, (1961), Spaniel, (2014), and Sutton, (1986). Table 5-1 discusses the roles they potentially play in IBA negotiations. Seeing how IBA processes can be different from case to case, the factors outlined in Table 5-1 can either help or impact either of the players depending on the situation. These factors will be further discussed in relation to IBAs in the next sections.

Table 5-1 Bargaining Factors (Adapted from Binmore (2007), Harsanyi, (1961), Spaniel, (2014), and Sutton, (1986))

Factor	**Description**
Control over proposals	Whoever makes proposals has an advantage. Whoever has the last say in making proposals has an advantage. Generally, mining companies control proposals, but this could change if communities are better supported, and their capacities improve.
Patience	Whoever has the most patience has better outcomes. Conversely, the player who is desperate for a deal has a disadvantage. This can apply to either player. Communities, like Canada's northern communities, who have little economic opportunities, and are in dire socio-economic conditions, can potentially be less patient, or cannot afford to be less patient. Companies can be less patient due to the increasing costs of development and delays from permitting.
Outside options	Having credible and competitive outside options gives the player an advantage. Depending on the mining company, some companies have a large portfolio of development properties to choose from, and some have only one property. Companies with a larger portfolio could potentially have better outside options to invest their money. For communities, they could have different types of development opportunities in their territory.
Monopoly	Having a unique quality other players want is an advantage. This could apply to a mining company that has a strong reputation, but more likely to the mineral development property and community. Viable mineral development properties are rare and can even be unique in specific economic climates.
Reputation	A strong reputation, where you typically get better deals than average, will provide a player with an advantage. This can be applied to either player.
Credible commitments/threats	If a player can be credible to select a strategy in certain situations, then this can be an advantage. The threat could be many things such as a rejection, protest, or legal action.
Knowledge or information asymmetry	If a player knows the other player's preferences, bottom line, or cost-benefit criteria, they can use it to their advantage.
Uncertainty	Uncertainty can sometimes lead to negotiation breakdowns and inefficient outcomes. But also, uncertainty can potentially help players with less bargaining power.

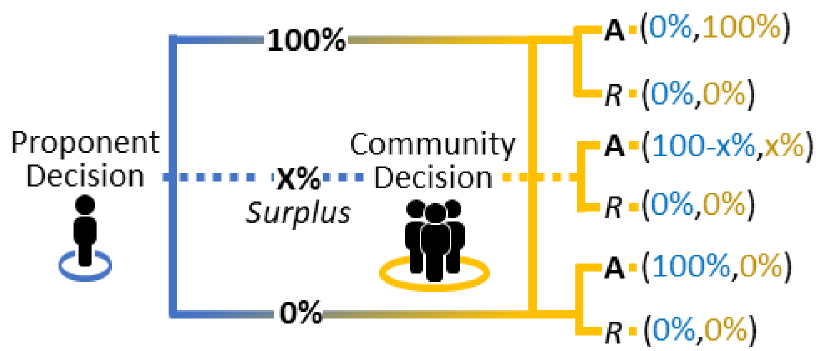

Figure 5-1 Simple Bargaining Game (payoffs in blue for the proponent, payoffs in yellow for the community)

5.5 Game Theory and MCDM Model for IBAs

This section combines the findings of Section 5.4 to provide a novel and structured analysis of IBAs. This research takes the MCDMs from a community's perspective, where the alternatives are different IBA proposals and a rejection alternative. This study considers IBA proposals in terms of the following criteria: (1) their environmental impact using the life of mine's total tonnes, (2) compensation to the community in dollars, and (3) a rating for socio-economic activities. The rating for "*socio-economic activities*" would be developed through a collaborative process with the community. Other criteria could be easily incorporated such as employment, wildlife compensation, contracting opportunities, but for this model three criteria are used. With IBA negotiations occurring near the beginning of the mine life-cycle, these criteria will be predicted criteria. This will be further discussed in the next section.

Reviewing literature that mixes Monte-Carlo simulation, game theory, and MCDM for sustainability based decisions, shows their integration is not common. Some notable examples include Madani and Lund (2011), Madani et al. (2015), Debnath et al. (2018), and Collins and

Kumral (2020b). Madani and Lund (2011) and Madani et al. (2015) specifically use game theory to model MCDM problems and Monte-Carlo to analyze uncertainty in the performance of alternatives. Instead, this paper assumes values for the performance of alternatives and uses Monte-Carlo simulation for preferences.

The criteria weightings (*W*) are a key unknown for this study and IBAs in general. Accepting impacts from one criterion should bring benefits from another. The amount of benefit/utility gained per impact however is unknown and depends on the *W* functions, which was introduced in Section 5.4.2. To determine the *W* function, MCDM methods like the Analytical Hierarchy Process (AHP) can be used. AHP for example, uses pair-wise comparisons to determine the relative importance of each criterion (Saaty, 1987). Methods like AHP bring together opinions from numerous members of a community or experts with often different values and opinions on trade-offs (Shen et al., 2015; Sivakumar et al., 2015).

This study uses a Monte-Carlo simulation-based analysis to model the unknown criteria weightings, as discussed in Mosadeghi et al. (2013). The Monte-Carlo simulation investigates how randomized criteria values affect alternative selection. With three criteria for the *W* function, their sum needs to equal one. The Monte Carlo simulation selects three random integers between one and a thousand, then finds the relative weight of each criterion. This is conducted by dividing each random variable by the sum of the three integers. These three variables are put through the MCDM program and this process is repeated one thousand times. Other distributions could be used for this process such as the normal, skewed, or triangle distributions, however when normalizing their sum to equal one, the original distribution characteristics are lost.

The MCDM process shows how a community looks at trade-offs. Bargaining game theory dictates how the surplus will be divided. Table 5-1 as previously discussed shows some of the key factors influencing how a surplus is divided. Exactly how much the factors affect the players' bargaining positions, and the division of the surplus is difficult to estimate. The goal of this study is not to provide exact figures but to provide an idea of which main factors affect the outcomes.

This model ranks alternatives with different relative levels of payments and environmental impacts. Using the scenarios shown in Table 5-2, this research developed a base case to model the relationship between benefits and impacts. The model then varies the environmental impacts and level of payments from the base case according to the increases or decreases outlined in Table 5-2. The socio-economic rating does not vary between IBAs; it is kept at a fixed value. All criteria go to zero for the reject scenario. Using the different relative levels of payments and impacts, this research provides an investigation on how relative trade-offs of sustainability criteria affect IBA negotiations. Short form codes of the scenarios are shown in the table, to present how impacts vs. payments vary from the base case.

Figure 5-2 and Figure 5-3 show the IBA output for this TOPSIS MCDM model with unknown criteria weights. In Figure 5-2, the graphs become darker blue when variability between payments and impacts increases. In Figure 5-3, again the darker the colour means higher variability; but instead with two different mines (one in blue and one in red). The variability term is used in this model to indicate the amount of criteria change that exists from the base case.

For an example, the base case scenario in Figure 5-2 shows the community has the option to: (1) select high payment (HP) and high impact (HI), which is "HP HI" in the figure, (2) mid payment, mid impact, "MP MI", (3) low payment low impact "LP LI", or (4) they can reject the proposal. Again, Table 5-2 shows the percent changes between the high, mid, and low for impacts and payments for the base case scenario. The Monte Carlo Simulation picks random criteria weights then using the TOPSIS MCDM the best alternative is selected. This is done one thousand times and Figures 5-2 (top right for base case) shows the percent chance each alternative is the highest ranked. Other scenarios look at different variabilities between alternatives. Figure 5-3 uses the same variabilities as Figure 5-1 but looks at two different mines with base case and high variability cases.

Figure 5-4 shows how MCDM and bargaining interact in this research. The factors outlined in Table 5-1 dictate the amount of surplus that will be shared (the x% in Figures 5-1 and 5-4). Depending on the mine plan, this surplus could provide community compensation, or it could be put into reducing the environmental impacts. The reducing of environmental impacts could be through technology investment or even reducing the mine's total tonnage. The amount of compensation that is available to use in a bargaining situation, which this study calls "NPVA", is dictated by the mine's NPV and the company's financial goals for the project. Their financial goals could include a minimum NPV, maximum payback period, or minimum internal rate of return. The MCDM process in this Figure (5-4) shows the community's ranking for how the surplus of the mine should be used. In this case it communicates the importance of environmental protection and the relative amount of compensation necessary. In addition, if the preferred option is to not have any development, this is shown as "reject".

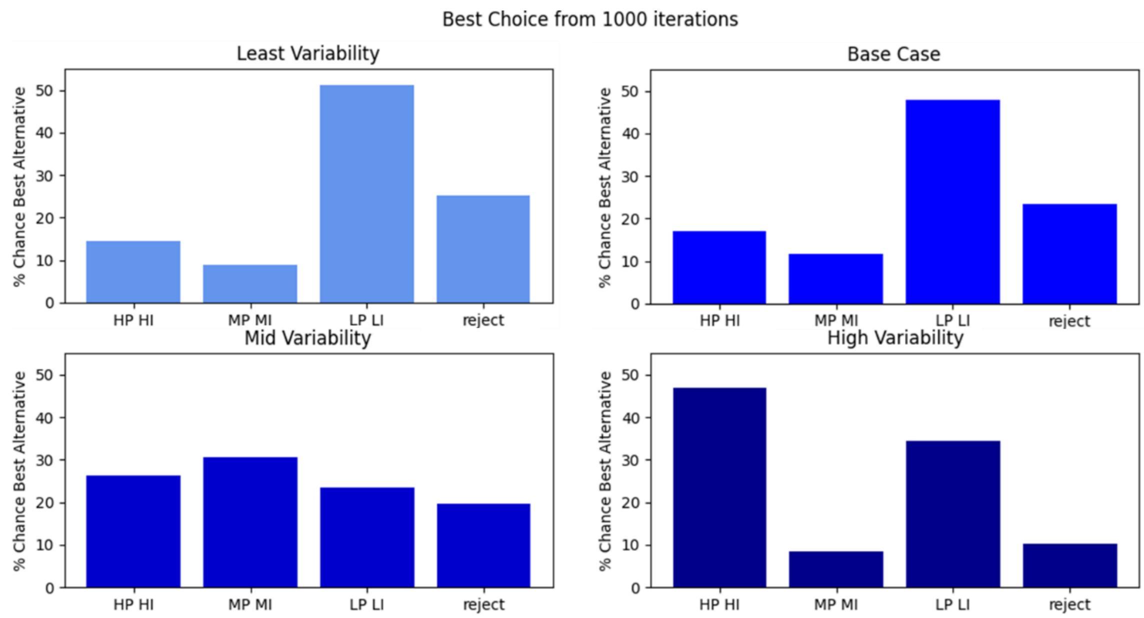

Figure 5-2 Monte-Carlo simulations between alternatives with different variabilities

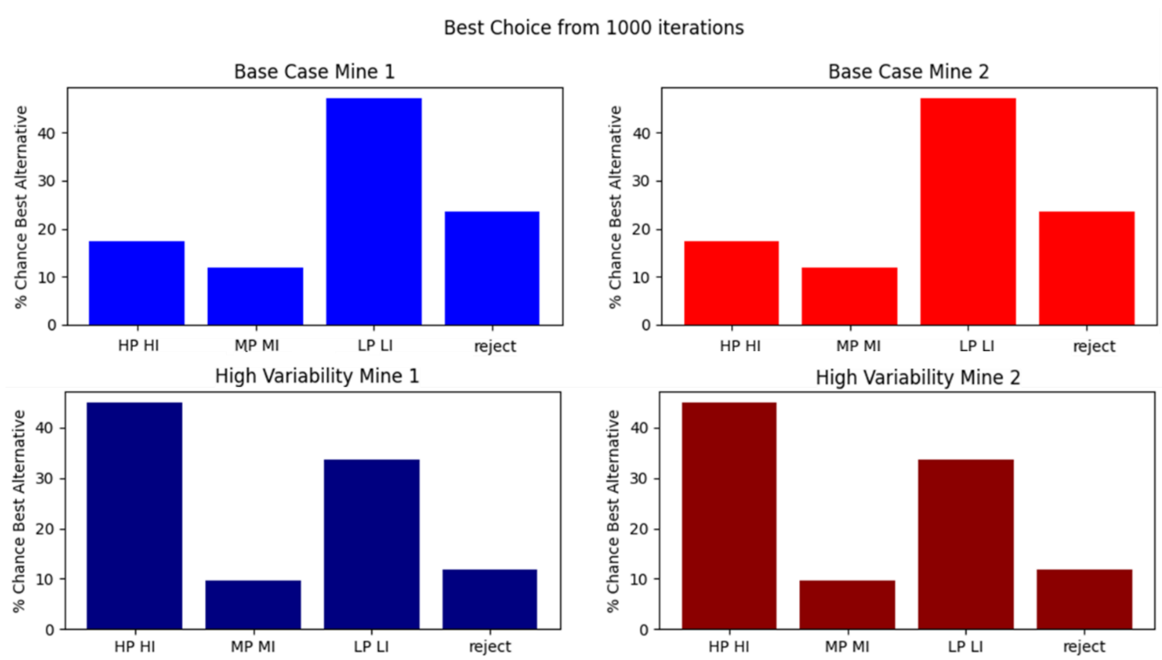

Figure 5-3 Monte-carlo simulation between two mines

Table 5-2 IBA Cases

All values in % change from base						
Alternatives / Scenario Name	High Payments (HP)	Mid Payments (MP)	Low Payments (LP)	High Impacts (HI)	Mid Impacts (MI)	Low Impacts (LI)
Least Variability	+10%	+5%	0%	0%	-5%	-10%
Base Case	+30%	+15%	0%	0%	-15%	-30%
Mid Variability	+100%	+50%	0%	0%	-33%	-50%
High Variability	+300%	+100%	0%	0%	-50%	-75%

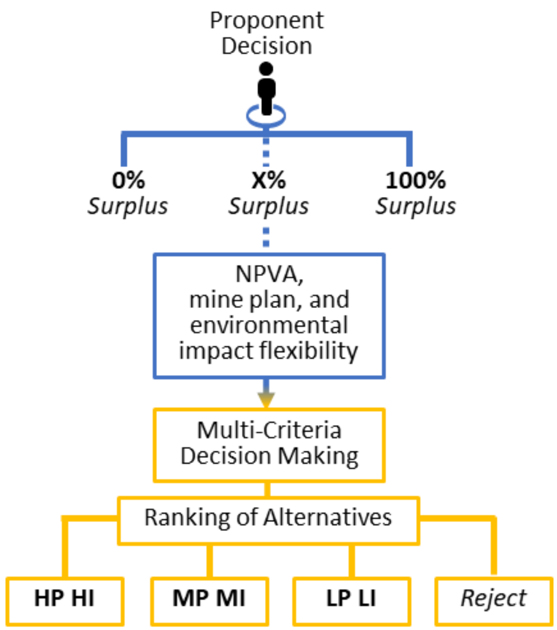

Figure 5-4 Relationship between Bargaining and MCDM

The outputs of Figure 5-4 can be analyzed as a strategic game as discussed in Madani and Lund (2011). To continue with the same example, the output of the base case scenario in Figure 5-2 is used. The output of the MCDM provides an ordinal ranking of the alternatives. The community ranking of ordinal preferences is summarized in the second column of Table 5-3. This study assumes the company for this case will rank the "Reject" scenario as the worst, but it is unknown how they prefer ratios between payments vs. environmental impacts. For this case, this model assumes the company is indifferent as the surplus was already decided in the bargaining step of this research.

Table 5-4 is the conversion of the ordinal ranking into a strategic game that shows scenarios of both cooperation and non-cooperation. When the two parties disagree the default scenario is the reject, as the mine will not be allowed to proceed. The highlighted cell in Table 5-4 shows the highest payoff which is achieved under cooperation where both players agree to the "LI LP" alternative. With the company indifferent, the maximum utility will be the preferred alternative of the community unless the community's top alternative is the reject, as shown in Tables 5-5 and 5-6. In this case there will be two situations with the highest total payoffs; the reject alternative and the community's next preferred alternative. The highlighted cells show the highest total payoffs situation which include all situations where they disagree.

An assumption this research makes is that if the community rejects the mine, the mine does not occur. This is not necessarily true and depends on how much importance a regulator puts on the relationship between a community and a company. This importance continues to grow for many nations. Regardless, the reject scenario will be damaging for a company. If a mine continues development without approval, major conflicts can arise which greatly affect the mine's profitability and the company's reputation (Ali, 2003).

Table 5-3 MCDM Output Example: Base Case

Base Case		
Name	**Company**	**Community**
HP HI	**2**	**2**
MP MI	**2**	**1**
LP LI	**2**	**4**
Reject	**1**	**3**

Table 5-4 Game Theory Conversion Table: Base Case

	Company				
Community		**HP HI**	**MP MI**	**LP LI**	**Reject**
	HP HI	**(2,2)**	**(1,3)**	**(1,3)**	**(1,3)**
	MP MI	**(1,3)**	**(2,1)**	**(1,3)**	**(1,3)**
	LP LI	**(1,3)**	**(1,3)**	**(2,4)**	**(1,3)**
	Reject	**(1,3)**	**(1,3)**	**(1,3)**	**(1,3)**

Table 5-5 MCDM Output Example: Reject Case

Reject Case		
Name	**Company**	**Community**
HP HI	**2**	**2**
MP MI	**2**	**1**
LP LI	**2**	**3**
Reject	**1**	**4**

Table 5-6 Game Theory Conversion Table: Reject Case

		Company			
		HP HI	**MP MI**	**LP LI**	**Reject**
Community	**HP HI**	**(2,2)**	**(1,4)**	**(1,4)**	**(1,4)**
	MP MI	**(1,4)**	**(2,1)**	**(1,4)**	**(1,4)**
	LP LI	**(1,4)**	**(1,4)**	**(2,3)**	**(1,4)**
	Reject	**(1,4)**	**(1,4)**	**(1,4)**	**(1,4)**

5.6 Analysis and Discussion

IBAs are major hurdles for resource development projects; however, they greatly lack advanced analysis tools and methods. This section discusses some of the issues and important considerations when applying this paper's MCDM and game theory approach.

To implement these methods, data needs to be collected collaboratively from all stakeholders. The impacts of mining can be collected from mining companies and the criteria preferences is collected from of impacted communities. Some impact data can be found in National Instrument (NI) 43 101 feasibility reports, company reports, and sustainability reports but these documents do not provide adequate data for this analysis (Collins and Kumral 2020b). To test this research's model, this study developed impact and benefit data from the Mary River (2018), Meliadine (2017) and Meadowbank mines (2017) in Nunavut. For a community, their preferences will be what dictates if the IBA is accepted, and how they make trade-offs. The issue is that determining their exact preferences is challenging, if not impossible. For many mining communities in Canada, there can be a distinct lack of trust with resource development industries. For

Indigenous communities specifically, this stems from generations of cultural genocide from colonial policies and companies. Meaningful collaboration requires trust. If a strong relationship can be developed between company and community, MCDM preference determination methods such as an Analytical Hierarchy Process (AHP), which uses pairwise comparisons between criteria, could be employed to understand how the community makes trade-offs. But, even if trust is established and an AHP can be conducted, it is very difficult to consider all concerns of a group. Individuals have their own wants, needs, and values which influence how they make trade-offs in sustainability. This research uses the Monte-Carlo simulation to investigate unknown criteria preferences for an alternative selection.

The exact values for the criteria used in this model may be difficult to quantify exactly due to the inherent uncertainty of a mine. At the beginning of IBA negotiations, there is considerable uncertainty with how the mine will develop, achieve profits, and impact the environment. NI 43-101 feasibility studies provide a qualified prediction for these numbers for the IBAs, but in the end it is still a prediction. Even though these are predicted values and not exact figures, the potential payments and impacts can be used, and probabilities can be implemented if desired. It is important to note however, that the indicators used in this paper are just some of the many indicators that could be used for this model. The key contribution from this research, is to create a model that can incorporate this type (or any other type) of data, and compare it to other indicator data types.

Regarding the application of MCDM, it provides a structured approach to analyze and communicate trade-offs between impacts and benefits. However, implementing it for resource development decisions, which have a reject alternative, can provide results that are overly sensitive to values. Using TOPSIS, the vastly different outcomes of having a mine and receiving benefits, or having no mine and receiving no benefits, creates few opportunities to compromise when criteria preferences are unknown. With vastly different alternatives, the decision becomes very sensitive to criteria preferences and insensitive to the scale of benefits. See Figure 2, which models two different mines, but the MCDM output is very similar. According to this model's MCDM, the chances of a community rejecting an IBA are independent of how profitable the mine. This is arguably seen in practice too; the relative profitability of a mine does not seem to have a correlation to community-company conflict risk (Andrews et al., 2017; Hilson, 2002). Contradictorily and according to assumptions in mainstream economics, the more profitable the mine, the better chance the mine should be accepted. A more profitable mine should provide more resources for communities to be prosperous and healthy. However, mainstream economics often fails to adequately value ecosystems' intrinsic values as shown by ecological economics scholars; it should not be utilized without more holistic methods like MCDM (Daly and Farley, 2011; Shmelev, 2012).

It is imperative to discuss a possible conflicting view to this study's assumptions in O'Faircheallaigh (2016), who found that trade-offs between his developed criteria in fact do not occur in a major way, but they do occur at the margin. He finds that IBAs that are most positive on economic criteria also are strongest on environmental and cultural heritage indicators. This paper, by contrast, as shown in Table 2, creates alternatives that trade-off between criteria. When O'Faircheallaigh (2016) discusses criteria trade-offs, he examines the trade-offs between different types of IBAs, but not necessarily between having a mine versus not having a mine. A mine decision is inherently a trade-off. It trades the environmental health of a region for economic opportunities. The major trade-off occurs between the "reject" alternative and the non reject alternatives (i.e., the remaining alternatives). The differences between the non-reject alternatives may not be too dissimilar as shown by O'Faircheallaigh (2016). In Table 2 we have the alternatives trading off significantly, but this is selected to show differences in non-reject alternatives. In the end, the mix of impacts vs. benefits will be established based on factors outlined in Table 1, and these will dominate the decision space of non-reject alternatives. For the community, the trade-off of criteria will then occur between the dominant non-reject alternative and the reject alternative.

Another important consideration regarding the MCDM of this model, is how variability in terms of options changes alternative rankings. The higher the variability, which is the ability to have more trade-offs between environmental impacts and benefits, the lower chance the community will reject the mine (see Table 3). With these scenarios, they show a higher chance the mine will be accepted as is but requiring more payments. Providing flexibility to alter impacts or increase payments creates fewer rejections. The main takeaway is a flexibility provides more cooperative outcomes.

This paper uses the term flexibility for the propensity of companies to provide more varied alternatives. Flexibility in alternatives can provide better results but providing alternatives to mine plans is not common. Mine plans and methods are generally selected by the mining company. They are selected to maximize net present value (NPV) first and foremost, but also to follow regulations and maintain safety. There is typically limited flexibility in the design of the mine plan at the IBA negotiation stage. The only flexibility is in the amount of compensation, local employment, local contracts, general economic opportunities, and communication protocols. This research’s model shows the benefit of providing flexibility in a mine plans’ environmental impact as it reduces the chance of IBAs being rejected. For example, mining companies should communicate the alternative mining method options for more destructive mining methods like underground caving and large-scale open pit mining. In addition, more flexible alternative options for mine closure, mine waste management, mineral processing, and water treatment can provide a sustainability focussed and accepted project.

The term mining methods used in this paper is more holistic. It does not just consider open pit vs. underground vs. open-cast type operations, but the staging of the operation, the tonnes per day, and the scheduling as well. How the mine is mined on every level is part of the mining methods. Currently, many mining methods (and many mining processes) are unfortunately inflexible. The mining method for a property is selected by the mining company to consider the geology and the maximization of NPV, but it is rarely altered. There are strong constraints on mining methods by the site's geology, mineralogy, and local site conditions, but engineers and innovation must be pushed to make mining methods more flexible to the wants and needs of local communities, and to the uncertainties of mineral development. Different mining alternatives need to be seriously considered and discussed with community members during negotiations.

For the bargaining process, the factors outlined in Table 1 can either help or impact either of the players. If it helps the proponent, then the options to the community will most likely become less variable. If it helps the community, the option to the community will be more variable. If the community has bargaining power the company has to convert more NPV to NPVA. Relating this to the previous paragraph, the more variable the lower chance the community will reject the mine. Meaning, the more the community has power in the bargaining process the more likely they will accept the mine. This makes intuitive sense, the party with more say in the proposal will more likely accept the offer.

Several of the factors affecting bargaining power shown in Table 1, such as control over proposals, patience, outside options, and knowledge, are generally in favour of mining companies, and typically give mining companies advantages in IBA negotiations as also discussed in Bradshaw et al. (2018), St-Laurent and Le Billon (2015), and Caine and Krogman (2010). The unique qualities factor, however, which in this case is the mineral resource, would be an advantage to the community depending on the global state of exploration and project development of the specific commodity. If many projects are available around the world for mining companies, they could have more options if bargaining breaks down, giving them an advantage. Conversely, if there are few sites then the community's site has less competition and they would have the advantage. Uncertainty and reputation can also alter bargaining outcomes for either party, but in countless ways. The definitions of these bargaining factors in the end can be interpreted for numerous criteria and situations, and could be an advantage or disadvantage for either party. However, the factors that are typically an advantage for mining companies need to be understood by regulators, and a bargaining process needs to be established where communities can receive fair deal during negotiations.

Scholars in ecological economics argue using money to value nature, as is often done by society's current economic and legal systems, is extremely problematic (Brown and Timmerman, 2015; Daly and Farley, 2011; Shmelev, 2012). Ecosystems can be infinitely complex; the planet's current understanding continues to improve but significant knowledge gaps remain (Vasseur et al., 2017). When reviewing the state of our planet's ecosystems, working within western economic growth paradigms has proved to be highly damaging (Gray, 2015). With the addition of MCDM, this research's goal is to provide a more pluralistic analysis of how different groups can value nature and its complexity. Unfortunately, this method still focusses on a human-centric viewpoint, where nature provides to society rather than the planet being a symbiotic system. In the end, for mineral development decisions, decision makers must make trade-offs to ensure better sustainability outcomes. This method provides a structure to understand and communicate these trade-offs.

5.7 Limitations

The limitations of this model and paper occur due to the nascence and limited integration of MCDM and game theory for the mining industry. The model developed in this paper is informed by data shown in the appendix, but for further applications a significant data collection endeavour would have to occur. Taking this paper's more theoretical model to a more applied level would require data from communities and mining companies on mine design parameters, criteria selection, criteria values, traditional knowledge, traditional economies, socio-environmental relationships, ecosystem parameters, biodiversity, and many more site specific considerations. Collecting that data requires strong local partnerships and is best done collaboratively with all players. At this point, this data collection undertaking is outside of the scope of this research. At this stage, this research's proposed model provides the first step for the integration of game theory and MCDM for IBAs and shows users the main considerations when making complex sustainability focused decisions. The data used in appendix provides an adequate framing for the model's development and for aligning it for future work.

The variables used in the model--1. environmental impact using the life of mine's total tonnes, 2. compensation to the community in dollars, and 3. a rating for socio-economic activities—present a simplistic representation of real-world considerations in IBA negotiations. More criteria should be implemented, which can easily be done with this model. At this stage, the key was to use criteria that represented different areas of sustainability and that could be valued in very different ways. With the goal of developing MCDM and game theory methods for IBAs adding more criteria at this stage would not provide create a better discussion. The next steps will be to engage directly with communities to understand and develop more criteria for project development.

Modeling MCDMs without value functions is not common and can make this model look more complex and less user-friendly than it is. Further data collection and the incorporation of value functions would simplify the models for easier use. At this stage, by keeping the value functions unknown, the model provides an ability to incorporate uncertainty of another party's strategy, which is common during negotiations. The model at this stage provides a way of analyzing often incommensurable criteria which is not easily done during negotiations.

This model developed provides new tools and methods to analyze IBAs, which can be used for future data collection steps when looking at specific sites. In all, this paper provides a structured approach for dealing with multiple criteria and multiple stakeholders with different value systems. The next steps will be to engage directly with mining companies and communities to collect the necessary data to understand the ideal trade-offs between criteria. These trade-offs will take place through agreeing to the mine plan, compensation schedule, and environmental impacts.

5.8 Conclusion and Recommendations

To summarize, the following list provides several key recommendations uncovered from this research for individuals looking to develop IBAs or predict if it will be accepted:

1. A project which provides alternatives which can trade-off between all important criteria, can make a project more likely to be accepted.

2. Before negotiations, bargaining factors should be analyzed to understand which group will potentially be at an advantage. The main factors–patience, knowledge, uncertainty, and power to make proposals–should be discussed and mediated.
3. Mineral policies should require proponents to provide flexible alternatives for all important criteria to communities.
4. Alternatives designs should be included for mine plans, mine closure plans, waste management plans, hiring policies, contracting policies, environmental monitoring plans, research and development initiatives, mine ownership, and compensation.
5. Transparent alternative assessments should be conducted to bring understanding to the economic-environmental trade-offs that exist between project benefits and impacts.
6. The model developed in this study can provide a method to organize and communicate the complex sustainability trade-offs that exist within mineral development.

IBA negotiations raise a lot of questions, uncertainties, expectations, and conflicts regarding resource development projects. This research's unique contribution was in its analysis and application of tools like bargaining theory, strategic games, and MCDM to help mineral development push towards sustainability focussed outcomes for society. To keep up with demand, mining's impacts are continuing to grow despite efficiency gains in many environmental mining technologies for water treatment, green-house-gas emissions, and waste management. With mining projecting to grow as society pushes towards lower carbon technologies, IBAs will continue to be key steps for resource development projects. IBAs must evolve to consider the increasing impacts of mining and the growing expectations and bargaining power of communities. To push for sustainability focused outcomes and informed decisions, IBAs should use methods like MCDM and game theory to better communicate the inherent and complex sustainability trade-offs in mineral and resource extraction.

5.9 Next Steps

This section analyzed impact and benefit agreements using the game theory and multiple-criteria decision making approach, which was first proposed in the previous section. Through creating this section's game, it was apparent that there can be countless approaches to incorporating multiple-criteria and developing game theory assumptions. The next section takes another approach for multiple-criteria and game theory using non-cooperative game theory. Nash equilibrium functions are developed for several games during the mine closure planning process.

5.10 Appendix – Impact and Benefit Agreements in Nunavut

The Nunavut mining industry in Canada was analyzed to provide an applied scenario to better understand IBAs. Nunavut was selected as the analysis area because it is one of the few regions where several IBAs are public. The following data in Table 5-7 helped guide the development of this study's model.

Table 5-7 Mines and IBAs in Nunavut

Mine	Company	Community Association	Proven and Probable	Life of Mine	After-tax NPV ($	Internal rate od return	Incentives	Cash incentives	References
Mary River (Iron ore)	Baffinland	Qikiqtani Inuit Association	60.7 M tonnes Ore	20 years	$1,030 (8% discount rate)	30.6%	Financial Participation Royalties Contracting Opportunities Employment Inuit Education and Training Community support Wildlife compensation Inuit Engagement Project Monitoring and Mitigation	20 million (M) + 1.25 M per construction quarter. $75 M max. If mine keeps operating. Royalty of 1.25% or percent of net revenue.	(Baffinalnd Iron Mines Corporation, 2011; "The Mary River Project Inuit Impact Benefit Agreement," 2018)
Meadowbank (Gold)	Agnico Eagle	Kivalliq Inuit Association	24.771 M tonnes Ore	7 years	$202.0 (5% discount rate)	25.7%	Contracting opportunities Training Employment Promotes social and cultural wellness Financial Compensation Wildlife compensation	$2.5M + 6.5 +1.4% Net Smelter Return)	(Agnico Eagle Mines Limited, 2017; "Meadowbank Mine Inuit Impact and Benefit Agreement between Agnico-Eagle Mines Limited and Kivalliq Inuit Association," 2017, "The Whale Tail Project Inuit Impact & Benefit Agreement," 2017)
Meliadine (Gold)	Agnico Eagle	Kivalliq Inuit Association	13.944 M tonnes Ore (10.048 Mt undergr ound)	14 years	$267 (5% discount rate)	10.3%	Business Opportunities Preferred Contracts Training and Employment Advancement of Women, Youth, and Challenged Workers Education Social and Cultural Wellness Financial Compensation Training. Contracts Community support Wildlife compensation Monitoring and Mitigation	$3M +1.2% Net Smelter Return	("Meliadine Project Inuit Impact and Benefit Agreement between the Kivalliq Inuit Association and Agnico Eagle Mine Limited," 2017)
Hope Bay (Gold)	Agnico Eagle	Kitikmeot Inuit Association	16.782 Ore (Mt)	15 years	$486 (5% discount rate)	19.7%	Details not public. Employment Training Business Opportunities Compensation for traditional, social, and cultural matters, and effects on Inuit water rights	Information not public	("IMPACT/BENEFIT AGREEMENT Miramar, KIA Concur on Hope Bay Project," 2004)

Chapter 6 - A Game Theoretic Decision-Making Approach to Reduce Mine Closure Risks throughout the Mine-life Cycle

6.1 Abstract

Mine closure planning requires flexibility in its design to reach the property's end land-use goals. Mine closure is a key component of mining's impact or contribution to the sustainability of communities and the environment. To align the post-mining site to the wants and needs of local communities and stakeholders, mine closure needs to consider criteria that may be difficult to value using conventional cost-benefit analysis, for example, criteria associated with the environment, socio-environmental relationships, health, and long-term sustainability. Using game theory with sustainability criteria, this study analyzes some key decisions throughout the mine life that affect closure. The decisions analyzed relate to mine closure plan selection, progressive closure, mine expansion, and care and maintenance. Game theory models are investigated by developing Nash equilibrium equations which are based on the change in environmental risk, economic potential, and impacts on company reputation. Scenarios are modelled using non-cooperative game theory for two cases. The two cases alternate which player's preference will be selected when there is conflict. This is to symbolize a regulator choosing either the impacted stakeholder or the company's preferences. The equilibrium formulas developed show how to better manage the multi-faceted sustainability considerations that need to be balanced in closure decisions. Findings are aligned to mining stakeholders to assist in understanding their position during the mine closure process. The game theory and

multiple-criteria models can help manage the long-term multi-faceted risks at closure throughout the mine life-cycle.

6.2 Introduction

Maximizing sustainability in mining operations requires reclaiming and re-aligning the site after the mine ceases operation according to the needs of the local environment and stakeholder. The methodic planning and ongoing management required for this is generally referred to as mine closure planning or simply mine closure (Manero et al., 2020). Best practices dictate that closure planning commences during the permitting stage before construction or mine operations (Getty and Morrison-Saunders, 2020). Closure planning can have several goals, but at its most basic, it attempts to bring a mine site back to a chemically and physically safe state (Bingham, 2011). Mine closure now attempts, if possible, to bring the site back to a usable state, or to align it to land use as agreed upon by the mine site's stakeholders. Nearby communities, like many Indigenous communities, are especially vulnerable to poor mine closure practices, as they can have strong cultural and socio-economic ties to the area (O'Faircheallaigh and Lawrence, 2019). Successful closure planning requires numerous complex considerations throughout the mine life-cycle. Considerations such as whether to progressively reclaim, which criteria to prioritize, and when exactly to stop operations and begin closure work. This article develops an interdisciplinary model for the entire closure planning process and interrogates some of the key decisions by both the property's stakeholders and the mining company. More particularly, a combination of game theory, ecological economics, multi-criteria decision making (MCDM), mineral economics and decision theory are employed. The goal for this model is to bring light to the intricacies of closure planning and provide recommendations to predict, plan, and manage mining's long-term risks for mining companies, Indigenous communities, local communities, regulators, and all other impacted stakeholders.

Mining and mine closure planning are interrelated, but are often considered separately (Nehring and Cheng, 2016). During mining, a mine plan can shift drastically, which alters what is required for successful mine closure. Mine closure planning must work in conjunction with mining to adapt as mine plans shift. Mine planning, on the other hand, must consider its closure implications as it shifts to maximize profits (Espinoza and Morris, 2017). There are complex trade-offs that take place in these decisions where you must consider many different types of criteria and how different stakeholder groups value the various criteria (Collins and Kumral, 2020a). The mining industry typically uses sustainability guidelines to account for non-market criteria, which include, for example, socio-cultural-environmental uses of the land. Towards sustainable mining (TSM), ICMM's integrated closure plan are some examples of guides used for holistic closure planning (Espinoza and Morris, 2017). The issue is that these guides typically do not provide any discussion on how prioritization or trade-offs should take place on criteria during mining decisions (Collins and Kumral, 2021). The mining industry needs methods that can provide a more integrated approach to sustainability. Building on the methodologies shown in Collins and Kumral (2020b, 2021b), this paper creates a novel approach of using multiple criteria and game theory to fill these gaps.

As compared to the previous application of game theory and MCDM in Collins and Kumral (2021b), this research incorporates multiple criteria into the payoffs of a non-cooperative game rather than a bargaining game. This requires different techniques to calculate equilibriums and game assumptions to trade-off between sustainability criteria. In addition, this paper applies the methods to mine closure decisions rather than impact and benefit agreements. In general, MCDM creates a structured approach to prioritize criteria and alternatives based on stakeholders, decisions makers, or expert preferences (Linkov et al., 2020). Game theory can show the outcomes of cooperation or competition between two or more groups or individuals (Collins and Kumral, 2020b). This research uses these two methods to interrogate mine closure, and mining methods to provide a more all-encompassing analysis of sustainability for mineral development.

Well-planned mine closure is essential for the long-term environmental sustainability of ecosystems and for protecting Indigenous communities, but there are many challenges with current practices (ICMM, 2019). Firstly, the inherent destructive nature of today's mining technologies makes it at times impossible to bring a site back to a usable state. Environmental reclamation technologies continue to improve, but mines are growing to meet demand, causing major environmental risks at closure (Bardi, 2013). There also can be a gap in what is expected for reclamation by local Indigenous communities and what is possible with reclamation technologies (Collins, 2015). Clear communication of what is possible with the mining methods used is imperative to find the best possible land uses post-mining. Sustainability trade-offs need to be openly communicated between economic viability, ecosystem health, and socio-environmental relationships. MCDM, which is seldomly used in mine closure planning, can be an effective tool to communicate the complex trade-offs and decisions that are made in mineral development (Govindan, 2015). This research shows where to incorporate an MCDM into a mine closure game-theoretic decision framework.

The originality of this paper lies within its game-theoretic approach to mine closure planning and its methodology of combining multiple-criteria and game theory for resource development challenges. The next section outlines the methods and applications used in this research. Section

6.4 will discuss the relevant literature in mine closure planning, sustainability in the mining industry, and relevant applications with MCDM and game theory. Section 6.5 presents the mine closure decision making model developed from findings Section 6.4. Section 6.6 provides a discussion on the results and findings of the model. And finally, Section 6.7 concludes this research and discusses how to align mine closure decision making for a more sustainable future.

6.3 Methods and Materials

This study examines literature over the past twenty years for relations between mine closure planning, decision theory, game theory, sustainability decision making, and MCDM. Journal articles, conference proceedings, and books were analyzed and organized using the Mendeley software package. Environmental sustainability applications of game theory were used as a reference and were adapted for developing the non-cooperative game-theoretic approach for this research. Nash equilibrium formulas are developed based on non-cooperative game theory, also outlined in Collins and Kumral (2020b). Types of criteria incorporated into the game theory pay-off functions were adapted from recommendations from mining sustainability guides like ICMM (2019). Discussions and conclusions are developed from the issues and assumptions uncovered when creating the closure games in Section 6.5.

6.4 Literature Review – Decision Making Gaps in the Mining Industry

6.4.1 Terminology and related activities

Mine closure, reclamation, restoration, remediation, and rehabilitation are terms used by the mining industry to discuss activities to reclaim and re-orient a mine site after mining ceases (Kaźmierczak et al., 2017). The terms are often used in different ways, but for this study, mine closure refers to simply the work needed to bring a mine site to a post-closure state. This can include constructing covers for tailings/waste rock, closing of excavations, or decommissioning mine infrastructure. Mine closure can also signify the point where all work is complete at the site, and when the area goes into a state of post-closure monitoring or into another land use. Reclamation, restoration, remediation, and rehabilitation are generally synonymous terms used to describe activities that reclaim the land, such as treatment of soil and water, or re-introducing native species. Reclamation, restoration, remediation, and rehabilitation generally fall under the activities of mine closure (Manero et al., 2021). The required mine closure, reclamation, or rehabilitation work needed is dependent on the local site's ecosystem, the mine method chosen, and the desired end land-use. Sustainability-focused mine closure, also sometimes referred to as integrated closure, must also consider socio-cultural, socio-environmental, and economic impacts of mines closing (ICMM, 2019).

6.4.2 Mine closure planning and sustainability

Mine closure is a major issue for the mining industry's contribution to sustainability and reputation (ICMM, 2019). Poor closure practices can directly impact a company's reputation, which can negatively affect its ability to start new projects, develop trust and agreements with stakeholders, and find investors. A poor reputation can also increase the chances for protests, blockades, project delays, and litigation. The state of closed mines has historically been abhorrent. Many mines around the world, once closed, have become billion-dollar environmental liabilities, destroying local ecosystems and greatly impacting many socio-environmental connections (Ali, 2003; Faro Mine Remediation Project, 2018; Leech, 2018; Sandlos and Keeling, 2016). After reaping the economic benefits during mining operations, a site can be left drastically different from what it once was, and historically major environmental risks are created from the tailings management structures, water usage, mine effluents, animal habitat displacement, massive excavations, and increased acid rock drainage potential (Lottermoser, 2010). Additionally, on a social and economic level, economic opportunities that a community once relied on can quickly vanish once the mine closes (Bainton and Holcombe, 2018). Many of these issues were under-regulated or not even considered for many years. Even after following best practices and regulations, the environmental risk may persist after closure. Financial compensation for negative environmental impacts of mining is often implemented, but it is often inadequate for the long-term health of communities and ecosystems (Silva et al., 2021). Environmental risk must therefore be well-managed throughout all stages of the mine life. In general, mine closure is not a single process; it is a sum of continuous activities spreading over many years.

In the 1990s, mining executives concerned with the reputation and state of the mining industry came together to develop sustainability guidelines to help push towards more sustainable outcomes (MMSD, 2002). The push for the mining industry to adopt more sustainable practices led to the creation of the Mining, Minerals, and Sustainable Development (MMSD) by the world’s biggest mining companies (MMSD, 2002). This then morphed into the International Council of Mining and Minerals (ICMM), which now provides twenty-eight mining and metals company members with principles, recommendations, and resources to guide their sustainability contribution (ICMM, 2020). Other guidelines provide similar resources, such as the Mining Association of Canada (MAC) (2004) and Australia’s leading Practice Guidelines (2011). These guidelines discuss approaches and some of the key considerations to improve their members' reputation, social license, social and environmental risk management methods. All mining guides discuss the importance of best practices for mine closure planning (Australian Government, 2016; MAC, 2008). They implore that closure planning needs to be an integrated approach throughout the mine life to maximize the long-term sustainability of the area and minimize the potential environmental, social, and economic risks. The ICMM (2019) specifically provides an integrated mine closure guideline which discusses the importance of closure vision and objectives, engagement with stakeholders, progressive closure, social transition, and success criteria. Regarding success criteria, the importance of specific, measurable, attainable, relevant, and time-based ("SMART" criteria) is discussed and is paramount for successful closure. Global Reporting Initiative (GRI) standards and criteria are commonly used, but imperative criteria need to be developed collaboratively with stakeholders to ensure the goals are aligned to the wants and needs of the impacted groups (Virgone et al., 2018).

These standards are robust and point the industry in the right direction, but implementation continues to be an issue for mine closure. The implementation of these standards is generally viewed as a work-in-progress (Sethi and Emelianova, 2011). Measurable outcomes and improvements have yet to be seen in terms of scale and stakeholder relationships. The mining industry has known for a long time about the many environmental issues caused by mining, yet implementing environmentally innovative approaches for mine planning is at a standstill. The guides provide no advice on how to make the difficult trade-offs between criteria alongside impacted stakeholders. Questions remain regarding which criteria should be prioritized. Who should make decisions regarding criteria and land use? What should the concrete objectives be for mine closure planning for the future? It is easy to say, mining should minimize environmental damage and maximize profitability, but at what point does one get prioritized over another? This analysis shows that there is a critical lack of approaches for sustainability trade-offs in mine closure planning for companies, regulators, and stakeholders. MCDM is argued for in this research to help communicate and make trade-offs between the important criteria. The next section discusses literature regarding MCDM and game theory and their applications in mining and mine closure planning.

6.4.3 Mine closure planning with MCDM and game theory

This study argues for adapting MCDM, be able to incorporate various sustainability criteria that may not be easily comparable or commensurable. MCDM, also known as multiple-criteria decision analysis, is a method that considers different preferences and criteria, which may be conflicting or corresponding, to assess the performance of alternatives. It is a method that is both mathematically rigorous and transparent to stakeholders (Linkov et al., 2020). With applications across numerous fields, it is grounded in decision science and operational research (Ozsahin et al., 2021). Different MCDM techniques combine preferences and score alternatives in different ways. Techniques such as AHP, ELECTRA, PROMETHEE, VIKOR, TOPSIS, and fuzzy MCDM are some of the most used techniques, with most mining applications using AHP (Collins and Kumral, 2020a). Even though MCDM can provide a method to consider complex decisions with multiple criteria, which is often seen in the mining industry, there is a lack of MCDM applications in sustainability-focused decision making.

More specifically, MCDM applications for the post-mining stage of the mine life-cycle are also limited. Using different MCDM methods, they mainly focus on finding a post-mining land use. This is seen in Amirshenava and Osanloo (2017), who use a combination of PROMETHEE and SIR techniques, Narrei and Osanloo (2011) use AHP, SAW, and TOPSIS for post-mining land-use selection, Soltanmohammadi et al. (2009, 2010) use PROMETHEE and TOPSIS respectively, and Yavuz and Altay (2015) use Fuzzy AHP. Applications can also focus on specific areas of a mine site, as seen in Bangian et al. (2012, 2011), who use Fuzzy Multi Attribute Decision Making (MADM) modeling to provide a land use for a pit area, and Golestanifar and Bazzazi (2010) uses fuzzy TOPSIS and AHP for tailings dam site selection. Other studies integrate risk into the model, as seen in Amirshenava and Osanloo (2018) and Cui et al. (2020). These studies look at one issue during the closure but fail to consider the complexities of the entire process and the dynamic nature of closure throughout the mine life. This research creates a decision-making mine closure process that considers the long-term and integrated nature of closure planning alongside the entire mine life-cycle. In addition, with mines affecting stakeholders in different ways, methods need to incorporate how they interact and find cooperative or uncooperative solutions. Game theory, which this study uses, has the potential to fill this gap.

The incorporation of game theory and MCDM, which this study employs, is based on previous research and applications in Collins and Kumral (2021b, 2020b). Game theory, which has numerous applications, analyzes the strategic decisions in various situations between groups, individuals, or, as game theory terminology uses, players. Game theory is divided into two fields, cooperative and uncooperative game theory, but there are infinite ways for how to set up a game. Setting up games typically requires many assumptions on the players' knowledge and strategies. These assumptions must be very specific for certain situations, which makes it difficult for the models to work consistently in real-world scenarios. What game theory provides is a method to look at situations where two or more groups interact, and communicate how outcomes could take place under certain assumptions.

An analysis of game theory applications for sustainability-focused situations for the mining industry was conducted in Collins and Kumral (2020a). Even though game theory's potential to model interactions between groups for strategic decisions, it has not been extensively applied to the mining industry**.** Learnings can be gleaned from applications in international environmental negotiations, common-pool resources, and stakeholder interactions regarding carbon emissions, pollution abatement, and renewable resource sharing (Albiac et al., 2008). Mining applications include Podimata and Yannopoulos (2016), who analyzed a game between regulators and companies for riverbed mining, Sinha et al. (2013) analyzed taxes and profits between mining companies and regulators, Figueroa (2013) analyzed the conflicts between mining companies and communities, and Collins and Kumral (2021b) analyzed impact and benefit agreements in a bargaining game between a community and a company.

The combination of MCDM and game theory is also not common but has great potential to provide a more integrated analysis of human-environmental relationships. Conversely, game theory aids MCDM techniques by considering the competitive environment of decision-makers (Chen et al., 2013; Deng et al., 2014). A challenge with developing games is the creation of the payoff functions for each player under different strategies. Typically, it is done using a single criterion like monetary value, but the incorporation of MCDM allows the integration of other criteria. This allows a more nuanced and holistic analysis of the environment. Solely, monetary valuation of the environment can inadequately consider the environment's cultural, ethical, and aesthetic dimensions as well as the countless connections within ecosystems (Farley and Kish, 2021). Some examples of MCDM and game theory include Aplak and Sogut (2013), Chen et al. (2013), Debnath et al. (2018), and Hashemkhani Zolfani et al. (2015), who make simultaneous games and use MCDM to analyze player strategies. As discussed in Collins and Kumral (2021b), the few mining examples are useful to draw upon, but when applying them to another problem, like mine closure planning, methods need to be greatly altered and new assumptions need to be made which create a novel model.

6.5 Closure Decision-Making Model

Closure planning is an iterative process throughout the mine life. Even after establishing a closure plan, numerous decisions need to be made to manage the risks at closure. As noted, MCDM and game theory can be utilized to analyze these decisions. This section implements MCDM and game theory to analyze some of these key decisions during the closure planning process. First, this paper presents some of the key inputs needed for the game theory models.

6.5.1 Model inputs and game considerations

For these models, this research uses environmental risk (EVR), economic potential (ECP), and company reputation (CR) as its criteria. Other criteria could be easily implemented, but these criteria are still able to provide this research with a thorough analysis. To determine the payoffs to each player, each player's values must be considered. The function for the company's value system is named "CV" while the community or impacted stakeholder is named "SV". Using an MCDM, CV or SV provide a value to each of the criterion, to then calculate a payoff. Different MCDM methods like AHP, can be utilized, which uses pairwise comparisons to put a relative evaluation for each criterion. It considers preference trade-offs between criteria.

The environmental risk associated with mine closure can come in many forms, such as water quality and quantity, soil contamination, biodiversity impact, acid rock drainage potential, landscape deterioration, and stability of tailings dams, waste rock piles, long-term subsidence potential, and underground workings. Environmental risk for closure needs to be managed throughout mine operations and grows as the mine operates. If the environmental risk is not managed, then the site can turn into a billion-dollar liability threatening the local ecosystems and community’s socio-environmental relationships. This study's models make a couple of assumptions that generally hold true. The longer the mine puts off closure work, the environmental risk grows. As mines expand, which requires more consumables, and creates more waste, the environmental risk grows. If the mine carries out its previously planned closure work in a timely manner, the closure risk stays the same. Unfortunately, it is very difficult to determine exact levels of environmental risk. Acceptable levels of environmental risk need to be determined based on environmental assessments and stakeholder discussions. This study uses relative levels of risk for these games, by modeling decisions that increase or decrease the environmental risk.

These games also consider the changes to economic potential from mine closure decisions (ECP). As a mine operates, it operates under the original plan from the feasibility study. But, as mining continues, ore body knowledge improves and metal prices change. During these changes, decisions of whether to alter the original mine plan need to be made. Expanding, closing, temporarily closing can all occur during a mine life. Decisions of expanding vs. not expanding, or closing vs. temporarily closing, have impacts on the mine’s economic potential. Expansion can increase the amount of minerals extracted and closing early can do the opposite. ECP in these models considers the relative change in ore extraction and, therefore, economic profitability.

In the models, there are cases where the community/stakeholder and company disagree with the decision. The regulator chooses who gets to have the final decision in these games. In cases where the company and the community disagree, and the regulator lets the company make the decision, there can be an increased risk to the company-community relationship, social license to operate, and the project's contribution to sustainability. Improperly managing these relationships can affect a company's reputation, which can impact its environmental social governance (ESG) evaluation and sustainability rating. Protests, blockades, and legal prosecution from impacted groups. This study uses "CR" to signify the increased risk of company-community disagreements.

6.5.2 Incorporating multiple criteria

For the first decision/game—establishing a closure plan—rankings are calculated using an MCDM then cardinal rankings are used between alternatives. For the other decisions/games, MCDM methods are used to calculate a score. It is important to note, that MCDM processes are generally used to find a ranking between alternatives, not a score. MCDMs provide a method to consider different criteria, value systems, and alternatives, which can be translated into a score. MCDMs generally normalize criteria and calculate a score based on the player's value function. This could be through calculating distances from the ideal solution, as shown in MCDMs like VIKOR. The distance to the ideal solution can be the payoff, which is a unitless value. It can be used to create comparable payoffs, if the same MCDM is used. This research does not argue for one specific method over another. Rather, this research shows where to implement an MCDM for payoffs in Games 2-4 and to calculate rankings in Game 1. The next subsection discusses the specific games and decisions analyzed with game theory and MCDM.

6.5.3 Closure decisions and games

6.5.3.1 Game 1: Establishing mine closure plan alongside mine plan and desired land use

Before any development and during the permitting stage, a mine closure plan is established alongside a mine plan. Financial assurance is also established at this time to ensure adequate funds are available to reclaim a mine site; this is often in the form of bank bonds. To find an appropriate post-mining land use, coordination with local stakeholders, such as Indigenous communities, needs to be conducted. Typically, a mine plan is first established, followed by the land use plan and closure plan. The closure plan is, unfortunately, typically an afterthought when planning for a mine, but for a more integrated closure plan, these should be done at the same time. Mine planners should be thinking about closure planning and the end land use when designing a mine. Given some of today's technical limitations in reclamation and environmental technologies, the mine closure plan is dependent on the mine plan. For example, some mining methods, like caving methods, create an area of land subsidence in perpetuity, and the closure best practices today is to simply fence off the site. If site access is an important aspect of the post-mining land use plan, then mine closure planners and mine planners need to work together to find different mining methods. The trade-offs that are done to make decisions between the mine plan with the closure and land use plan are very complex and require incorporating numerous criteria.

In Table 6-1, the decision matrix is shown of an impacted stakeholder (player 1) and a mining company (player 2) for closure alternatives A1, A2, and A3. The impacted stakeholder could be a local community, affected business, regulator, or non-governmental organization. In Table 6-1, as an example, the stakeholder ranks the alternatives A1, A2, and A3 in that order and the company ranks the alternatives in the opposite order. An MCDM would calculate this order and would input the different criteria for each alternative and calculate a ranking for the stakeholder and the mining company. At areas of conflict, meaning where the company and the community choose different alternatives. Table 6-2 shows the same game, but in areas of conflict, the company's decision will be the outcome regardless of what the stakeholder prefers. This is to simulate the regulator siding with the company. In Table 6-3, it shows the case where the stakeholder's selection is the outcome and the regulator sides with them. There are impacts to times of conflict in terms of reputation to the company or the relationship between the company and stakeholder. These will be discussed further in the next games.

Table 6-1 Desired land use game with unknown conflict outcomes

Stakeholder \ Company	A1	A2	A3
A1	(3,1)	(X)	(X)
A2	(X)	(1,2)	(X)
A3	(X)	(X)	(2,3)

Table 6-2 Desired land use game with company decision preferences

Stakeholder \ Company	A1	A2	A3
A1	(3,1)	(1,2)	(2, 3)
A2	(3,1)	(1,2)	(2, 3)
A3	(3,1)	(1,2)	(2,3)

Table 6-3 Desired land use game with stakeholder decision preferences

Stakeholder \ Company	A1	A2	A3
A1	(3,1)	(3,1)	(3, 1)
A2	(1,2)	(1,2)	(1,2)
A3	(2,3)	(2,3)	(2,3)

6.5.3.2 Game 2: Progressive closure

A way to lower the environmental risk at closure is to progressively reclaim the land while mining. This requires careful mine planning and staging of mining operations. Once one area of the mine site is complete, then mining moves on to another site. When mining changes locations, reclamation activities can be carried out on the previous site. Progressive reclamation is only possible with certain mining methods, where there is a staging approach. In large open pits, it can be more difficult to find progressive reclamation opportunities in the ore extraction area, but other mine infrastructure areas can be progressive reclaimed. Strip mining, internal dumping option, and multi-pit operations can allow the mine management to implement progressive reclamation.

Tables 6-4 and 6-5 show two games, one where the company will have their preference chosen, and one where the stakeholder have their preference chosen. In practice, the regulator will have to decide which group to side with, and thus both cases are modelled. To note, in the "Company has influence" game, the company dictates what will occur, but at cells where the company and the stakeholder are in conflict, the company's reputation will be impacted, which is denoted by "↓CR". The arrows beside the variables denote an increase (↑) or decrease (↓), which depending on the variable, provides a better or worse payoff. An increase in EVR, for example, reduces the payoffs, but an increase in ECP increases the payoff. In the stakeholder game, there is no company reputation impact because the stakeholder has the final say in times of conflicting preferences. This is a simultaneous game, as will be all other games in this section.

Table 6-4 Progressive reclamation and company has influence game

Company

Stakeholder	Do not reclaim (DNR)	Reclaim Site (RS)
Do not Reclaim (DNR)	((↑EVR, 0)*SV, (↑EVR, 0)*CV)	((↓EVR, ↓ECP)*SV, (↓EVR, ↓ECP, ↓CR)*CV)
Reclaim Site (RS)	((↑EVR, 0)*SV,) (↑EVR, 0, ↓CR)*CV))	((↓EVR, ↓ECP)*SV) , (↓EVR, ↓ECP)*CV)

EVR: Environmental risk, ECP: Economic potential, CR: Company reputation

Table 6-5 Progressive reclamation and stakeholder has influence game

Company

Stakeholder	Do not reclaim (DNR)	Reclaim Site (RS)
Do not Reclaim (DNR)	((↑EVR, 0)*SV, (↑EVR, 0)*CV)	((↑EVR, 0)*SV, (↑EVR, 0)*CV)
Reclaim Site (RS)	((↓EVR, ↓ECP)*SV, (↓EVR, ↓ECP)*CV	((↓EVR, ↓ECP)*SV, (↓EVR, ↓ECP)*CV

To solve these two games for the Nash Equilibrium, the matrices must simplify into variables. The payoffs will use an MCDM to score the criteria with the value functions. To solve the matrices, those are simplified into a single variable. As an example, in the case where both players prefer DNR in Table 6-4, the payoffs to the Stakeholder is ((↑EVR,0)*SV and the payoff to the company is (↑EVR, 0)*CV. In the simplified game (Table 6-6), the payoff to player 1 is now $X_{1,}$ and the payoff the player 2 is Y_1.

Table 6-6 Simplified game - Progressive reclamation and company has influence

Company

Stakeholder	Do not reclaim (DNR)	Reclaim Site (RS)
Do not Reclaim (DNR)	(X_1, Y_1)	$(X_2, Y_2 - CR_2)$
Reclaim Site (RS)	$(X_1, Y_1 - CR_1)$	(X_2, Y_2)

Note that CR_1 and CR_2 will be different values because the company's reputation will be affected differently if their DNR decision is selected versus their RS decision. For the company now, the unknown is what the stakeholder will prefer. The probability of the stakeholder preferring DNR is denoted by P_{DNR}. Therefore the company will selected the RS case if the expected value of RS is greater than DNR. Thus the equation below will hold true, when calculating the expected value.

If $(P_{DNR} - 1)(Y_2) + (Y_2 - CR_2)(P_{DNR}) > Y_1 P_{DNR} + (Y_1 - CR_1)(1 - P_{DNR})$,

Then the company will select RS. Solving for P_{DNR}. If $P_{DNR} > \frac{Y_2 + Y_1 - CR_2}{2Y_2 - CR_1 - 1}$ then the company should selected RS and if $P_{DNR} < \frac{Y_2 + Y_1 - CR_2}{2Y_2 - CR_1 - 1}$ then the company should select DNR.

For the stakeholder game the matrix is simplified to:

Table 6-7 Simplified game - Progressive reclamation and stakeholder has influence

Company

Stakeholder	Do not reclaim (DNR)	Reclaim Site (RS)
Do not Reclaim (DNR)	(X_1,Y_1)	(X_1,Y_1)
Reclaim Site (RS)	(X_2,Y_2)	(X_2,Y_2)

Simply for this game the stakeholder will select whichever provides a better payoff, X_1 or X_2.

6.5.3.3 Game 3: Expansion

As a mine operates, it is common that more areas of the site are explored and more deposits are found. Altering the mine plan, or expanding, can greatly change the requirements for closure to reach the expected land use and closure goals. The regulator has to decide if closure objectives can still be made and the growing environmental risk can be managed. Expanding a mine can increase the overall environmental risk at closure.

Table 6-8 Expansion decision and company has influence game

Company

Stakeholder	Expand	No Expand
Expand	((↑EVR, ↑ECP)*SV, (↑EVR, ↑ECP)*CV))	(0, ↓CR)
No Expand	((↑EVR, ↑ECP)*SV, (↑EVR, ↑ECP, ↓CR)*CV))	(0,0)

Table 6-9 Expansion decision and stakeholder has influence game

Company

Stakeholder	Expand	No Expand
Expand	((↑EVR, ↑ECP)*SV, (↑EVR, ↑ECP)*CV)	((↑EVR, ↑ECP)*SV, (↑EVR, ↑ECP)*CV)
No Expand	(0,0)	(0,0)

Simplifying the company game as per the previous games, the following matrix is produced.

Table 6-10 Simplified game - Expansion decision and company has influence

Company

Stakeholder		Expand	No Expand
	Expand	(X_1, Y_1)	$(0, -CR_2)$
	No Expand	(X_1, Y_1-CR_1)	$(0,0)$

Now taking P_{ex} as the probability the stakeholder prefers to expand, The following equation can be written.

The company will select expand if $Y_1 P_{ex} + (Y_1 - CR_1)(1 - P_{ex}) > -CR_2$. Solving for P_{ex}. The company will

select expand if $P_{ex} > \frac{CR_1 - CR_2 - Y_1}{CR_1}$ and $P_{ex} < \frac{CR_1 - CR_2 - Y_1}{CR_1}$ for the company to not expand.

For the stakeholder game, the game is simplified to:

Table 6-11 Simplified game - Expansion decision and stakeholder has influence

Company

Stakeholder		Expand	No Expand
	Expand	(X_1,Y_1)	(X_1,Y_1)
	No Expand	$(0,0)$	$(0,0)$

So simply, the stakeholder will select expand if $X_1 > 0$.

6.5.3.4 Game 4: Care and maintenance or closure activities

A very difficult decision is when exactly closure work should start. Often mines operate and close for certain time periods based on commodity prices. When the mine is temporarily closed, it is called “care and maintenance”, where closure work does not need to occur. The issue is that many mines are under care and maintenance for many years, even decades, before any closure work is done. This can increase the environmental risk as well as the risk the company will go bankrupt and not be able to conduct the necessary closure work. However, by going into closure too early from the care and maintenance stage, the mine’s reserves remain in the ground, and the impacts per metal recovered increase. The impacts per metal recovered increase because it takes a considerable amount of upfront construction and development before any mining takes place. Stopping operations early impacts the ability to pay back the original construction economic and environmental costs.

Table 6-12 Commencing closure decision and company has influence game

		Company	
		Care and Maintenance	Commence Closure work
Stakeholder	Care and Maintenance	((↑EVR,0)*SV, (↑EVR, 0)*CV)	((0,↓ECP)*SV, (0,↓ECP, ↓CR)*CV)
	Commence Closure work	((↑EVR,0)*SV, (↑EVR, 0, ↓CR)*CV)	((0,↓ECP)*SV, (0,↓ECP)*CV)

Table 6-13 Commencing closure decision and stakeholder has influence game

		Company	
		Care and Maintenance	Commence Closure work
Stakeholder	Care and Maintenance	((↑EVR,0)*SV, (↑EVR, 0)*CV)	((↑EVR,0)*SV, (↑EVR, 0)*CV)
	Commence Closure work	((0,↓ECP)*SV, (0,↓ECP)*CV)	((0,↓ECP)*SV, (0,↓ECP)*CV)

These games turn out to be very similar to the progressive closure decision game. The simplified matrix for the Company decision game can be seen below:

Table 6-14 Simplified game - Commencing closure decision and company has influence

Company

Stakeholder	Care and Maintenance	Commence Closure work
Care and Maintenance	(X_1,Y_1)	(X_2,Y_2-CR_2)
Commence Closure work	(X_1,Y_1-CR_1)	(X_2,Y_2)

If P_{CM} is the probability the stakeholder will prefer Care and Maintenance, then the company should choose Commence Closure Work if $P_{CM} > \frac{Y_2+Y_1-CR_2}{2Y_2-CR_1-1}$ and select Care and Maintenance if

$P_{CM} < \frac{Y_2+Y_1-CR_2}{2Y_2-CR_1-1}$.

Then for the simplified stakeholder game, the following matrix is made.

Table 6-15 Simplified game - Commencing closure decision and stakeholder has influence

Company

Stakeholder	Care and Maintenance	Commence Closure work
Care and Maintenance	(X_1,Y_1)	(X_1,Y_1)
Commence Closure work	(X_2,Y_2)	(X_2,Y_2)

The stakeholder will again choose Care and Maintenance (X_1) or Commence Closure work (X_2), depending which has a bigger payoff. Table 6-16 summarizes the Nash equilibrium calculations based on the opposite players' selection probabilities.

Table 6-16 Game Summary Solutions

Game	Decision Power	Solution
Progressive	*Company*	If $P_{DNR} > \frac{Y_2+Y_1-CR_2}{2Y_2-CR_1-1}$ then the company should select RS and if $P_{DNR} < \frac{Y_2+Y_1-CR_2}{2Y_2-CR_1-1}$ then the company should select DNR
Progressive	*Stakeholder*	the stakeholder will select whichever provides a better payoff, X_1 or X_2.
Expansion	*Company*	The company will select expand if $P_{ex} > \frac{CR_1-CR_2-Y_1}{CR_1}$ and $P_{ex} < \frac{CR_1-CR_2-Y_1}{CR_1}$ for the company to not expand.
Expansion	*Stakeholder*	The stakeholder will select expand if $X_1 > 0$.
Starting Closure	*Company*	Commence Closure Work if $P_{CM} > \frac{Y_2+Y_1-CR_2}{2Y_2-CR_1-1}$ and select Care and Maintenance if $P_{CM} < \frac{Y_2+Y_1-CR_2}{2Y_2-CR_1-1}$.
Starting Closure	*Stakeholder*	the stakeholder will select whichever provides a better payoff, X_1 or X_2.

6.6 Discussion

The closure planning games developed highlight how closure decisions require the consideration of different criteria, time-horizons, stakeholders, impacts, and policies. This section discusses the complexities of these considerations to show where the model is useful and its limitations.

The Nash equilibrium formulas developed show the relationship between the criteria functions and decisions. As shown in the games, the companies must consider an additional factor, the reputation factor (CR), during potential conflict scenarios. The functions developed provide a method for a company to structure their decisions. By internally deciding how certain they are about conflicts and weighing it against the potential damages and benefits of decisions, the formulas can provide a method to frame these multi-factorial decisions problems. In each Nash equilibrium shown in Table 16, the player making the decision is factoring in the potential benefits or impacts—the “Y” or “X” functions—and weighing it against CR, in the case of the company. For the company, essentially, the functions show that they must find the balance between the uncertainty of the stakeholder’s decision with the potential benefits of their decision. For the community, they simply choose the scenario that provides them with the most benefit. Additional factors could be added into the MCDM functions, similar to the factors ECP and EVR.

This research has the goal of incorporating multiple-criteria to provide a more holistic analysis of sustainability. The issue is that often it is unclear which criteria exactly provides this holistic analysis for sustainability. “SMART” indicators are proposed from sustainability guides like ICMM, and generally indicators need to be selected and developed for specific projects alongside the site’s stakeholders. But at times, this still does not provide a full analysis. Ecosystems and environmental health, for example, are difficult to model because their complex connections and functions are not fully understood (Knoke et al., 2020). Finding and selecting appropriate indicators to model environmental health can also be lacking (Collins and Kumral, 2020a). Given the environment’s inherent complexities, valuing the environment is solely an estimate. In addition, the criteria society uses is generally anthropocentric, and may not be able to fully value all the connections within ecosystems that seem unimportant to us at this time (Gowdy, 2011). The model developed shows how incorporating multiple criteria can provide a more sustainability-focused decision, but its success hinges on which criteria are selected or developed.

A major consideration for the developed models is time. Most economic models require an assumption for the time-value of money or discount rate (Daly and Farley, 2011). Meaning they assume how much today's dollars would be worth in some future date and vice-versa. When working with closure, with costs of closure incurring at the end of long mine life, discounting can make closure costs not really a major concern for mining's profitability. To ensure longer time horizons are better considered, alternatives should not use discounting but instead have different levels of profits versus environmental risk reduction.

The games display several of the players as stakeholder. A key consideration in decision making is who should be involved in the decision and who should have a say. In some cases, different impacted communities differ in their wants and needs. Even within a community, they can differ in their decisions. MCDM techniques in this paper's model attempt to bring together different values, but there still can be some groups that may be under-represented in final decisions. Indigenous communities, which have historically been ignored, are starting to be more involved in decision making in their territory (O'Faircheallaigh and Lawrence, 2019). Strong focus is now being placed on their involvement through sustainability decisions, but when communities have different values and wants than what the mine can provide, there can be conflicts that arise. Indigenous communities around the world are extremely diverse, and their wants and needs should not be conflated between groups. Each community needs to be collaborated with and consulted. The model allows different value systems from stakeholders like Indigenous communities, but the calculation of the value function can be very difficult to ascertain. In Canada, for example, after years of unacceptable policies against communities sowing distrust with the government, there is evidently apprehension with collaborating with developers on their territories.

Finally, analyzing these games through mechanism design can be a useful approach for developing policies. Mechanism design is a solutions-first approach. Meaning, a game is created that in order to get to the desired outcome. For closure planning, it can be used for helping a regulator create incentives for a desired outcome through taxation or regulations. The developed games show the cases where the regulator sides with either the company or stakeholder, but before the regulator sides with one player or the other, the regulator could affect the payoff functions by increasing taxes and distributing payments to communities. In the games in Section 6.5, these taxes or payment distributions would affect the X or Y values in Table 16, which would lead to certain decisions (e.g., expansion, closure, or progressive closure), being more favorable. Through taking a mechanism design approach, the equations in Table 16 can be utilized to determine how to establish a game with a wanted outcome.

6.7 Conclusion

Closure planning requires multi-dimensional thinking with consideration of numerous sustainability criteria and project stakeholders. This research used game theory and multiple criteria to bring a more all-encompassing analysis of sustainability into decision making for mine closure. The models developed were able to consider multiple sustainability criteria regarding environmental risk, economic potential, and company reputation. The models provide a way to structure decision making for key decisions in the closure planning process such as final land use selection, progressive reclamation, mine expansion, and commencement of closure. The Nash equilibrium functions show how to consider uncertainty regarding the other players' strategies and balance it with the potential benefits as calculated by an MCDM. Taxation levels and regulations can be implemented into the games through the X and Y functions to understand the most likely decisions by impacted stakeholders and mining companies. The best outcomes for all groups need to be well understood, and the games developed can show which criteria affect the most desired outcome for each player.

As the mining industry continues to expand to satisfy the world's demand, sustainability-focused closure planning will be crucial to reduce mining's growing environmental risks. Poor closure planning continues to greatly affect the long-term health of stakeholders and the environment. The methods developed can consider the nuances and complexities of sustainability but collecting the sustainability data required to analyze the trade-offs between impacts and benefits of mining will be extremely difficult. This study acknowledges this, and provides formulas for Nash equilibriums to present how to think about these issues even with a lack of sustainability data available. This applied method can be used for many other decisions that require balancing various criteria with multiple players. When developing policies, this model can be used to look at closure planning in a multi-level holistic way.

Stemming from this research, future work could create game-theoretic approaches for the mining industry to incorporate sustainability criteria into mineral processing, mine planning, and mine waste management decision making. Additionally, this research could be adapted for decision making in other resource development industries like forestry, agriculture, renewable energy, and oil and gas. To better implement this methodology, future work should focus on collecting stakeholder preferences for sustainability, developing and selecting sustainability criteria, and pushing environmental technologies to bridge the gap between stakeholder preferences and technical constraints.

6.8 Next Steps

This section solved several Nash equilibrium functions for games during the mine closure planning process. The functions incorporated multiple criteria to bring a structured analysis to how decisions affect different mining stakeholders; specifically mining companies and impacted communities. The next section takes some of the general findings outside of game theoretic approaches from the past few sections to critique the terminology and approaches regarding community acceptance and collaboration. The term social license to operate is analyzed and critiqued for three Canadian mineral development properties.

Chapter 7 - A Critical Perspective on Social License to Operate Terminology for Canada's Most Vulnerable Mining Communities

7.1 Abstract

"*Social license to operate*" (SLO) terminology was developed to improve the reputation of the mining industry and to minimize the risks of communities interfering with mining activities. The conception of the social license term has succeeded in bringing local social challenges into the consciousness of mining proponents, but unfortunately has provided little direction to solve them. In Canada, SLO terminology sometimes conflates dire social issues of many Indigenous communities into a risk reduction exercise focussed on continuing mine operations. After generations of cultural genocide across Canada, Indigenous communities have finally gained some influence with mineral development decisions through impact and benefit agreements and during the environmental assessment process. This article investigates three case studies to understand the application of social license and social risk terminology with mineral development in Canada. This investigation gleans a diversity of issues in Canada through the selection of mines in three different jurisdictions which have unique histories, communities, and lands. This research demonstrates that mining companies operating in Canada should have tailored, comprehensive, and collaborative approaches to create symbiotic relationships with communities and should avoid using general terminology such as social risk and social license to operate.

7.2 Introduction – An overview of social license with major projects in Canada

Mineral development negotiations have great potential to be adversarial due to its reputation of creating immense environmental risks and social challenges. Mining companies fear a local community with the ability and motivation to stop or slow down mineral development activities, affecting budget, project schedule, and shareholder value. Mining companies can be left with a feeling of frustration when, after following all the required regulations, their project is still seen by the local community as being too harmful for their region. The term "*social license to operate"* (SLO) developed out of a recognition by mining companies of the ongoing risks of operating without the approval from the local community or key stakeholders (Joyce and Thomson, 2000; Thomson and Boutilier, 2011). An SLO framework gives mining companies a goal to strive for and some piece of mind when it comes to dealing with a region's complex social structures and associated challenges. Thomson and Boutilier (2011) discussed that SLO can also bring an interpretation of "*quality*" into analysing company-community relationships, where trust, credibility, and legitimacy define levels that lead to project acceptance and potentially co-ownership.

Unfortunately, achieving an SLO is impossible to measure or quantify. It can even be detrimental, as it can mask the gap between companies and communities with a term championed by industry and consultants with the primary motive of promoting a stable investment (Hitch et al., 2020; Owen and Kemp, 2013). Nevertheless, the emergence of the term has brought social challenges of local communities into the conversation of mining companies and many other industrial activities around the world (Koivurova et al., 2015; Komnitsas, 2020; Laurence, 2020; Lesser et al., 2020; Lindman et al., 2020; Ofori and Ofori, 2019; Saenz, 2019). Community wants, needs, and values change drastically around the world. Flexible perspectives and tailored approaches are needed for each unique community. This is especially true in Canada, which is home to many diverse Indigenous communities who still bear cultural scars from colonial development and systemic racism. The term indigenous is used in Canada to encompass First Nations, Inuit and Métis communities who have unique histories, cultures, wants, needs, and values, but share the intergenerational trauma caused by cultural genocide. Through the analysis of different regions and mineral development properties in Canada, this article provides a glance into Canada's application of the term social license to operate and its ability to help solve social challenges of the local mining communities.

The term cultural genocide in the Canadian context conveys how the colonial governments of the British and French Empire established Canada's legal system, which destroyed the culture and social structures of Indigenous communities and excluded them from decisions impacting their territories (Mahoney, 2019). Specifically, residential school systems were established to force Indigenous children to leave their communities and learn under a Western and Christian pedagogy which was severely abusive physically, sexually, emotionally, and spiritually (Hutchings, 2016). Children were often beaten and ridiculed if they used the language of their ancestors or showed any ties to their culture. The intergenerational trauma caused by these schools can still be seen today in Indigenous communities throughout Canada (The Truth and Reconciliation Commission of Canada, 2015).

The emergence of the term social license has found its way into other key industrial sectors in Canada such as forestry, energy infrastructure, hydro-electric dams, aquaculture, and wind turbine projects (Bunnell, 2013; Edwards et al., 2016; Mather and Fanning, 2019; O'Brien and Hipel, 2016). Even though the mining industry developed this term, the Northern Gateway Pipeline Project and pipeline projects in general (e.g., Trans Mountain Expansion Project, NGTL

System Expansion Project, Towerbirch Expansion Project, Eagle Spirit Pipeline, and Line 3 Replacement Project) galvanized arguably the most social disruptions nationwide. The Northern Gateway Pipeline Project, owned by Enbridge, planned to construct 1,177 km length twin pipelines from Alberta to British Columbia that would deliver 525 thousand barrels a day of diluted bitumen to Kitimat, BC. The potential for oil spills around the Douglas Channel created a vivid debate in Canada. Despite opposition from Indigenous groups, local communities, and environmental groups, the Canadian government approved the project in 2014. Eight Indigenous communities and organizations such as Ecojustice and Unifor appealed the decision. The Federal Court of Appeal then overruled the previous decision in 2016. The Federal Court of Appeal concluded that the Federal Government did not seek sufficient approval from the Indigenous communities along the pipeline route. Furthermore, the BC Supreme Court ruled that the provincial government did not adequately consult with the Tsimshian and other Indigenous communities. This controversial project demonstrates the importance of legitimacy and acceptance from impacted communities in Canada (Thistlethwaite et al., 2019).

The requirements to develop or maintain an SLO are often unclear. Work for achieving an SLO can overlap or even be confused with corporate social responsibility (CSR), general sustainability, Free Prior and Informed Consent (FPIC), and Indigenous reconciliation (Boutilier and Thomson, 2018; Koivurova et al., 2015; Komnitsas, 2020; The Truth and Reconciliation Commission of Canada, 2015). Many guidelines from industry and governments, such as the International Council on Mining and Metals (ICMM, 2015), attempt to provide direction for mining companies on social risk (ICMM, 2015),. These frameworks can provide a useful start, but again, tailored approaches developed collaboratively with communities are what is required. Mining companies can unfortunately be guilty of oversimplifying nuanced approaches using blanket terms like social license and social risk, without actually uncovering the complex issues of the local communities and understanding what they require to thrive.

The term community can signify a group living in the same location, or more generally a group sharing the same interests, goals, and attitudes. The social structures and power divisions within a community play a key role in the attempted measurement of SLO. For example, some groups may be vehemently against a mine but may not actually have much influence to disrupt mining activities. Generally, the focus of mining companies and SLO literature is with the local communities who live near the mine and are relatively more impacted by mining activities than general society (ICMM, 2015; Thomson and Boutilier, 2011). There can be cases where an impacted community needs to be further divided into subgroups, which creates challenges to ascertain the general opinion of the community. In this case, a social license to operate may never be possible to grant if opinions of the various groups are contradictory and power dynamics are unclear (Demuijnck and Fasterling, 2016).

Through the investigation of mines located in different regions in Canada, this article will outline the challenges using the term social license to operate and shed light on the general social risks in Canada for mineral development. Key features of the Canadian perspective will be highlighted, including impact and benefit agreements (IBAs), environmental assessments (EAs), sustainability reporting and Indigenous community collaboration. This research will explore how or if SLO is being used by mining companies, regulators and communities for the three mines described in the case study section. The next section will outline the methodology of this research which will lead into the case studies from British Columbia, Nunavut, and Ontario. The article will then provide a discussion on how the case studies portray the implementation of social license to operate, and its related challenges. Finally, the article will conclude by discussing how we should reorient discourse around social license and the impacts of mineral development in Canada for the future.

7.3 Methodology

This article uses case studies to provide a detailed perspective on the application of social license to operate and social risk strategies in Canada. The cases highlight the unique regions of Canada and present the differences in communities, mining companies, and regional regulations. Cases 1 and 2 present mines located in the provinces of British Columbia and Ontario while Case 3 presents a mine in the territory of Nunavut. Canadian mining companies are the owners of the mines in Cases 2 and 3 while a European mining company owns the mine in Case 1. Mines in different regions were selected, to highlight communities with unique socio-economic situations, cultures, and history. The mines selected all recently went through a permitting process, which provides an important perspective on how current government regulations, societal attitudes, and company policies are being applied. The mines also vary in terms of proximity to major populations. Case 1 is located near the city of Kamloops while Cases 2 and 3 are in the remote region of Kivalliq, Nunavut and Northern Ontario, respectively. In addition, the historical onset of mineral development activity varies between the selected regions.

The authors of this article have previous experience researching these regions both in academic and professional settings. In Collins (2015), one of the authors investigated the Stk'emlupsemc te Secwepemc Nation from Case 1, but with the adjacent New Afton Mine instead of Ajax, and with a focus on closure planning instead of SLO. Additionally, recent documentation was analyzed as shown in Table 7-1. Each case study provides an overview of the region (province or territory), the surrounding community and stakeholders, and the mineral development site. Sustainability reports, environmental assessment documentation, National Instrument (NI) 43-101 feasibility reports, and socio-economic reports were analyzed for each mine. NI 43-101 reports follow the Canadian standards for disclosure of information regarding mineral projects. NI 43-101 feasibility reports specifically present how a mining company calculates a mineral property's reserves and resources. To support this calculation, these reports discuss all aspects of a project including socio-economic conditions, community engagement, and environmental risks. This article investigates these documents for their application of social license to operate terminology, social risk methodologies, and community engagement protocols.

7.4 Case Studies

This section presents three case studies which discuss the property history, current state, mining company, communities, local social challenges, social risks, and the use of social license to operate (SLO). Documentation, which was reviewed for each case, is presented in Table 7-1. Table 7-1 also highlights the nearby Indigenous communities for each mine but does not attempt to list all the relevant stakeholders such as NGOs, nearby non-Indigenous communities, affected businesses, insurers, employees and contractors (Azapagic, 2004). However, local non-Indigenous communities are discussed within each case study. Furthermore, the locations of each case study are shown in Figure 7-1.

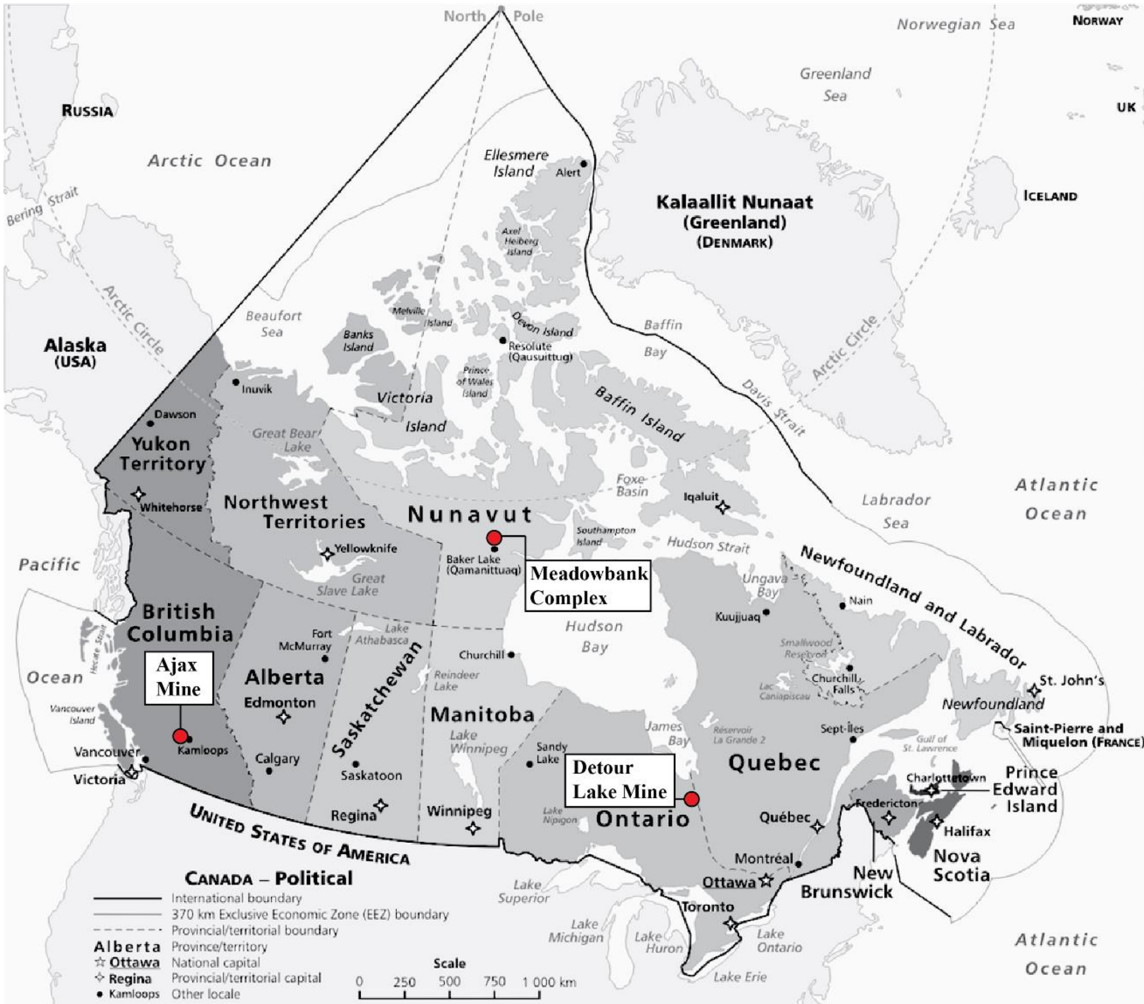

Figure 7-1 Map of Research Area (map modified from open source material)

7.4.1 Case study 1: British Columbia – Ajax Mine

British Columbia (BC) is Canada's westernmost province, situated adjacent to the Pacific Ocean. BC has a relatively short history of European settlement, but an extensive and rich history of diverse Indigenous communities. The province was colonized by Europeans much later than the eastern settlements of North America; the first permanent European settlement was established in the early 19th century for the fur trade (Barman, 2007). Further, it has a significant history of mining, which includes several gold rushes in two different regions in the 19th century. BC continues to be a global hub for mining and mineral exploration. Vancouver, where the majority province's population resides, is home to the head offices of many mining and exploration companies. Due to several epidemics brought by European settlers, many Indigenous communities in BC were decimated in the 19th century. Thankfully, compared to many other regions in North America, numerous diverse Indigenous communities survived and remain throughout the province.

The majority of BC is unceded or non-treaty land (Bunnell, 2013; Royal Canadian Geographical Society, 2018). Treaties, which were signed throughout the history of colonialism between Indigenous groups and the Government of Canada, historically defined Indigenous rights and Canada's obligations. Indigenous rights, mineral rights, water rights, hunting, fishing, and general land development procedures typically outlined in treaties have never been agreed upon in most regions of BC. Instead, the rights, title and land ownership for Indigenous communities continues to be defined through supreme court rulings such as Delgamuukw (1997) and Tsilhqot'in (2014) (Dylan et al., 2013; Ignace, 2008). The BC government is continuing to negotiate modern treaties, but it is a long process (BC Treaty Commission, 2019). With a history of unfair and racist negotiations, treaties may not even be the best method to restore, stimulate, and help Indigenous communities.

The proposed Ajax Mine currently owned by KGHM Polska ("KGHM") was originally owned by Teck as part of the Afton mine property. The Ajax property is located just outside of Kamloops, British Columbia. The closest mine infrastructure, the east mine rock storage facility, was proposed to be just 1.5 km away from the nearest housing developments (KGHM, 2016). The proposed mine is also in the traditional territory of the Skeetchestn and Tk'emlúps te Secwepemc Nation. The two communities make up the Stk'emlupsemc te Secwepemc Nation (SSN), which was created to negotiate and make decisions for development on their territory. In 2010, the Ajax Mine started to develop their Environmental Assessment (EA) for the development of their open pit copper-gold mine (KGHM, 2016). In addition to the SSN, who require a "*high*" consultation depth, the Ashcroft Indian Band, Lower Nicola Indian Band, Whispering Pines/Clinton Indian Band, and Métis Nation British Columbia require consultation at moderate to low levels (KGHM, 2016). Consultation depth for the Ajax mine was determined by the Canadian Environmental Assessment agency, which dictates the levels of documentation and notice required for each community. The consultation depth generally depends on the potential impacts of the project on each community.

The owner, KGHM, is an international Polish mining company which operates in Europe, North America, and South America. Following the Global Reporting Initiative's (GRI) standards, KGHM publishes a sustainability report each year that outlines the company's performance and strategies on environmental actions, sustainable development, stakeholder engagement, impacts on local communities, and risk management. They discuss that they "*observe the license to operate principle*", which will be further outlined in their Social Dialogue Policy to be developed (KGHM Polska Miedz, 2019). Additionally, they list one of their risks as "*The risk of lack of acceptance by the public, local governments or other stakeholders for the conduct of development and exploration work*." (KGHM Polska Miedz, 2019). This risk stems from ineffective stakeholder relation management, which could cause in "*extreme cases*" blocking of development. To mitigate this risk, CSR strategies, cooperation with government bodies, meetings with stakeholders, publications, and meeting the highest public relations standards are listed (KGHM Polska Miedz, 2019).

The mine development application created a lot of friction in Kamloops. The municipal city council voted against the mine, but was intensely divided by the opportunities the mine provided versus the impacts it created (CBC News, 2017). Kamloops, with a population of about ninety thousand in 2016, is typical of many cities in Interior BC, where many non-Indigenous residents first arrived for opportunities in resource development like mining and forestry or agriculture. At that time, the Canadian Federal Government forced and displaced Indigenous communities onto reserves. These small pieces of land generally failed to provide adequate housing and to preserve traditional ways of life for many Indigenous communities. Reserves still exist; the Tk'emlúps te Secwepemc Nation reserve is located adjacent to the city of Kamloops, while the Skeetchestn reserve is located 50 km outside of Kamloops. With a long history of mining in the region, stemming from the gold rush of the 1860s, some of the long time residents of Kamloops welcome mineral development. However, many other residents organized in groups to communicate their concerns related to air quality, dust, noise, water quality, and general effects on their quality of life and health (Kamloops Area Preservation Association, 2014; Kamloops Physicians for a Healthy Environment Society, 2013). To respond to their concerns, KGHM intensified public engagement and added topics of concern to the Environmental Impact Statement and EA application (KGHM, 2016). In addition, KGHM re-designed the southern edge of the property to be farther away from the residential areas.

Throughout this process, KGHM was actively consulting under the Canadian EA process while trying to create an impact and benefit agreement with the SSN. EA processes are common internationally, but peculiar to Canada, EA requirements for consultation and collaboration with Indigenous communities continue to be reformed and redefined to better protect Indigenous rights. The SSN conducted their own assessment of the project where they analyzed how the mine would effect their community. They incorporated their wants, needs, values, culture, and traditions into the assessment process, where they provided their community members a chance to voice their concerns. The SSN reviewed all stages of the mine-life cycle from construction to post-closure. In the end, the community decided to reject the project as it greatly impacted the culturally significant area called Pipsell, which included Jacko Lake. The mine plan could not adequately mitigate the impacts to this area. The SSN informed KGHM that the area has "*spiritual, cultural, and historical importance to them*" and that the effects of previous mining in the area, gives them concern for the Ajax Property (KGHM, 2016; Stk'emlupsemc te Secwepemc, 2017).

The province of British Columbia rejected the mine application in 2012 and 2017, due to the "*significant adverse environmental effects that cannot be justified in the circumstances*". The effects to heritage, current land use, and resources for traditional purposes for the Indigenous communities by the mine were noted as key reasons why the mine was rejected by the province (Canadian Environmental Assessment Agency, 2017; Natural Resources Canada, 2018). After the Environmental Assessment rejection in 2017, KGHM is now focused on re-engaging with the First Nations communities to improve relations. KGHM does mention how the mine's proximity to Kamloops and being in the traditional territory of several Indigenous communities elevates the concern and interest of the project (KGHM Polska Miedz, 2019).

7.4.2 Case study 2: Nunavut – Meadowbank Complex

Mining in Nunavut is an expensive and technically challenging endeavour that requires consideration for the high transportation costs, unclear regulatory processes, shortages of skilled workers, limited infrastructure, expensive mine closure planning, permafrost, and the harsh climate (The Conference Board of Canada, 2013). Even with these challenges, mining is one of the few industries available for the local communities. The majority of the sparse population in Nunavut is of Inuit descent (84%), who are starting to see how mining can bring economic opportunities but also disruptions to culture, land, and traditional ways of life (Carter, 2013; Collins and Kumral, 2020; Government of Nunavut, 2018; Maksimowski, 2014; Pauktuutit Inuit Women of Canada and School of Social Work at the University of British Columbia, 2016; Peterson, 2012; Rixen and Blangy, 2016). Unfortunately, climate change continues to create major issues for mining and general development in Nunavut. Warmer temperatures are decreasing permafrost layers, which are essential for the construction and maintenance of roads, port facilities, and mine waste management facilities (Collins and Kumral, 2019).

The Amaruq region was first mapped by the Geological Survey of Canada in 1976, and in 1983 the area started to be prospected for gold. The Meadowbank mine was owned by Cumberland Resources who completed the environmental assessment for the mine in 2005 and 2006 (Agnico Eagle Mines Limited, 2017a; Cumberland Resources Ltd., 2005). The mine was then bought by Agnico Eagle in 2007 who still own and operate the property today (Agnico Eagle Mines Limited, 2017a). Agnico Eagle is a major Canadian gold mining company with operations in Canada, Finland, and Mexico. Operations at Meadowbank started in March of 2010. Stemming from traditional knowledge and environmental studies, the Meadowbank property was considered a low usage area due to the low abundance of caribou and its distance from Baker Lake.

Prior to mining, employment, training, and housing were raised as concerns for the community (Stratos Inc., 2016). An Inuit Impact and Benefit Agreement was signed with the Kivalliq Inuit Association that ensured accessible local employment, training, and business development for all stages of the mine life-cycle. 58% of the Nunavut operations spending was with Indigenous, Nunavut Tunngavik Inc (NTI) registered suppliers in 2019 (Agnico Eagle Mines Limited, 2019). Over the last decade, the mineral property has been preparing for expansions and exploring for new resources. The most recent expansion, the Amaruq Whale Tale Pit, required its own Impact and Benefit agreement which was signed in June of 2017. The agreement included a $6.5 million payment to the community, resource royalties (e.g., 1.4% net smelter return for the Amaruq project), investment in training programs for Inuit employment, and preference points for contracts for NTI registered companies (Kivalliq Inuit Association and Agnico Eagle Mines Limited, 2017). In August 22, 2019 Amaruq was officially opened.

In their sustainability report, Agnico Eagle highlights Meadowbanks' significant use of diesel fuel for energy, leading to high GHG emissions (Agnico Eagle Mines Limited, 2019, 2017b, 2017c). The report discusses the company's environmental impacts related to material use, energy use, water consumption and contamination, biodiversity impacts, emissions, effluents, and mine waste using GRI standards. They only highlight Meadowbank-specific information pertaining to energy, water, and land. In addition, there is a high-level discussion on the company's corporate strategy regarding social impacts and community engagement, where an entire mine life-cycle approach is taken for collaboration (Agnico Eagle Mines Limited, 2019). There is company focus on hiring and eliminating barriers for Indigenous Women; 34% of the Inuit workforce at Meadowbank were women in 2019 (Agnico Eagle Mines Limited, 2019). Finally, the Socio Economic Monitoring Program was established in 2014 for the region and Agnico Eagle developed their own implementation plan alongside the community (Stratos Inc., 2016).

The social issues stemming from mineral development for remote Kivalliq communities are well documented. Existing research demonstrates how mines do provide communities with opportunities, but can greatly disrupt traditional ways of life and cultural economies that are closely attached to the land, and are generally preferred (Carter, 2013; Maksimowski, 2014).

Specifically, the lifestyle of working at the mine can be deeply strenuous on the community's socio-structural culture. The two-weeks on two-weeks off work cycle can create significant challenges resulting from being away from home, such as arranging child care and upkeeping traditional ways of life (Government of Nunavut, 2018; Peterson, 2012). Inuit workers also typically start at lower level positions with the janitorial staff or in the kitchen, but can eventually be promoted to higher paid positions with the mine operations. As Inuit workers generally hold lower paying jobs, less of the economic opportunities are captured in the local region. All of this leads to high rates of absenteeism and to an extremely high turnover rate (80%) of Inuit labour force at the Meadowbank mine (Carter, 2013). Future development plans in Nunavut are often faced with the challenge of striking a balance between strengthening traditional economies, which better promote Inuit culture, and growing wage-based economies stemming from resource extraction (Carter, 2013; Hitch, 2006; Keeling and Sandlos, 2016).

Even with opportunities and economic growth from mineral development, there continues to be significant issues for communities in Nunavut. For example, more than 20% of the Nunavut population are "*heavy drinkers*", the rate of teenage pregnancy is over 10 times the national Canadian rate, Nunavut has the highest level of food insecurity in Canada and is increasing (36.7% of households as compared to 13% nationally), unemployment rates are consistently over 50%, overcrowding in dwellings continues to be an issue, the percentage of Inuit peoples without any education certificate has dropped but still remains high at 60%, and finally the rate of suicide for Inuit communities is unacceptably high with 72.3 deaths per 100,000 person-years at risk, which is approximately nine times higher than the non-Indigenous rate (Government of Nunavut, 2018; Statistics Canada, 2016). These grim statistics show the challenges these communities continue to face and the ongoing impacts of generations of cultural genocide.

7.4.3 Case study 3: Ontario – Detour Lake Mine

Ontario is Canada's most populous province and acts as Canada's main economic centre. Toronto, Ontario is home to many of the country's mining companies, financial institutions, and investment groups. Like the rest of Canada, Ontario also has a long history of mining with major mining regions near Sudbury and Timmins. Unlike BC and northern regions like Nunavut, Ontario has established over 40 treaties and other land agreements, where land use was negotiated with the Indigenous communities starting in the late 18th century. Even with these agreements, discrimination and coercion persisted in the Canadian political and legal systems to ensure dominion and power over Indigenous communities (Burrows, 2007).

The Detour Lake Mine is located in northeastern Ontario, 185 km northeast from Cochrane, near James Bay. The mine previously operated as an open pit and underground mine between 1983 and 1999. The new low grade gold mine opened in 2013 as an open pit and operated by Detour Gold Corporation until it was purchased in 2020 by Kirkland Lake Gold. Kirkland Lake Gold is a major Canadian mining company with operations in Canada and Australia. The Detour Lake mine is located within Treaty 9 and in the territory of the Moose Cree First Nation (MCFN), Taykwa Tagamou Nation (TTN), and Wahgoshig First Nation (WFN). The MCFN and TTN are both Cree communities while the WFN is an Algonquin community that has members of both Algonquin and Cree descent (Dylan et al., 2013; Royal Canadian Geographical Society, 2018; Taykwa Tagamou Nation, 2020; Wahgoshig First Nation, 2020). The Métis Nation of Ontario (MNO) as well as the Grand Council of the Crees, representing the Waskaganish First Nation, have also asserted Indigenous rights and title on the mine location. These communities have a long history of colonial cultural genocide stemming from the fur trade and resource development in their territories (Royal Canadian Geographical Society, 2018).

During the EA several valued ecosystem components and valued socioeconomic components were noted to be potentially impacted by the mine. The valued ecosystem components included: "*air quality, local watercourses and their associated lakes and wetlands, groundwater system, vegetation communities and their relation to terrestrial habitats, wildlife and migratory birds, and species at risk*" (Canadian Environmental Assessment Agency, 2011). In terms of valued socioeconomic components, land and resources use, traditional land use, and public health and safety were identified as being potentially impacted. The Indigenous communities have signed impact and benefit agreements with the mine for the current operation (Kirkland Lake Gold, 2018). These agreements ensure the communities receive local employment, business opportunities, financial compensation, and that the mine operates within established limits for environmental impacts. In addition, each Indigenous community has direct involvement in the site's environmental monitoring and approval process. In general, as noted by the WFN, the IBA discusses the mine's commitment in protecting the environment and wildlife (NationTalk, 2010).

The proponent is currently negotiating with the Government Ministries and Indigenous communities to apply for permits to expand the mine into the West Detour Pit. As of 2018, MCFN has currently not expressed support of the 2017 Environmental Study Report (ESR), which includes the West Detour Project. Therefore, the North pit development has been rescheduled until 2026, any impacts to Walter Lake will now occur in 2028, while the development of the West Detour pit will remain in 2025 (Detour Gold, 2018). The company was allowed greater flexibility by the regulators for their ESR, to provide more time to work with the community that opposed the new ESR (Detour Gold, 2019).

Kirkland Lake Gold discusses the importance of social license in their first sustainability report in 2018. It seems that the motivation to create a sustainability report stems from the company wanting to promote the reporting of the "*key drivers*" of social license. Its key drivers include "*health and safety, the employment and development of people, economic value creation, environmental management and community engagement and outreach"* (Kirkland Lake Gold, 2018). In the report, there is a focus on policies that incorporate and respect local communities and develop lines of communication. Unfortunately, there is no up-to-date specific information on the Detour Lake Gold mine as it was only recently acquired by Kirkland Lake Gold from Detour Gold Inc. However, as stated in Detour Gold's NI 43 101, Detour staff are required to receive cultural awareness training, and training programs such as "*Aboriginal Women in Mining*" are offered for the Aboriginal people working for the mine. In 2017, 23% of the workforce at Detour Lake is of Aboriginal descent (Detour Gold, 2018).

7.5 Discussion

Table 7-1 Summary of Mineral Properties Analyzed

Region	Mineral Property	Current Company	Indigenous Communities	Current Stage	Documentation Reviewed
British Columbia	Ajax Mine	KGHM Polska	• Stk'emlupsemc te Secwepemc (SSN) • Ashcroft Indian Band • Lower Nicola Indian Band Whispering Pines/Clinton Indian Band • Métis Nation British Columbia	• Mine plan proposal rejected by BC Government • Mine rejected by the SSN. • Proponent re-engaging with communities	• 2016 NI 43 101 Feasibility Report • Integrated Report of KGHM Polska Miedź S.A. for 2019 • Ajax Mine Project Joint Federal Comprehensive Study and Provincial Assessment Report • Decision of the SSN Joint Council on the Proposed KGHM Ajax
			Cont. next page.		

Region	Mineral Property	Current Company	Indigenous Communities	Current Stage	Documentation Reviewed
Nunavut	Meadowbank Complex	Agnico-Eagle	Kivalliq Inuit Association (KIA), which represents: Arviat, • Baker Lake (Qamani'tuaq) • Chesterfield Inlet (Igluligaarjuk) • Coral Harbour (Salliq) • Naujaat • Rankin Inlet (Kangiqtiniq) • Whale Cove (Tikirarjuaq)	• Mine in operation since 2010. • Has expanded into the Amaruq deposit in 2019. • IBAs have been signed with KIA	• 2017 Technical Report on the Mineral Resources and Mineral Reserves at Meadowbank Gold Complex • Sustainable Development Summary Report 2019, 2018.2017 • Inuit impact and benefit agreement between Agnico-Eagle Mines Limited and Kivalliq Inuit Association • Meadowbank Gold Mine Socio-Economic Monitoring Report • Final Environmental Impact Statement by Cumberland Resources
Ontario	Detour Lake Mine	Kirkland Lake Gold	• Moose Cree First Nation (MCFN) • Taykwa Tagamou Nation (TTN) • Wahgoshig First Nation (WFN) • The Métis Nation of Ontario (MNO) • The Grand Council of the Crees, representing the Waskaganish First Nation	• Current open pit development opened in 2013 • Kirkland Lake Gold bought mine in 2020 • All communities have IBAs signed • Aiming to expand mine • MCFN has not yet agreed to the new expansion	• 2018 Detour Lake Operation, NI 43-101 Technical Report • 2018 Kirkland Lake Gold Sustainability Report • CEEA Comprehensive Study Report - Detour Lake Gold Mine • 2019 Annual Information Form

The purpose of this research was to analyze documentation of several Canadian mines to present how the intricacies of social license apply to a specific nation. Table 7-1 summarizes the case studies' current state and documentation analyzed. Each jurisdiction includes communities with their own unique values, cultures, history, wants, and needs which play an important role when collaborating on mineral development decisions. As shown in Table 7-1, many Indigenous communities can be affected by a mineral development project. It is common that different groups use similar areas for hunting, fishing, plant gathering, and cultural practices (Royal Canadian Geographical Society, 2018). After generations of cultural genocide from colonial laws and racist land use policies, Indigenous communities now play a critical role in mineral development decisions, which has emancipated from over a hundred years of lobbying and petitioning for equal rights, social justice, and Indigenous justice. Social and Indigenous justice in this context translates to having a fair distribution of opportunities, a focus on mitigation of mining impacts, and reconciliation activities to help elevate communities. The rest of this section analyzes the three case studies alongside SLO literature to discuss similarities, differences, and important factors.

SLO literature discusses that the main risk of "*losing*" an SLO are the threats of protests, blockades, or social unrest, which cause delays to operation, construction, or any other activity in the mining life-cycle (Owen, 2016; Prno and Slocombe, 2012). As discussed in the cases, at two different points of the mine life, the implications of not having full community support can be seen. First, the Ajax mine where the SSN conducted their own assessment and decided not to approve the mine, the BC government followed suit and also rejected the mine (Natural Resources Canada, 2018). Second, with the Detour Lake Mine, as the MCFN had not agreed to the new ESR in 2017, the scheduling of the North Pit and impacts to Walter Lake were significantly delayed (Detour Gold, 2018). From these two cases, one could say that Indigenous communities and governments are becoming relatively more aligned, however at the same time direct community-company agreements are increasing (e.g., IBAs), which can circumvent community and regulator negotiations (Caine and Krogman, 2010; O'Faircheallaigh, 2018).

The use of IBAs by Indigenous communities can help ensure mineral development brings adequate benefits for the communities (Caine and Krogman, 2010; Hitch, 2006). Additionally, they can help with the recognition of the rights of Indigenous communities for free, prior, and informed consent (Bradshaw and McElroy, 2014). Unfortunately, IBAs are generally confidential and act outside of Canada's democratic regulatory regimes and environmental assessment systems (Fidler and Hitch, 2007). Their confidentiality can impede Indigenous communities from sharing information regarding the potential benefits that may be achieved. Communities negotiating IBAs do not have the ability to gain lessons-learned from past agreements. Thus, they are at a disadvantage when negotiating with industry who have access to lawyers and consultants who can share their experiences on past files (Caine and Krogman, 2010). Furthermore, there is no guarantee that the benefits from these IBAs are disseminated to all corners of the community, or to where it is needed most. IBAs signed by the communities impacted by the Meadowbank Complex and the Detour Lake mine have provided the Indigenous communities with considerable economic opportunities, investment, training, and involvement in environmental negotiations. These communities remain at an economic disadvantage however, with many complex social issues such as higher suicide rates, health issues, and drug and alcohol addictions. IBAs are not necessarily the answer for developing prosperous and healthy communities, but with generations of abuse spearheaded by the Canadian Government, they can help align benefits directly for the community, which can potentially aid the long journey towards reconciliation.

Critiques of the term social license to operate state that it is impossible to measure, evaluate, and is a term used by corporations to minimize social risks to mines, but may not actually help improve communities and promote social justice (Hitch et al., 2020; Owen, 2016; Owen and Kemp, 2013) After a review of these case studies, it is indeed unclear exactly if and how social licenses are being granted. However, in the Ajax case the SSN never agreed to an IBA or the development of the mine. In addition, many groups were created to oppose the mine from the local communities living in Kamloops. It is obvious in this case that an SLO was never granted. For the Meadowbank mine and Detour Lake mine, it is still impossible to tell from sustainability reports, company documentation, signed IBAs, and accepted provincial EAs if the community at large is satisfied, dissatisfied, or at risk of disrupting the mine.

The mines analyzed in the cases follow global best-practices and standards outlined by the ICMM. The mining companies report their social, environmental, and economic impacts using GRI standards while integrating UN sustainable development goals. Many common themes of developing an SLO can be seen in sustainability frameworks such as the UN sustainable development goals. In addition, KGHM Polska even trades on the FTSE4GOOD ethical investment stock index, WIG-ESG socially responsible stock index, and is a member of the European Technology Platform on Sustainable Mineral Resources (ETP SMR) (KGHM Polska Miedz, 2019). However, even when considering a company’s memberships to sustainability indices and organizations, a company’s true performance remains opaque (Azapagic, 2004; Boiral and Henri, 2017). Companies following GRI reporting discuss their social performance in very different ways, making social risk incommensurable between operators. Even though the incorporation of social risk and social issues terminology was apparent in all the companies' and regulators' documentation, the term social license was not used extensively.

Although not discussed in detail in the cases, mine closure planning and determining post-mining land use is an essential aspect of all EAs (including the EAs of Cases 1-3) and many IBAs across Canada. After several instances of poor closure planning, resulting in almost billion dollar liabilities, the post-closure state of mines is now a crucial responsibility for mining companies in Canada (Collins, 2015; Keeling and Sandlos, 2015). Indigenous communities impacted by improper mine closure have faced countless health, social, and environmental impacts from heavy metal contamination, radiation exposure, and damaged landscapes from abandoned mines (Bainton and Holcombe, 2018; Keeling and Sandlos, 2016; Gibson and Klinck, 2005; Sandlos and Keeling, 2016). Well-planned mine closure is essential to align the mine property to the wants, requirements, and values of the local communities (Rixen and Blangy, 2016). Traditional knowledge studies developed for closure planning help to communicate and protect key environmental and socio-cultural components of a region (Boiral et al., 2020; Gondor, 2016). As local communities are typically impacted the most by poor mine closure, ensuring a closure plan is aligned with community expectations is a crucial component of SLO and company-community relationships in Canada.

Documentation by Canadian regulators for the permitting process of the cases does not directly mention or discuss SLO. The permitting process, typically developed by the provincial or territorial governments, provides communities with an opportunity to raise their concerns. Regulators have a duty to consult and try to appease communities, but legal merits and compatibility with regulatory standards are typically the essential components for governments to issue permits and make decisions. Environmental assessment processes are now requiring more direct involvement and partnerships with Indigenous communities, as seen in the BC Environmental Assessment Revitalization in 2018. As community expectations can greatly shift during a mine life (Boutilier and Thomson, 2018) with SLOs being gained, lost, and sometimes regained, proponents want assurance from regulators that their investments will be safe from social risk. Regulators can not guarantee this and thus IBAs have precipitated. In addition, as mines typically go through different owners and management from exploration to operation, careful consideration is needed for maintaining positive relationships (Thomson, 2016). As mentioned, the Detour Lake mine was recently bought by Kirkland Lake Gold; addressing the risks of change management with local communities will be essential for this property's future company-community relations.

Based on existing literature regarding the Meadowbank mine, Inuit communities have mixed feelings about mining in their territory. The community is seeing some significant economic opportunities, but are still greatly struggling with their health, education, employment, and practicing of cultural traditions (Bernauer, 2012; Carter, 2013; Hitch, 2006; Keeling and Sandlos, 2016; Maksimowski, 2014). In addition, as explored by Dylan et al. (2013) who analyzed the Victor Diamond Mine, these types of concerns also exist with the Moose Cree First Nation (MCFN). The community was generally in favour of the IBA, but had concerns similar to the Meadowbank mine communities, who also had a 2 week on, 2 week off work schedule. With IBAs signed and operations ongoing, one could perceive that a social license to operate exists. However, suggesting an SLO exists in this case could hide countless social issues and underrate the future work needed to reinvigorate these communities.

7.6 Conclusion

Working towards a social license in Canada requires compassion and respect for Indigenous history, Indigenous culture, and the impacts of intergenerational trauma from colonial development. It requires a sensitivity and understanding of Indigenous justice and social justice to fairly share opportunities and mitigate impacts from mineral development. Simply, if mines on Indigenous territories are unable provide adequate value to help these vulnerable communities thrive for future generations, then mines should not be allowed; be that through communities disrupting mining operations or the refusal of permits by regulators.

Some of the most serious social issues in mining communities, which stem from historical and current policies, may not be solvable for capitalistic mining enterprises. To help these communities, collaboratively developed government support programs, strong leadership, and staunch advocates are needed. If mining is accepted by the community, mining companies have an ethical duty to do more than create jobs, provide economic incentives, and minimize social risks to their operation (e.g. blockades, protests). As mining companies profit from a community's environment and create environmental risks, they should be held accountable for ensuring flourishing communities are being developed throughout the entire mine life-cycle.

In summary, the use of the term SLO in the cases analyzed is low on a government, community, and company level. However, many considerations discussed in SLO literature were gleaned from the case studies' documentation. Mineral development in Canada now requires both IBAs with communities and permits with regulators. The IBAs have emancipated from Indigenous communities historically being excluded from mineral development decisions and their related economic opportunities. However, they are not always the most efficient agreements to distribute opportunities back to the impacted communities. The development of sustainability reports following GRI frameworks are the focus of most mining companies to demonstrate that they are working well with their communities. Unfortunately, these reports and frameworks do not adequately show if the wealth generated by the mine is truly helping the communities and if the environmental damage caused by the mine is in line with their expectations. Indeed, the mining industry should continue its efforts towards better sustainability reporting, but bold new goals to improve communities are what is required. It is evident that many of Canada's vulnerable Indigenous communities, who live on the front lines of mineral development, continue to struggle in terms of health, employment, and housing. To help these communities, new scrupulous, earnest and empathetic approaches from mining companies are needed; rather than the general strategies and activities outlined in sustainability reports that purport a promoting of social license.

Chapter 8 - Conclusion and Future Work

8.1 Conclusion

Our demand for metals and our rate of consumption is increasing (Schaffartzik et al., 2016). Energy use, water use, land requirements, and waste creation will all increase as demand for metals is predicted to increase with the rise of renewable energy (Bardi, 2013; Tost et al., 2018a). A major shift of both consumption patterns and technological advancement is needed for a less impactful and more sustainable future. This thesis argues that a better understanding of the impacts versus benefits trade-offs from mineral extraction is imperative. This understanding requires the incorporation of multi-criteria, such as environmental, social, and economic indicators, as agreed upon by the impacted stakeholders. Differences in stakeholder value systems should be incorporated as best as possible, but most importantly respected.

This thesis adapted game theoretic approaches to consider multiple-criteria. These approaches were then applied to some of the mining industry's major sustainability challenges: impact and benefit agreements and mine closure planning. Both issues, like many of the most pertinent issues in the mining industry, must consider the implications to different impacted groups such as Indigenous communities. There are many unknowns, assumptions, and complexities to consider when modelling these human-environmental interactions. Different impacted groups can value indicators in very different ways. This thesis was able to develop a structured approach to analyze these complex interactions. Different methods of incorporating multiple-criteria and conflict/cooperative scenarios were explored. The IBA model in Chapter 5 was tested using a Monte-Carlo simulation with unknown value-functions. The mine closure planning model in Chapter 6 developed Nash equilibrium functions out of environmental, economic, and company reputation indicators. In the end, each decision or game theoretic approach is unique, and assumptions need to be adapted. This thesis showed how tools that consider multiple-criteria, value systems, and conflict/cooperative scenarios could be created.

As discussed, a social license to operate with local communities and environmental, social, and governance (ESG) considerations are now essential components to most mining company's strategy. A risk reduction approach is often used when working with Indigenous communities and impacted stakeholders. Mining companies hope that by working within regulations and agreements signed with local leaders that the risk of delays due to protests or litigation will be low. This strategy is not necessarily helping to create flourishing communities and to protect our environment. In Canada, working with local communities, who are often Indigenous communities, requires respecting their history, culture, and the impacts of intergenerational trauma from colonial development. It requires a sensitivity of Indigenous justice and social justice to find the balance between opportunity creation and impact mitigation from mineral development. If mineral development on Indigenous territories is unable to help these communities thrive for future generations, then the mines should not be allowed (Collins and Kumral, 2021).

Climate Change is occurring on a global scale, and its potential issues for the mining industry cannot be ignored. However, it is not just the mining industry that has to change, the world must change. We have already surpassed global thresholds for the nitrogen cycle, biodiversity loss, and climate change (Rockström et al., 2009). We continue to heavily rely on fossil fuels and the consumption of materials (e.g., metals, forest products, etc.). If we continue with current growth and development, other global thresholds will be breached. The planet will continue to see a significant increase in droughts, heatwaves, forest fires, sea level rise, loss of marine life, and flooding (Government of Canada, 2014; NASA, 2017). The shift to a more ecological minded society no doubt requires an understanding of the upstream and downstream impacts as metal users.

Game theoretic approaches bring a simplified approach to these complicated sustainability issues for the mining industry, which require considering a multitude of factors, criteria, and various stakeholders. Decisions for the mining industry must consider energy, water, mine waste, tailings, mine closure, and different stakeholders. Game theoretic approaches can help decision makers organize and communicate the trade-offs that need to take place between affected groups.

The limitations of this research however are that the assumptions and how the game is set up can be very subjective. It can be difficult to recreate or test in real-world applications. In addition, how the players value criteria plays a key role in the predicted outcome, but can be very subjective and difficult to model. In the end, the approaches developed provide a decision maker a means to assemble and consider all important factors, and easily alter game assumptions to compare outcomes.

8.2 Future Work

Going forward, environmental impact thresholds and limitations need to be in place on both global and local scales for decision making. Understanding what society needs from non-renewable mineral resources is essential. These steps, although extremely complex, can be done with enough political will and a shift in demand and values from global leaders. Potential future work stemming from this thesis to create a less impactful relationship with metals could include:

1. Developing new game theoretic approaches for mining sustainability challenges such as mineral processing methods selection, international pollution protocols for the

mining industry, cumulative impacts in a region with some users being mining companies.

2. Use game theoretic approaches to help develop investment and incentives strategies for technological advancements that could improve energy consumption, recycling, GHG emissions, and other environmental impacts. Minerals and metals will always be an important part of society. Finding technologies that reduce our environmental footprint and respects the carrying capacity of our planet is essential.
3. Through comparing assumptions in game theoretic approaches, explore how to either cap or tax the overall environmental impacts of mining while considering the downstream energy use of the metals put in the global market. For emissions as an example, the mining industry consumes 10% of the annual global energy usage and will increase more as resources become more difficult to mine. This energy typically comes from fossil fuels or other sources that have high environmental impacts ("The Framework for Reducing Energy Consumption in Mining," 2015; The Mining Association of Canada, 2005). Theoretically, capping or taxing should both reduce emissions, but they have their advantages or disadvantages. A careful analysis should be conducted to understand which method would better work to improve the mining industry.
4. Analyze how to better develop cumulative effects studies. Rather than conducting individual cumulative effects assessments each time an environmental assessment is started, regulators should conduct an overall cumulative effects assessment for the minerals industry. Through cooperatively sharing the responsibility of this type of assessment, it would be more easily accepted by the industry. This study could be

performed on an annual basis with progress reports on a quarterly basis. Game theory can be applied to develop strategies (incentives or penalties) of how to share local resources and potentially minimize cumulative impacts of users.

5. Better explore the downstream effects of the minerals that we are mining. Minerals have a long-life cycle which has numerous steps after mining such as smelting, manufacturing, packaging, and recycling. Each of these processes can have its own unique environmental impacts. We must understand our metals' life-cycle impacts. For example, the mining of coal deposits has its own local impacts from the mining operations, but the steel manufacturing for which the coal is used takes place in numerous locations globally and creates considerable waste and emissions. Life-cycle assessments need to be further developed to consider the impacts of mining.
6. Investigate how to best create required sustainability reporting standards for the entire mining industry. To truly understand which operations are holistically performing well, we need standardized ways of recording and presenting environmental, social, and economic indicators. There are a number of standards that currently exist, but these are voluntary, and not all mining companies follow.
7. Analyze sustainability trade-offs alongside Indigenous communities and mining stakeholders to ensure wants, needs, and values are carefully considered. Communities need to be involved in the process to understand how environmental decisions are being conducted and to provide valuable information on what is important to them.
8. Develop new metrics that define mining project success. A main driver for developing resource projects is to achieve economic growth, Net Present Value,

> Internal Rate of Return, or other economic indicators. The problem is that as we try to achieve this type of economic growth, our impacts on the environment and contribution to climate change increase (Daly, 2017). How we value growth needs to change, and we need to rethink what the objectives should be for resource development projects. The growth that ignores the consequences of depleting our natural resources and the strain we are putting on our environment is uneconomic. Our current economic models and viewpoints, incorrectly discount future sustainability and promote growth without regard for planetary boundaries (Brown, 1992; Nordhaus, 2007). We can not have projects developed whose sole goal is to help us achieve economic growth as defined by our current models. We need to have metrics that help us develop as a society while respecting and conserving our environment.

We are in a human-influenced age, the Anthropocene, where our choices greatly affect the environment on a global scale (Steffen et al., 2017). Canada is a global producer of many commodities (i.e., copper, gold, coal, and potash); our environmental decisions make a significant difference at a global scale. We have the economic and technological capacity to reduce our environmental impacts. Therefore, we have a responsibility to lead the world in the push towards a symbiotic relationship with our planet.

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