

# Seafloor Massive Sulphides: Assessment of Sustainable Mining Potential through an Iterative Decision-making Framework

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by

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A thesis submitted to The Robert M. Buchan Department of Mining

In conformity with the requirements for  
the degree of Master of Applied Science

Queen's University

Kingston, Ontario, Canada

December, 2011

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## Abstract

Extraction of metals from the seafloor has been considered for decades, beginning with manganese nodules in the 1970s. Today, the targets are massive sulphide deposits rich in copper, zinc, gold, and silver that are associated with hydrothermal vents or black smoker chimneys that occur at divergent and convergent plate margins such as mid-ocean ridges and volcanic island arcs respectively.

A recent objective of the mining industry is to develop industry practices that coincide with concepts of sustainability or sustainable development. This objective, known by some as sustainable mining, has indeed become an essential part of the commissioning of any new project, regardless of geographical location. While there has been much work on sustainable mining practice for terrestrial mining, these frameworks are not directly applicable to seafloor projects.

There are two problems facing the development of a seabed mining industry. First, there is a regulatory vacuum when considering the mining of seabed deposits, leading to important policy issues. Second, the economic, environmental, and social impacts of a seabed mining project are theoretical, and the real impacts are unknown. Thus, the identification, characterization, and analysis of the sustainability issues facing a seabed mining project are essential steps. To assist with performing these three steps, this thesis provides a process model based on the IDEF0 (Integration DEFinition) standard to assess seafloor massive sulphide mining projects from sustainable mining perspectives. This adaptation of IDEF0 provides a clear, visual representation of a hierarchical framework that can be used to identify “go no-go” sustainability criteria to assist decision makers interested in the potential development of an ore body.

**Keywords:** Sustainability, sustainable mining, seafloor massive sulphides, IDEF0

## **Acknowledgements**

My supervisor, Vic Pakalnis, Kinross Professor in Mining and Sustainability, for his support and patience

Hugh Agro and Scott Trebilcock for their encouragement and support

Kinross Gold Corporation and Nautilus Minerals Inc. for generously funding this research

Dr. Steven D. Scott at the University of Toronto for his guidance and insights into the mining of seafloor massive sulphides

Robert Johnstone and Ryan Hum at the Sustainable Mining and Materials Policy Division of Natural

Resources Canada for their assistance with the regulatory issues facing seafloor mining issues mining in Canada

Dr. Laeeque Daneshmend for his assistance in adapting the IDEF0 standard

Dr. R. Anthony Hodge, president of the International Council on Mining and Metals and previous Kinross Professor in Mining and Sustainability at Queen's University, for his inspiration

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# Chapter 1: Introduction

## 1.1 Background

Despite new developments in recycling technologies, there will always be a demand for the raw mineral and metal materials that mining provides as developing countries expand their urban infrastructure and consumers around the world purchase electronic devices, jewelry, automobiles, and other machinery. However, the availability of some key materials such as copper is in decline and global demand for jewelry-grade gold, particularly in Asia and India, is forecasted to continue to grow (Economist Intelligence Unit, 2011). The supply-demand gap is driving the prices for these metals higher, allowing mining companies to consider previously uneconomic, larger deposits of significantly lower grade for production - a process that could take decades, be subject to periodic shutdowns should market conditions change, and leave highly visible surface infrastructure such as large open pits. To combat this, a movement to mine metals from the seafloor has re-emerged after more than 35 years. Seafloor massive sulphide (SMS) deposits of copper, zinc, gold, and silver have been discovered 1.5-2 km below the surface of the ocean, and more are being discovered every year. It is possible that many of these deposits may be of sufficient size and grade to mine for these highly-demanded metals, but to date no metals have been commercially mined from a seafloor deposit.

It is widely known that the mining industry has not always acted with care regarding the environmental and social impacts of its operations. In 1987, the Brundtland Commission introduced the concept of sustainable development, defining it as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Weber, 2007).

In the intervening years, much literature on sustainable development and sustainability has been published but it is generally agreed that sustainable development consists of three elements, or pillars, that must be

considered equally: (a) environmental sustainability, (b) social concerns, and (c) economic considerations. The changing expectations of governments, financial institutions, shareholders, and other key stakeholders has put the industry under considerable pressure to change its image and obtain a “social license to operate” by contributing positively to local and global communities. To respond to this pressure, many mining companies have incorporated sustainability issues into their business plans. Additionally, industry associations and initiatives such as the International Council on Mining and Metals (ICMM), the Mining Association of Canada (MAC), and the Mining Minerals and Sustainable Development (MMSD) project under the International Institute for Environment and Development (IIED) have all sought to develop definitions, metrics, guidelines, and goals for mining companies seeking to contribute positively to sustainable mining.

## **1.2 Motivation**

Since mining will be a necessity for the foreseeable future, and considering the emerging importance of sustainability in all aspects of the industry, it is essential that new deposits and mining techniques are developed and employed in a sustainable manner. The work undertaken by the previously mentioned organizations has provided significant guidance for mining companies to achieve sustainable mining. However, these guidelines and tools were developed for terrestrial, or land-based, operations and thus the direct application of these tools to seafloor mining projects is not appropriate. A seafloor mining project contains environmental and social challenges that are very different from those encountered on shore – challenges that must be considered for any sustainable mining effort. It is the objective of this thesis to provide an assessment framework for sustainable seafloor mining that addresses these singular considerations, allowing for decision makers to make the most informed decisions regarding the proposed operation. Through a hierarchical, logical process, any potential SMS mining project can be evaluated

through a sustainability lens, resulting in a decision as to whether the project can be considered to conform to sustainable mining principles, or not.

### **1.3 Scope of Work**

This thesis provides a framework to assist decision-makers with addressing the two key problems facing seabed mining: (1) Policy and regulatory deficiencies, and (2) unknown economic, social, and environmental impacts. The proposed framework is intended to be used by incorporating information prepared in other reports, allowing decision-makers to have the most important information readily available and clearly presented, so as to be able to make the best possible decision. The thesis is organized as follows:

- Chapter 2 discusses the geological settings of SMS deposits, including locations, formation processes, and metal contents
- Chapter 3 provides an overview of sustainable mining, describing the three components (economic, social, environmental) and their application to mining projects
- Chapter 4 outlines the factors governing the sustainable mining of SMS deposits. It provides overviews of the following:
  - Technological considerations
  - Mineral economics
  - Law and regulatory considerations
  - Potential social impacts based on jurisdictional area

- Environmental impacts at the local and global scale
- Chapter 5 develops the decision-making framework. The framework is based on the IDEF0 standard and provides a systematic, hierarchical method for sustainable mining analysis of a SMS project
- Chapter 6 provides an overview of how the framework should be applied through various levels of study
- Finally, Chapter 7 provides conclusions and recommendations for further work

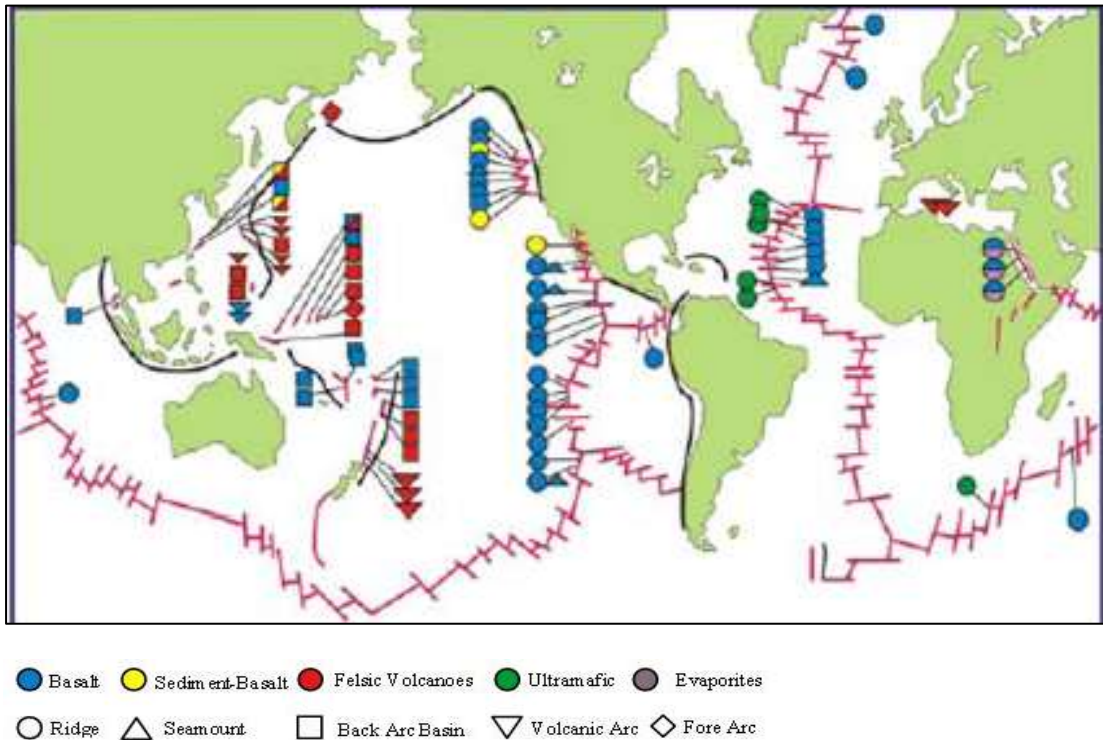
## **Chapter 2: Geological Settings of SMS Deposits**

### **2.1 Tectonic Setting**

Hydrothermal venting systems, and associated seafloor massive sulphide (SMS) deposits, are generated primarily at tectonic plate margins along mid-ocean ridges and island arcs (Hannington, de Ronde & Petersen, 2005). The size, distribution, and composition of the deposits is dependent on the frequency of tectonic activity, magma characteristics, morphology, basement rock composition, and spreading rate (Fouquet & Scott, 2009; Hannington et al., 2005; Rona, 2007). Fouquet and Scott (2009) have identified four major environments in which SMS deposits occur:

1. Fast-spreading ridges
2. Slow-spreading ridges
3. Arcs and back-arc basins
4. Intra-plate volcanoes

Figure 1 is a map of known hydrothermal vent sites, identified by host rock type and tectonic setting. Although large deposits are favored in settings with infrequent volcanism and extended periods of intense tectonic movement (intermediate- and slow-spreading centers), they can occur in any setting and rate provided the appropriate geological controls exist (Hannington et al., 2005; Rona, 2007; Tivey, 2007). Recent investigations show that arc rifts are the likely source for 80% of known VMS deposits on land (Hannington et al., 2005). According to Fouquet and Scott (2009), one dozen 2cm diameter smokers emitting fluid at a rate of 2 m/s containing 100 ppm dissolved metals would produce 250 tons of metal sulphides per year.



**Figure 1: Locations of known hydrothermal systems (Scott, 2007)**

### 2.1.1 Fast-spreading Mid-ocean Ridges

Mid-ocean ridges are characterized by an axial zone of magmatic intrusion and volcanic extrusion flanked by extension zones (Rona, 2007). Fast-spreading mid-ocean ridges, such as the East Pacific Rise, spread at a rate of 6-18 cm/yr., occur in thin oceanic crust, contain a shallow (1-2 km) magma body, and undergo frequent volcanic activity (measured in decades) (Hannington et al., 2005; Rona, 2007). Due to the frequency of volcanic eruptions and fast spreading rate, the hydrothermal systems at fast-spreading ridges are unstable, resulting in deposits that are typically small and cannot accumulate enough mineralization to be of economic importance (Fouquet & Scott, 2009).

### 2.1.2 Slow-spreading Mid-ocean Ridges

Intermediate- (4-6 cm/yr.) and slow- (<4 cm/yr.) spreading ridges are hosted in thick crust and are characterized by deep faults that allow fluid circulation down to depths of 5-8 km (Hannington et al., 2005). The sub-axial magma chamber of intermediate ridges, such as the Juan de Fuca Ridge, is located 2.5-3.5 km deep, compared to the 1-2 km deep source exhibited by fast-spreading ridges, while the sub-axial magma chambers of slow-spreading ridges may be non-existent (Hannington et al., 2005). Volcanic activity at slow-spreading ridges occurs over periods of hundreds to thousands of years while non-volcanic tectonic activity is usually long-lived, providing stability for hydrothermal systems (Hannington et al., 2005; Rona, 2007). The hydrothermal systems at slow-spreading ridges contrast those of fast-spreading ridges in three ways:

1. Due to spreading rate and volcanism, hydrothermal activity occurs over 50,000 years (Fouquet & Scott, 2009)
2. Due to the fluid pathways provided by faulting, vent sites are not restricted to the axis but have been found kilometers off-axis (Rona, 2007)
3. The deep-to-non-existent magma chambers in slow-spreading ridges imply that hydrothermal activity is generated by deeply penetrating seawater reacting with hot crystalline rock (Hannington et al., 2005)

Thus, slow-spreading systems “may host some of the largest hydrothermal systems on the sea floor” (Hannington et al., 2005).

### **2.1.3 Volcanic Arcs and Back-arc Basins**

Volcanic arcs and back-arc basins, in contrast to mid-ocean ridges, occur at convergent plate boundaries (Martinez, Okino, Ohara, Reysenbach & Goffredi, 2007). They can be developed in areas of converging

oceanic crust (intraoceanic back-arc rifts) such as seen in the Western Pacific, or in areas of submerged converging continental crust (intracontinental back-arc rifts) such the Okinawa Trough (Herzig & Hannington, 1995). These tectonic settings are the most favorable for concentrating potentially economic SMS deposits when compared to mid-ocean ridges due to the influence of melts generated by the subducting plate, which increase the metal content of the hydrothermal fluids and associated deposits (Martinez et al., 2007; Rona, 2007). Additionally, these environments are ideal targets for mining projects because they are located within the exclusive economic zones of sovereign island states (i.e.: Tonga, Papua New Guinea, New Zealand) (Rona, 2007). While hydrothermal processes are similar to mid-ocean ridges, the spreading rates of back-arc basins vary from <5-10 cm/y (Hannington et al., 2005; Rona, 2007). As back-arc basins mature from rifts near the arc front to seafloor spreading centers, the new oceanic crust changes from a felsic (i.e.: andesite) composition to a mid-ocean ridge-type basalt, indicating that the influence of the arc volcanic magmas has been removed (Fouquet & Scott, 2009; Martinez et al., 2007; Rona, 2007). A more detailed description of formation processes is included in Section 2.2.

## **2.2 Formation Processes**

Although there are variances in hydrothermal fluid compositions and associated SMS deposits between the previously discussed tectonic environments, the processes by which seawater becomes high-temperature hydrothermal fluid are similar for all (Birney et al., 2006; Scott, 2007). In a mid-ocean ridge setting, hosted in un-enriched basalt, the magma chamber drives convection which pulls seawater through the “recharge zone,” into the “reaction zone,” and finally through the “up-flow zone” to be discharged at the seafloor (Fouquet & Scott, 2009; Tivey, 2007). As the water heats to 150C,  $\text{CaSO}_4$  precipitates as anhydrite and further increases in temperature result in the precipitation of smectite and chlorite, resulting in a solution devoid of magnesium (Tivey, 2007). Subsequent sulfate reduction increases the acidity of the

fluid, allowing sulfur and metals to be dissolved from the host rocks, producing an acidic, hot, buoyant fluid that is approximately 350C when it discharges (Fouquet & Scott, 2009; Tivey, 2007). The reaction of the hot venting fluid with the cold (2C) seawater results in the precipitation of sulphides, forming SMS deposits (Fouquet & Scott, 2009).

Where ridges are buried beneath sediments, high-temperature fluids react with the sediment cap, depositing sulphides below the seafloor by replacing the host sediments (Hannington et al., 2005). The sediment cap retains the heat, prevents metal losses through hydrothermal plumes, and protects the deposit from weathering and oxidation, leading to larger deposits than are seen on bare ridges (Hannington et al., 2005). These deposits occur on the Juan de Fuca ridge, in the Guaymas basin, and Middle Valley (Hannington et al., 2005).

Back-arc basins and volcanic arcs, while exhibiting similar hydrothermal mechanics to mid-ocean ridges, tend to have more felsic volcanic rocks (Rona, 2007). Back-arc basins form in two phases, first by rifting near the arc front and eventually by becoming seafloor spreading centers. These two phases exhibit different magmatism, and are characterized as “immature” and “mature” respectively (Fouquet & Scott, 2009; Martinez et al., 2007). At the beginning of arc and back-arc basin formation, the subducting plate allows seawater to enter the system, lowering the melting point and providing the felsic lavas for the arc volcanism, a process known as hydrous melting (Fouquet & Scott, 2009; Martinez et al., 2007). The arc magmatism is also affected by the addition of magmatic volatiles which contribute to a pH decrease, providing an ideal setting for the dissolving of metals from the host rock (Hannington et al., 2005). Thus, hydrothermal fluids in immature back-arc basins, where the rifting center is located in close proximity to the arc front and rifting is occurring in continental or island arc crust, are strongly influenced by the hydrous melts, leading to increases in metal contents, particularly gold. In contrast, as the basin matures to become a seafloor spreading center, the crustal compositions become analogous to the basalts found at

mid-ocean ridges, and exhibit similar metal contents in the associated hydrothermal deposits (Fouquet & Scott, 2009; Hannington et al., 2005; Martinez et al., 2007).

Once formed, all types of SMS deposits, whether on convergent or divergent boundaries, may be destroyed by faulting or carried off axis and buried by sediment or lava flows (Rona, 2002). These inactive deposits are more difficult to find, as they are no longer expunging a hot sediment plume but would be the most practical targets for a mining operation as active vent fluid is highly corrosive and would damage the mining equipment (Fouquet & Scott, 2009).

### **2.3 Metal Contents**

The primary metals that could be economically obtained from a SMS deposit are copper, zinc, lead, barium, silver, and gold (International Seabed Authority [ISA], 2004; Scott, 2006). As mentioned previously, formations in back-arc basins are more enriched in these metals than deposits associated with divergent ridges, as shown in Table 1.

**Table 1: Comparison of metal contents of mid-ocean ridges and back-arc spreading (Herzig & Hannington, 1995)**

	Mid-Ocean Ridges		Back-arcs	
	Volcanic-hosted	Sediment-hosted	Intraoceanic	Intracontinental
# of samples	890	57	317	28
Fe (wt. %)	23.6	24.0	13.3	7.0
Zn	11.7	4.7	15.1	18.4
Cu	4.3	1.3	5.1	2.0
Pb	0.2	1.1	1.2	11.5
As	0.03	0.3	0.1	1.5
Sb	0.01	0.06	0.01	0.3
Ba	1.7	7.0	13.0	7.2
Ag (ppm)	143	142	195	2766
Au	1.2	0.8	2.9	3.8

Generally speaking, SMS deposits are fairly small and only a few may contain tonnages in the 100-10,000 tonne range; however, the smaller deposits may be economically recoverable due to the non-permanent, reusable nature of the mining infrastructure and equipment (Fouquet & Scott, 2009).

Nautilus Minerals Inc. has filed a technical report compliant with Canadian NI-43-101 standards that reports the grades and tonnages for the Solwara 1 deposit off the coast of Papua New Guinea shown in Table 2. This deposit may become the first SMS deposit to be mined commercially.

**Table 2: Solwara 1 resource and reserve estimates (Jankowski, 2011)**

<b>Classification</b>	<b>Domain</b>	<b>Tonnes</b>	<b>Cu (%)</b>	<b>Au (g/t)</b>	<b>Ag (g/t)</b>	<b>Zn (%)</b>
Indicated	Massive sulphide	870,000	6.8	4.8	23	0.4
Inferred	Chimney	80,000	11	17	170	6
Inferred	Lithified Sediment	2,000	4.5	5.2	36	0.6
Inferred	Massive sulphide	1,200,000	7.3	6.5	28	0.4
<b>Indicated</b>	<b>Total</b>	<b>870,000</b>	<b>6.8</b>	<b>4.8</b>	<b>23</b>	<b>0.4</b>
<b>Inferred</b>	<b>Total</b>	<b>1,300,000</b>	<b>7.5</b>	<b>7.2</b>	<b>37</b>	<b>0.8</b>

## **Chapter 3: Background on Sustainable Mining**

Sustainable development, as a term, came to prominence in 1987 when the World Commission on Environment and Development, known also as the Brundtland Commission, defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Weber, 2007). Since the report, literature has seen a plethora of authors attempting to provide definitions and guidelines for applying the concept in a myriad of industries, as the Brundtland Commission provided no such implementation methodologies (Hilson & Murck, 2000; Jordan, 2008). However, throughout all the volumes of literature produced, there is a central theme that sustainable development involves the unification of socio-economic development and environmental protection (Hilson & Murck, 2000).

### **3.1 The Mining, Minerals, and Sustainable Development Project**

Mining, by its nature, involves the removal of non-renewable resources and the very essence of this process may seem contrary to the ideas of sustainability or sustainable development. In fact, with appropriate design and planning throughout the entire project phase, the *implications* of a mining project can provide a net-positive benefit to the community and ecosystem, even though the mine life itself is finite (Mining, Minerals, and Sustainable Development [MMSD], 2002a). One of the most important documents for sustainable mining is entitled *Breaking New Ground: The Report of the Mining, Minerals, and Sustainable Development Project* (Weber, 2007). The project, undertaken in 1998 and culminating with the report in 2002, was a joint effort between mining companies, mining NGOs, development agencies, the World Business Council for Sustainable Development, and the International Institute for Environment and Development. It was through this project that some important definitions and concepts for the application of sustainability principles to the mining industry were presented.

One such concept is capital. The MMSD report defines five forms of capital: (1) natural capital, or ecosystem benefits such as biodiversity, natural resources, clean air, and clean water; (2) manufactured capital, or infrastructure; (3) human capital, or knowledge, skills, health, and culture; (4) social capital, or institutions for collaborative social development and; (5) financial capital, or the monetary value assigned to the other forms. There is significant debate on whether these forms of capital can be substituted with each other or whether some forms should not be considered “tradable” (MMSD, 2002a). To avoid decision-making based on sustainability to be clouded by these theoretical debates, the report provides three types of decisions based on sustainability concepts (MMSD, 2002a):

- ‘Win-win-win’ decisions are decisions that satisfy all the objectives of socioeconomic growth and environmental protection as identified by sustainable development
- ‘Trade-off’ decisions are decisions that require careful evaluation of the gains and losses generated by the decision. If the losses can be compensated appropriately, the decision may proceed. However, the criteria for establishing such a decision should be evaluated based on a mechanism acceptable to all stakeholders
- ‘No-go’ decisions are decisions that should not be allowed to proceed as the resulting implications are unacceptable. These include, for example, violations of human rights or the permanent, deleterious destruction of natural capital

Furthermore, the MMSD report separates the concept of sustainable mining into four spheres. Each sphere must be considered fully, and no one sphere should dominate decision making. Thus, it is convenient to regard the spheres as pillars, each essential to support sustainable mining. These pillars are:

- *Economic pillar:* This pillar involves not only the economic viability of the mining company, but also of the local (or affected) community (MMSD, 2002a). In the community, this can be achieved through employment, community development, or other means to alleviate poverty (Hilson & Murck, 2000). For the corporation, a financially feasible project will ensure that a company has access to mineral resources and financing, allowing it to contribute to the sustainability of the community but also to that of the industry (Humphreys, 2001).
- *Social pillar:* This pillar addresses the often-overlooked distribution of costs and benefits, human rights protection, capital substitution as a means to ensure the well-being of future generations, and cultural integrity (MMSD, 2002a).
- *Environmental pillar:* This pillar addresses the complicated issue of ensuring environmental sustainability. The MMSD report details the environmental responsibilities for mining companies as: responsible environmental management, adherence to standards, and minimization of waste and damage throughout the life-cycle. However, adherence to legislated standards may not be sufficient, especially in countries with underdeveloped legal regimes for mining. Thus, proactive management using legislated values as baselines will likely lead to a greater net-positive contribution to environmental sustainability (Hilson & Murck, 2000).
- *Governance pillar:* Governance, as a stand-alone foundation to sustainable development, is rarely discussed in literature. However, particularly in the mining sector, appropriate governance is a paramount concern (MMSD, 2002a). Some key responsibilities of governance are (MMSD, 2002a):
  - Supporting participatory decision-making

- Establishment of checks and balances to avoid concentration of power
- Ensuring that clear and fair rules and incentives are established to promote free enterprise
- Provision of information to all key stakeholders
- Accountability for all decisions and actions

This pillar should not be considered to be restricted only to national or state governance, but to corporate governance as well.

Although MMSD proposes four pillars of sustainable development by describing governance separately, the elements of governance are very much incorporated into each of the other pillars. For the purposes of this thesis, the three “core” pillars will be considered, factoring in relevant governance factors as necessary.

Finally, sustainability is very much based on the values of the affected stakeholders, and thus there is no one, single, method for ensuring a project's net-positive contribution to sustainable development. Therefore, it is important that all key stakeholders be allowed to participate in public engagement processes before any aspect of the project life begins (MMSD, 2002b.). By conducting effective engagement, not only does a mining company ensure a social license to operate, but it can also easily identify the values of the community and develop sustainability indicators and metrics for each pillar.

### **3.2 The International Council on Mining and Metals**

Founded in 2001, the International Council on Mining and Metals (ICMM) is a multi-member organization that emerged out of the MMSD project. The goal of the organization is “to improve sustainable development performance in the mining and metals industry” (“ICMM | ICMM About Us,” 2011). Members include 21 mining and metals companies as well as 31 national and regional mining

associations, and each member is committed to upholding the Sustainable Development Framework. The framework establishes ten principles and requires public reporting to Global Reporting Initiative standards and independent third party audits from all its members (“ICMM | Our work • Sustainable Development Framework,” 2011). The ten principles of the ICMM framework are:

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

It is evident from these ten principles that economic, environmental, and social sustainability issues are deeply rooted in the sustainable development commitments of ICMM and its members. Additionally, engagement and collaboration is a high priority. ICMM has identified that sound governance at both the corporate and sovereign (national and regional) levels is a major factor for ensuring positive socio-economic contributions of mining and thus encourages the formation of industry, government, development agency, and societal partnerships to fill gaps in governance (“Mining: Partnerships for Development Position Statement,” 2010).

The ICMM has also developed a framework, *Mining: Partnerships for Development*, that provides a methodology for assessing positive and negative economic and social effects of mining activities and is intended be used in collaboration with key stakeholders (“Mining: Partnerships for Development Toolkit,” 2011). The framework consists of eight modules:

1. Mining and the host country
2. The participating mining operation and its economic and social initiatives and partners
3. Measuring the mining industry’s contribution to the host country
4. The proximate aspects of governance that help or hinder mining’s economic and social performance
5. Measuring the participating mine’s positive and negative contributions to local communities
6. Analyzing the life cycle impact of the participating mine on the host country’s macroeconomic aggregates
7. Impact of mining on governance

## 8. Communicating your findings

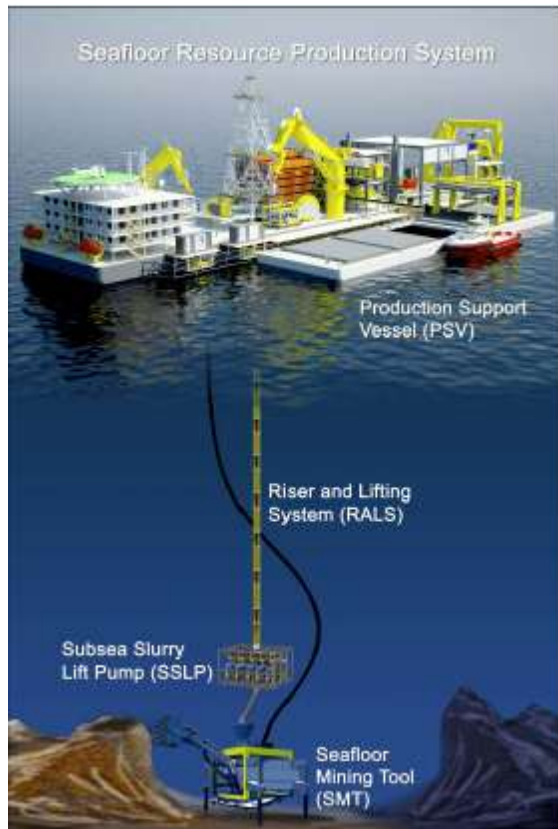
While the toolkit is not intended to replace environmental and social impact studies, it provides simple guidelines for the development of a country profile and assessing potential impacts and benefits of mining to a specific region that can be used to compliment these other studies. Additionally, by producing the reports specified by the toolkit, comparisons of mining's contributions to different countries can be easily carried out ("Mining: Partnerships for Development Toolkit," 2011).

## **Chapter 4: Factors Governing Sustainable Mining of SMS Deposits**

This chapter presents an overview of key factors governing the sustainable mining of SMS deposits for the economic, social, and environmental pillars, including technological considerations. Additionally, relevant legal considerations based on jurisdiction are highlighted.

### **4.1 Technological Considerations**

The extraction of minerals from SMS deposits requires the development of a new mining method, as no such deposits have been commercially mined. For the Solwara 1 project off Papua New Guinea, Nautilus Minerals has proposed a mining method comprised of four components: The Production Support Vessel (PSV), the Riser and Lifting System (RALS), the Subsea Slurry Lift Pump (SSLP), and the Seafloor Mining Tools (SMTs). These components are shown in Figure 2. This method has been designed to "minimize the application of new technology" (Blackburn, 2010, p. 143), and thus many of the components are based on or borrowed from proven technologies in the mining or oil and gas industries. As the seabed mining industry is in its infancy, there is a lack of deep sea mining-specific codes and standards by which equipment is to be designed and certified. Therefore, Nautilus has adopted the current codes and standards for the offshore oil and gas industry (Blackburn, 2010).



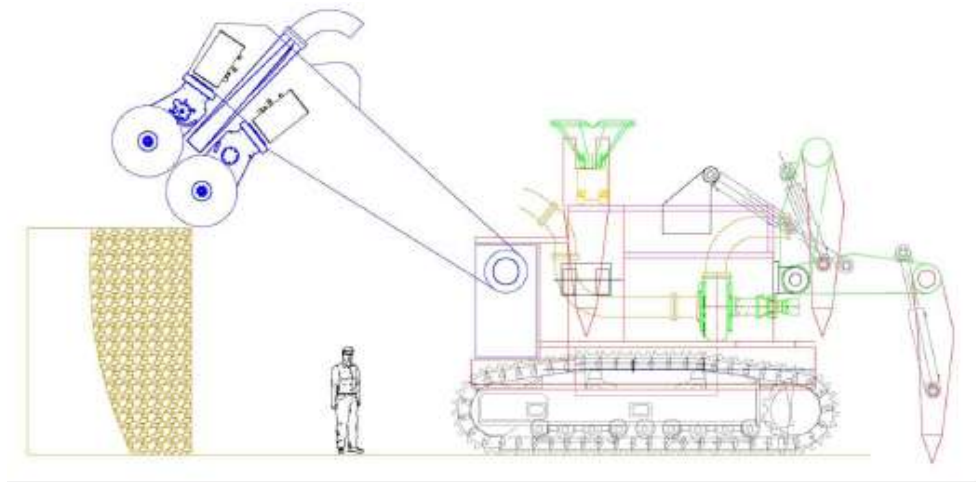
**Figure 2: Nautilus proposed mining system (Blackburn, 2010)**

These components form the backbone of the mining process, including cutting and gathering, pumping ore to surface, dewatering, and discharge (ore to transportation barges and return water to seafloor). Detailed discussion of the technological complexities of the seabed mining process are beyond the scope of this thesis, but is contained in the published *Offshore Production Definition and Cost Study*. However, some key elements of the proposed method are discussed below.

#### **4.1.1 Seafloor Mining Tools (SMTs)**

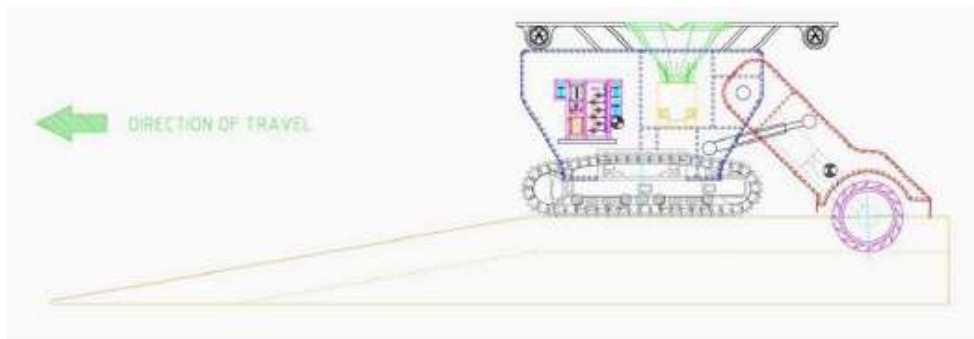
The proposed system is comprised of three seafloor mining tools: the Auxiliary Miner, the Bulk Miner, and the Gathering Machine. The Auxiliary Miner's primary purpose is to prepare the site for the Bulk Miner. This machine has a rock cutting head mounted on an articulated boom, similar to that found on

diamond mining machines (Blackburn, 2010). A conceptual drawing of the Auxiliary Miner is shown in Figure 3.



**Figure 3: Auxiliary Miner (Blackburn, 2010)**

Once the site has been prepared by the Auxiliary Miner, the Bulk Miner (Figure 4) is introduced. This piece of equipment is the primary production unit of the operation. It is track mounted and contains a cutting head similar to those found on conventional road-miner machines (Blackburn, 2010).



**Figure 4: Bulk Miner (Blackburn, 2010)**

The Gathering Machine is responsible for vacuuming up the crushed ore left by the Bulk Miner. It is also capable of vacuuming up any unconsolidated sediment which can be pumped to a seafloor storage site selected to minimize ecological impacts (Blackburn, 2010).

#### **4.1.2 Riser and Lift System (RALS)**

The RALS is designed to lift the ore gathered by the Gathering Machine to the PSV. This is done by pumping the material using a Subsea Slurry Lift Pump (SSLP) coupled to a vertical riser system attached to the PSV (Blackburn, 2010). Many of the components comprising the RALS are direct applications of proven technology from the oil and gas industry.

Although this mining system has not yet been employed on a commercial scale, the adaptation and adoption of proven technologies should minimize technological risks, facilitating the estimation of environmental impacts. In turn, this should provide the basis for a more comprehensive sustainability analysis to be conducted prior to operations.

### **4.2 Mineral Economics**

The economic pillar of sustainable development involves economic assessment of the potential project in order to determine whether there is economic benefit to proceed. This benefit is important to a mining company for two reasons:

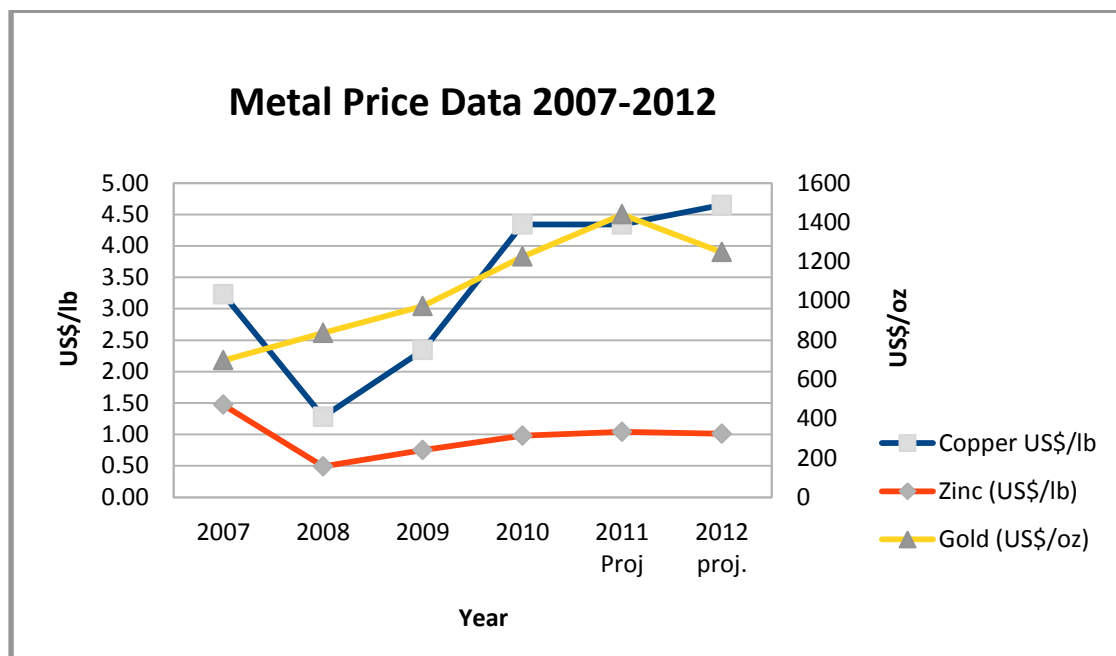
1. Corporate profitability
2. Ability to contribute to the economic sustainability of the communities affected by the project

This section will outline some of the market factors that influence economic sustainability and introduce the potential economic benefits of SMS mining.

#### **4.2.1 Market Overview**

During the global recession of 2008, prices for many commodities plummeted and producers shut down or cut production at mines and smelters to balance supply and demand (Mining Association of Canada [MAC], 2010). However, demand and prices for metals, such as copper and zinc, have recovered since,

mostly due to demand from China and India, as well as from other developing economies as they seek to increase their standard of living (Fouquet & Scott, 2009). This demand has continued to bolster prices and has once again piqued interest in mining minerals from the seafloor as corporations seek to ensure a steady stream of smelter feed in the face of increasing environmental and land claim issues related to land based projects (Hoagland et al., 2010; Scott, 2007). Figure 5 illustrates the prices for copper, zinc, and gold since 2007 and includes projections for 2011 and 2012. Clearly evident is a sustained increase in gold price through the recession due to investors buying gold amid fears about the economy; similarly evident is the shocking decrease in the price of copper and zinc in 2008.



**Figure 5: Metal prices from 2007-2012 (sources: (MAC, 2010; *World Commodity Forecasts Industrial Raw Materials*, 2011))**

Additionally, the prices for the two primary metals, copper and gold, have risen steadily since 2001, as shown in Figure 6. The effects of the recession in 2008 are clearly visible, particularly for copper, however the overall trend has been an increase in the price for both metals.



**Figure 6: 10-year copper and gold prices (InfoMine.com, 2011)**

According to the *World Commodity Forecasts Industrial Raw Materials August 2011*, published by The Economist Intelligence Unit, commodity consumption growth will continue at a rate slightly slower than 2010 due to sustained high prices and tighter monetary policy by China and India. Prices for metals are projected to remain high, but will ease slightly amid concerns related to global liquidity and the economic recovery (Economist Intelligence Unit, 2011). More detailed discussion pertaining to the metals of interest in a SMS deposit is included in the following subsections.

#### 4.2.1.1 Gold

Gold prices are, generally, expected to remain high through this forecast period (2011-2013) as investors seek a safe investment alternative in the face of “low interest rates and concerns about the civil unrest in

the Middle East and North Africa region, worries about European and US sovereign debt, and fears about global inflationary pressures” (Economist Intelligence Unit, 2011), although the price of gold is projected to ease in 2012. Demand for jewelry-grade gold from China and India, combined with demand for industrial gold from the electronics industry, will drive consumption growth in 2011. The growth, however, may slow in 2012 due to the previously mentioned price easing (Economist Intelligence Unit, 2011).

The Economist Intelligence Unit further postulates that the price of gold is at risk of collapse. This collapse could be precipitated by two divergent scenarios (Economist Intelligence Unit, 2011):

1. Double-dip global recession, in which the economic recovery is stymied to the point that investors are forced to release their gold stocks
2. Rapid economic recovery, in which investors diversify their investments assuming “peak gold” has occurred

Thus the price of gold is projected to fall to US\$1,000/oz. by the third quarter of 2013 (Economist Intelligence Unit, 2011). However, even at this gold price, SMS deposits may remain economically attractive as mining projects when considering the other metals of interest.

#### 4.2.1.2 Copper

Copper prices are forecasted to remain high through 2012, primarily due to supply problems and the easing, but still growing, demand from China and other Asian markets (Economist Intelligence Unit, 2011). Supply is being constrained by:

- Mine production uncertainty forcing increased use of scrap feed in smelters
- Declining grades, estimated at 0.75% globally, preventing output growth

- Lower mine utilization and lack of new mines coming into production

These factors, combined with labor disruptions, downtime, and other production problems in Chile, the world's largest copper producer, have seriously constrained the available supply of copper, such that it is projected that supply will fall short of demand from 2011-2013 (Economist Intelligence Unit, 2011). Thus, despite production slowdowns, economic uncertainties, and tighter fiscal policies, copper prices will remain high through 2012 (Economist Intelligence Unit, 2011). Sustained high prices should maintain interest in pursuing SMS deposits as copper sources.

#### 4.2.1.3 Zinc

The price of zinc is the only one of the three discussed that is expected to continue to rise through the forecast period. Due to the economic recovery, zinc production saw an increase which has saturated the market with zinc surplus (Economist Intelligence Unit, 2011). The sustained high prices indicate that production is not likely to wane, and thus the market will continue to exist in a state of oversupply. Thus, sustained high prices depend on speculative investing, which could lead to a slight price drop in 2012 (Economist Intelligence Unit, 2011). However, as the stocks become depleted (projected in 2013), the price of zinc will rise once again, estimated at US\$1.05/lb. in the third quarter of 2013 (Economist Intelligence Unit, 2011).

#### 4.2.1.4 Silver

Silver forecasts through 2013 are not available in the Economist Intelligence Unit report. However, an October 31, 2011 article describes a projected silver price, produced by CIBC World Markets, as \$37.50/oz. in 2011. It also describes the volatility of the silver price in 2011, reaching a high of \$50/oz. in April and reaching a low of around \$30/oz. in October ("CIBC lowers silver price guidance, downgrades PanAm, Minefinders - SILVER NEWS | Mineweb," 2011).

#### 4.2.2 Economic Benefits of SMS Mining

For a SMS deposit to become economically attractive, it must have demonstrable advantages in size, grade, or accessibility over mining for the same metals of interest on land (Hoagland et al., 2010). Herzig (1999) postulates that the ideal criteria for an economically attractive SMS deposit would include:

1. High grades of gold and base metals
2. Geographical location within territorial waters or an exclusive economic zone
3. Physical location in water less than 2000 m deep

As compared to onshore deposits, SMS deposits tend to have a grade advantage, although the sizes are comparatively small (1-5Mt vs. 50-60 Mt) (Hoagland et al., 2010). Nonetheless, due to the mobile mining infrastructure and lack of overburden stripping requirements, these smaller deposits could potentially be mined economically (Fouquet & Scott, 2009).

Like any mining project, the first SMS mining operation will have high start-up costs (Fouquet & Scott, 2009). Nautilus Minerals is seeking to become the first entity to produce metals from a SMS deposit. In the published *Offshore Production System Definition and Cost Study* of 2010 (Blackburn, 2010), the company details their estimates for capital and operating costs based on a 3,710 tonne per day average production for their Solwara 1 project. The project is expected to mine 2,000 kt of ore over an 18 month period. The estimated operating cost for Solwara 1 had been calculated to US\$70.47t. This includes costs associated with the operation of the PSV, the operation of the mining equipment, operation of the RALS, support services, and barging plus a contingency of 10% (Blackburn, 2010). With this information, it is possible to compare the costs of the proposed SMS project versus traditional open-pit and underground methods from which a majority of the world's copper and gold derives, see Table 3. Note the inclusion of various stripping ratios of tonnes waste to tonnes ore for the pits.

**Table 3: Cost comparison for “traditional” vs. SMS of comparable tonnages (Blackburn, 2010; Stebbins, 2010)**

<b>Method</b>	Open pit w Stripping Ratio 2:1	Open pit w Stripping Ratio 4:1	Open pit w Stripping Ratio 8:1	Block Cave (shaft entry)	Cut and Fill (shaft entry)	SMS
	<b>5000 tpd</b>	<b>5000 tpd</b>	<b>5000 tpd</b>	<b>20,000 tpd</b>	<b>200 tpd</b>	<b>3170 tpd</b>
CAPEX (US\$)	24,329,800	39,846,600	80,169,800	109,426,700	19,072,100	383,000,000
OPEX (US\$/t)	9.84	14.77	26.77	9.31	111.66	70.47
	<b>40,000 tpd</b>	<b>40,000 tpd</b>	<b>40,000 tpd</b>	<b>45,000 tpd</b>	<b>2000 tpd</b>	
CAPEX (US\$)	176,081,600	360,098,100	780,586,200	252,728,900	48,401,700	
OPEX (US\$/t)	7.91	12.96	24.32	8.87	55.85	

It is likely that any new open pit copper mine will produce significantly greater tonnage than 5000 tonnes per day. A recent (2009) attempt to open the Prosperity copper-gold mine in British Columbia was projected to produce 70,000 tonnes per day (Taseko Mines Limited, 2009). Due to environmental and social concerns with respect to First Nations’ rights, the Federal Prosperity Review Panel prevented the issuance of the applicable permits; however they did not consider the economic benefits the project would provide to the communities (Federal Prosperity Review Panel, 2010). The capital cost expenditure for an open pit mine at 40,000 tonnes per day with a stripping ratio of 4:1 is over \$360M, and can exceed \$1.4B for a pit producing 80,000 tonnes per day with a stripping ratio of 8:1. These costs do not include costs associated with exploration or permitting.

A capital cost of \$383 million for a SMS operation may seem high in comparison, but it must be understood that this expense is not a recurring expense for each deposit, where the capital expenditure must be spent in its entirety for each new terrestrial pit. For the SMS project, this capital expense is heavily weighted towards equipment that will only need to be purchased once, and then can move about

from site to site. The economic advantages of SMS mining can be summarized as follows (Fouquet & Scott, 2009; Scott, 2007):

- Lack of fixed permanent infrastructure such as roads, power lines, air strips, or towns
- Single purchase, multiple use mining equipment can be transported from site to site without leaving anything behind on the seabed

A final economic benefit of SMS mining could emerge as a direct result of the small size of the deposits. Considering the short mine life of the proposed Solwara 1 project as an example, and assuming other potential economic sites are of similar size, it is considered that production targets and times could be scheduled so as to make maximum benefit of the current market conditions. Additionally, during prolonged economic downturns, the ship and mining equipment could be easily stored in dock to weather the economic storm. This is in contrast to the large open pits, whose operational periods of decades make them extremely vulnerable to price fluctuations, as seen in 2008 when many mines reduced production or were put on care and maintenance.

### **4.3 Legislative and Regulatory Factors**

This section seeks to provide an overview of the existing international and national legal frameworks relating to SMS exploration and exploitation. It begins with an introduction to the United Nations Convention on the Law of the Sea and the International Seabed Authority before proceeding into the national legislation and regulations of some potential SMS mining countries. Many of these jurisdictions do not have legal frameworks specific to SMS mining, and, as such, this thesis seeks to identify the existing legislation that would be applicable to a seafloor mining project. Through this examination,

legislative gaps will be identified that could potentially hinder the development of seafloor mineral resources

### **4.3.1 International**

#### 4.3.1.1 UN Convention on the Law of the Sea

The most important piece of international ocean legislation is the *United Nations Convention on the Law of the Sea (UNCLOS)* (United Nations, 1982). The Convention contains 320 articles and nine annexes governing marine territorial boundaries; environmental protection; scientific, commercial, and economic activities; technology; and conflict resolution (Russell, 1992). Part XI of the Convention promulgates a regime for managing the resources of the seabed outside national jurisdiction (“The Area”). This Part, as detailed in the original Convention, generated controversy particularly among more industrialized states which were resolved through *The 1994 Agreement Relating to the Implementation of Part XI*, the result of informal consultations convened by Secretary-General Cuellar beginning in 1990 (Glasby, 2002; Harrison, 2010; Keyuan, 2003; Nandan & Lodge, 2002). The Convention, together with the 1994 Agreement, entered into force in November, 1994 (Harrison, 2010). Table 4 illustrates the Parts of the Convention particularly relevant to mineral resources on the seafloor.

**Table 4: Relevant Parts of UNCLOS relating to seafloor resources**

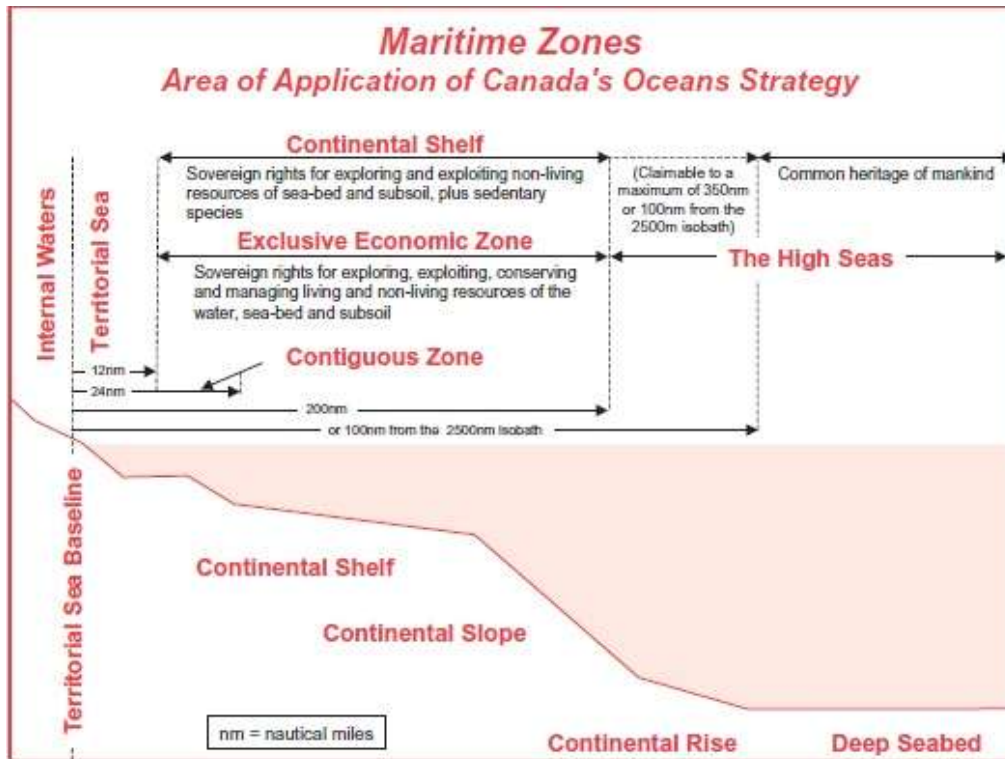
<b>Part</b>	<b>What Established/Addressed</b>	<b>Description</b>
V	Exclusive Economic Zone	A 200 nautical-mile zone extended beyond the baseline for the territorial sea in which a State has sovereign rights for “exploring and exploiting...the natural resources...of the seabed and its subsoil” (Art. 56, UNCLOS)
VI	Continental Shelf	Provides States with the ability to exploit resources in the seabed and subsoil of the continental shelf (Art. 77, UNCLOS) if it can be demonstrated to exceed 200 nautical miles, up to 350 nautical miles from the territorial sea baseline or 100 nautical miles from the 2,500 m isobath (Art. 76 par. 5, UNCLOS)
XI	The Area	The Area is the seabed and ocean floor beyond national jurisdiction (Art. 1, UNCLOS). This Part addresses the development of resources (Part XI, Sec. 3, UNCLOS) and establishes the International Seabed Authority (Part XI, sec. 4, UNCLOS) to oversee deep sea mining in the Area.
XII	Marine Environmental Protection	“States have the obligation to protect and preserve the marine environment” meaning measures must be taken to “prevent, reduce, and control pollution...from any source” (Art. 192, UNCLOS). Pollution includes installations used for exploration or exploitation of resources (Nagender Nath & Sharma, 2000)
XV, Annex VI	Settlement of Disputes	The Convention includes a dispute-settlement mechanism that all ratifying states are obliged to uphold. The Convention also establishes the International Tribunal for the Law of the Sea and the Seabed Disputes Chamber which handles disputes relating to Part XI.

#### 4.3.1.1.1 Jurisdictional Areas

As Russell (1992) explains, the UNCLOS defines six jurisdictional areas (Figure 7):

1. Internal waters
2. The territorial sea
3. The contiguous zone
4. The exclusive economic zone (EEZ)
5. The continental shelf
6. The high seas

Coastal states have full jurisdiction over the waters, seabed, subsoil, and airspace above the internal waters and territorial sea jurisdictional areas, while enjoying limited sovereignty over the “functional zones” (contiguous zone, EEZ, and continental shelf).



**Figure 7: Jurisdictional areas promulgated by UNCLOS (Government of Canada, 2002)**

All the coastal state jurisdictional limits discussed, except the internal waters, are delineated relative to a continental baseline. Baseline determination is outlined in Part II, Sec. 2 of the Convention, “Limits of the Territorial Sea.” In its simplest form, the baseline is defined as “the low-water line along the coast as marked on large-scale charts officially recognized by the coastal State” (Art. 5, UNCLOS). The following describe the previously defined jurisdictional areas in greater detail:

- The territorial sea has a breadth of twelve nautical miles as measured from the baseline (Art. 3, UNCLOS). Coastal States have full jurisdiction over the waters, seabed, subsoil, and airspace in and above the territorial sea (Art. 2, UNCLOS).
- The contiguous zone extends no farther than 24 nautical miles from the territorial sea baselines. It acts rather as a buffer zone, in that coastal States may, in the zone, act as necessary to prevent and

punish infringements of “customs, fiscal, immigration or sanitary laws and regulations within its territory or territorial sea (Art 33, UNCLOS).”

- The exclusive economic zone is a zone extending a maximum of 200 nautical miles from the territorial sea baseline (Art. 57, UNCLOS), in which coastal States can exercise sovereignty over the living or non-living natural resources of the seabed and subsoil, marine research, and environmental protection (Russell, 1992).
- The continental shelf is the final jurisdictional area that falls under coastal State jurisdiction. The definition of the continental shelf was initially defined under the 1958 *Geneva Convention* as either a depth of 200 m or the maximum depth at which technology could extract the resources of the shelf (Cronan, 1992; Russell, 1992). The Convention altered the definition of the shelf in Article 76 to include “the natural prolongation of its land territory to the outer edge of the continental margin.” The jurisdictional area of the continental shelf has a maximum breadth of 350 nautical miles from the territorial sea baseline, or 100 nautical miles from the 2,500 meter isobath. The convention outlines the steps necessary for a State to determine the extent of the continental margin. Coastal states may, in the continental shelf, enjoy sovereignty over sedentary species and non-living resources (Russell, 1992).
- The final jurisdictional area defined by the Convention is the high seas. The rights afforded to the international community in the high seas are beyond the scope of this research. Important to this study, however, are the seabed, subsoil, and ocean floor beyond national jurisdiction – a region called the “Area” (Art. 1, par. 1, UNCLOS). It is the resources of the Area, and the management thereof, that are defined in Part XI of the Convention.

#### 4.3.1.2 The International Seabed Authority

##### 4.3.1.2.1 Objectives of the Authority

The International Seabed Authority (ISA) is the international organization promulgated under Part XI, Sec. 4 of the Convention to oversee activities in the Area according to the Part and the *1994 Agreement* (Harrison, 2010; Lodge, 2009). The Authority has a legal mandate to ensure marine environmental protection, promote the development of seafloor resources, promote marine scientific research to be shared with the international community, and protect underwater cultural heritage in the Area (Harrison, 2010; Lodge, 2009). To effectively follow this mandate, the Authority has the power to develop regulations to supplement the Convention and the Agreement, as the Convention was not intended to provide a comprehensive mineral resource development regime (Harrison, 2010; Nandan & Lodge, 2002). Risk-assessment for commercial mining operations is essential for the Authority to fulfill its mandate. To be able to assess the risks in the most effective and responsible manner possible, the Authority is working on an expanding knowledge base on deep-sea ecology, with focus on environmental baselines, baseline variability, and impacts due to commercial activity (Lodge, 2009).

##### 4.3.1.2.2 Regulations Developed by the Authority

As mentioned previously, the Authority has the power to develop regulations that govern the activities of States' parties in the Area. While some of the regulations developed by the Authority relate specifically to the administration of the Authority (Harrison, 2010), it is more relevant to the scope of this work to examine the regulations developed to govern the activities of States' parties in the Area – namely, the exploration for, and extraction of, mineral resources.

The first set of regulations developed by the Authority is the *Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area*, adopted in 2000. It contains forty regulations divided into nine parts and detailing definitions, prospecting, plans of work application processes, exploration contracts, marine

environmental protection, confidentiality, general procedures, dispute settlement, and resources other than nodules (Harrison, 2010; Keyuan, 2003). These regulations were the first to be developed by the Authority since polymetallic nodules were the only marine resources known to exist on the deep seabed at the time the Convention was being developed. This explains the prevalence of language throughout the Convention that addresses the mining of nodule resources (Harrison, 2010). However, it is known now that there are other types of mineral resources below the waves: polymetallic sulphides (SMS) and cobalt-rich crusts. The Authority has recognized that the existing regulations would not be sufficient or completely applicable to these types of deposits and thus has exercised its ability to develop a new set that would be more appropriate to fulfill the objectives of the Convention (Harrison, 2010).

The *Regulations on Prospecting and Exploration for Polymetallic Sulphides in the Area* were adopted by the ISA Council in May, 2010 (ISA Council, 2010a), after an exhaustive consultation process which saw some changes to the existing regime relating to the size of the application area, anti-monopoly, overlapping claims, and the parallel-system of mining (Harrison, 2010; ISA Council, 2010b). These changes were made to better accommodate the obvious differences between nodule and sulphide deposits. After the adoption of the sulphide regulations, the China Ocean Mineral Resources Research and Development Association (COMRA) filed an application for approval of a plan of work for polymetallic sulphide exploration on the Southwest Indian Ocean Ridge (“COMRA Applies for Approval of Plan of Work for Exploration for Polymetallic Sulphides | International Seabed Authority,” May 25, 2010).

#### **4.3.2 National Regulation of Major Players**

##### **4.3.2.1 Papua New Guinea**

Papua New Guinea (PNG) has catapulted to the forefront of any discussion on the mining of SMS resources due to Nautilus Minerals Inc.’s Solwara 1 project in the exclusive economic zone. The country ratified the Convention in January, 1997, which allowed it to claim the resources in its EEZ as well as

participate in the dispute resolution process (Birney et al., 2006). In Papua New Guinea, the *Mining Act 1992* is the piece of legislation responsible for the extraction of natural resources within the country. However, the legislation is geared primarily to onshore activities, and the extent of its offshore applicability is the outer boundary of the territorial sea (McLeod, 1999). Recognizing the potential benefits to the country from resource extraction outside the territorial sea, the government convened a committee to develop *A Green Paper on Offshore Mining Policy* with the intention of filling the vacuum by developing a regime for the management of minerals in the EEZ. The Green paper, revised at the Offshore Mineral Policy Workshop held in Madang, Papua New Guinea in February, 1999, outlines policy related to the unique aspects of offshore mining. Included are policy recommendations for (Department of Natural Resources - Independent State of Papua New Guinea, 1999):

- Licensing, including a provision for pilot mining tests to be conducted, with approval, under the exploration license
- Fiscal regime such as royalties, taxes, and equity participation
- Environmental protection
- Benefit distribution
- Other issues including technology transfer, research, decommissioning, and dispute settlement mechanisms

#### 4.3.2.2 China

The basic mining law in China is the Mineral Resources Law of the People's Republic of China, enacted in 1986 and amended in 1996. It provides the legal framework for all mining activities in areas, marine

and terrestrial, under China's jurisdiction (Government of China, 1986; Keyuan, 2003). Article 32 of the law stipulates that “a mining enterprise or individual must observe the legal provisions on environmental protection to prevent pollution of the environment” in order to mine a mineral resource.

In addition, the Marine Environmental Protection Law of 1983 is a body of legislation designed to provide comprehensive protection of China's marine environment that was adopted after China signed the UNCLOS (Chen, n.d.). The law contains provisions addressing marine construction, pollutants from vessels, land-based pollutants, dumping, and pollution due to oil exploration or exploitation (Chen, n.d.), but does not, upon examination, directly address non-oil mineral resources.

#### 4.3.2.3 Canada

Canada ratified the Convention in November, 2003 and is in a unique position to engage in the mining of seafloor sulphide deposits. Deposits in Middle Valley, Endeavour Ridge, Juan de Fuca Ridge, and the southern Explorer Ridge lie within the exclusive economic zone off the coast of British Columbia (Scott et al., 2001; Stalport, 1992). Additionally, Canada has long established itself as a hub of mining activity, and has the governmental and research capacity to develop guidelines for seabed mining activity (Scott et al., 2001). The following subsections outline the current applicable legislation, both in federal and provincial levels.

##### 4.3.2.3.1 Federal Jurisdiction

Mineral resources in Canada are held by the Crown, but their extraction falls under the jurisdiction of the provinces. This system has led to conflict over the issue of offshore resource jurisdiction as early as 1965 when the Supreme Court was called to hear arguments over the jurisdiction of the seabed resources of the territorial sea and continental shelf (Head, 1968). The result was the *Reference Re: Offshore Mineral Rights, [1967] S.C.R. 792*, in which the Court concluded that these areas were, in fact, under the jurisdiction of the federal government. This decision was upheld in 1986 with the *Reference Re:*

*Newfoundland Continental Shelf*, [1984] 1 S.C.R. 86 (Stalport, 1992). An examination of the relevant federal legal frameworks is important, therefore, to assess the Canadian potential for SMS mining operations. These are: the *Metal Mining Liquid Effluent Regulations*, promulgated under the *Fisheries Act*; the *Canadian Environmental Assessment Act*; the *Navigable Waters Protection Act*; and the *Oceans Act*.

In addition to these Acts and their associated regulations, two Federal policies are applicable to the discussion of mineral resources: *The Mineral and Metals Policy of the Government of Canada*; and *Canada's Oceans Strategy*, a recent development in the Canadian policy realm providing the strategic framework for Canada's ocean programs strongly based on integrated management and sustainable development ideas (Government of Canada, 2002). The strategy dictates that Canada should promote the development of ocean resources. While oil is specifically mentioned in the strategy, it does not go as far as specifying seafloor minerals. There is no piece of legislation specifically geared towards seafloor mining.

#### 4.3.2.3.2 Provincial Jurisdiction

Since any potential mining targets in Canadian jurisdictional waters are off the coast of British Columbia, the provincial legislation of the province must be examined. Even though the mining operation itself would be conducted in federal waters, some infrastructure such as processing or storage facilities would likely be located under provincial jurisdiction. Regulatory conflicts are inevitable between federal and provincial levels in the offshore resource extraction context (Stalport, 1992). However, there are precedents for the resolution of these issues, as will be discussed in Section 4.3.2.3.3.

#### 4.3.2.3.3 Precedents for Cross-Jurisdictional Agreements

The federal/provincial jurisdictional issue over offshore resources came to light in practice for the first time off Canada's east coast in Newfoundland and Nova Scotia. These were resolved in the form of the

*Atlantic Accord* and the *Canada-Nova Scotia Agreement on Offshore Oil and Gas Resource Management and Revenue Sharing* respectively. In these agreements, the administration and management of offshore oil and gas was delegated to joint federal-provincial boards, while both levels of government worked to develop parallel legislation to allow the industry to comply with the regulatory requirements of both at once (Stalport, 1992). Since a mining operation has the potential to seriously affect onshore provincial interests, there is an even greater need for these joint bodies (Stalport, 1992), or, more permanently, a Canadian seabed mining legal framework.

The agreements are not, however, immune to legal challenges. Although the issue has not yet appeared, these agreements may unconstitutionally delegate federal powers to the province, and thus they may not be a final solution to the offshore jurisdictional problem (Stalport, 1992).

#### **4.4 Social Considerations**

The social pillar of sustainable mining addresses the human element of a project. It encompasses local, regional, national and international stakeholders and deals with individual and community concerns. A mining project, given legal sanction to proceed, can still face stiff opposition from these stakeholders that could potentially result in cessation of operations or other negativity including violence (MMSD, 2002). On land, many sustainability-oriented companies seek to obtain community approval for a mining project before proceeding, termed “social license,” in order to avoid the previously mentioned negative consequences (Mason, Paxton, Parr, & Boughen, 2010)<sup>1</sup>. This pillar addresses the values and concerns of many stakeholder groups, many of which include environmental and economic issues, as well as concerns surrounding the preservation of cultural integrity.

##### **4.4.1 Stakeholder Engagement**

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<sup>1</sup> This paper provides an insight into the development of seafloor aggregates off Australia, however the social concepts introduced are applicable to SMS projects

Stakeholder identification and social consideration management is essential to a successful assessment of sustainable mining. To assist with stakeholder identification and engagement, the *Community Development Toolkit* has been developed as a collaborative effort between the ICMM, the World Bank, and the Energy Sector Management Assistance Programme (ESMAP). The toolkit contains 17 tools that are “intended for use throughout the project cycle and which cover the assessment, planning, management, and evaluation phases of community development as well as stakeholder relationships” (“Community Development Toolkit,” 2005). Tool 1 provides steps for identification of stakeholders and involves three steps: (1) Brainstorm existing stakeholders; (2) ask stakeholders to suggest others; and (3) check you have included all possible stakeholders (“Community Development Toolkit,” 2005). Once a comprehensive list has been developed, Tool 10 provides a matrix for determining stakeholders’ level of interest. The matrix, shown in Table 5, is populated by considering nine questions about each stakeholder and categorizing the stakeholders into most, average, and least interest.

**Table 5: Stakeholder Analysis Matrix (reproduced from “Community Development Toolkit,” 2005)**

<b>Stakeholder Analysis Matrix</b>			
	<b>Stakeholders</b>		
<b>Questions to ask</b>	Most	Average	Least
Who will be affected by the negative impacts of the project?			
Who will benefit from the project?			
Who will be responsible for implementing measures to mitigate the negative impacts?			
Whose cooperation, expertise, or influence would be helpful to the success of the project?			
Who are the most vulnerable, least visible, and voiceless for whom special consultation efforts may have to be made?			
Who supports or opposes the changes that the project will bring?			
Whose opposition could be detrimental to the success of the project?			
Who might have resources to contribute?			
Who will make decisions?			

The results of this analysis are then fed into Tool 11, Consultation Matrix, to determine which stakeholders are engaged and which are passive, leading to an understanding of which stakeholders to approach as part of the engagement strategy and how (“Community Development Toolkit,” 2005). Some key stakeholders for any offshore mining or resource project are identified in Lola (1999). The list includes some stakeholders that would apply to terrestrial deposits but, due to the multi-use nature of an international resource such as the ocean, also includes some groups that are strikingly different from terrestrial deposits. Table 6 summarizes these stakeholder groups.

**Table 6: Seafloor mining stakeholder summary**

Stakeholders	
Seafloor and Terrestrial	Unique to Seafloor Mining
Mining company	Oceanographers and marine scientists
Governments	Shipping operators
Landowners	Industrial and traditional fishing organizations and groups
Other interest groups	International Seabed Authority
Communities	

It is evident that the impacted stakeholders for an offshore resource project extend beyond geographic, cultural, or economic proximity to the project site (as in terrestrial projects) to a much more global group of ocean users. Thus, stakeholder engagement processes must be developed that incorporate these global key players, as well as the stakeholders in the country. It does not necessarily follow that those stakeholders native to the country whose EEZ contains the target site have the highest power and interest in the project.

#### **4.4.2 Stakeholder Concerns for SMS Mining**

For the mining of seabed deposits such as SMS deposits, addressing the social pillar is essential for these new resources to be exploited in a manner consistent with sustainable mining principles. Due to legacy issues of terrestrial mining, it is imperative that the fledgling SMS industry establishes trust and collaborative relationships with stakeholders in order to be successful. While a seabed mining operation need not address many land-use issues related to terrestrial mining (Fouquet & Scott, 2009), there are issues unique to SMS mining that must be addressed. These issues primarily stem from stakeholders asserting usage rights to the offshore such as (Lola, 1999):

- Commercial fishing stakeholders who may assert a right to continue to operate in offshore areas

- Research organizations may assert a right to conduct research in an offshore area being considered for mining
- Mining companies may assert rights to explore and develop offshore resources
- Shipping organizations may assert a right to navigate certain routes
- Traditional fishermen and coastal communities may assert a right to traditional fishing areas and user rights to reefs

It can be asserted, therefore, that the primary stakeholder issue with these unique offshore mining stakeholders may be, primarily, an issue of compensation due to a mining operation's infringement on these user rights (Lola, 1999).

The following will illustrate some key concerns about seabed mining for the social pillar.

#### 4.4.2.1 Cost-benefit Distribution

The distribution of costs and benefits of a mining project is a key component of sustainable mining (MMSD, 2002b). Concerns about this aspect primarily revolve around revenue distribution and social impacts in local communities (Mason et al., 2010). The results of public consultation carried out by Nautilus Minerals, published in the Solwara 1 Environmental Impact Statement (EIS) (Coffey Natural Systems, 2008), indeed identifies the potential for the project to cause social change or generate conflict around benefit distribution; namely lack of local involvement and employment and that the benefits may not reach the most directly impacted governments and communities.

#### 4.4.2.2 Capital Substitution

Capital substitution involves the introduction of other forms of capital to replace the capital generated by the mineral resource once the deposit has been mined, thus sustaining future generations at an equal or

better quality of life (Mining, Minerals, and Sustainable Development, 2002a). This could be in the form of tourism, fishing, education, and the like to build up any of the five capital types discussed in Chapter 3. For example, revenues generated from mineral activity can be used to provide higher education opportunities, ensure the mineral activity does not interfere with traditional ocean uses such as fishing or tourism, or assist with infrastructure development. Through the consultation process, Nautilus identified the need for community health and education development and industry training programs to enhance employment capacity for Papua New Guineans.

#### 4.4.2.3 Cultural Integrity

Any mining project that wishes to abide by sustainable mining principles must avoid detrimental disturbance to local cultures and customs (Hilson & Murck, 2000). Although some culture clash is inevitable, attempts should be made by the foreign company to minimize exposure or provide cultural sensitivity training to its employees. Obviously, each mining project will have its own affected community and thus its own unique culture, so a sweeping description of cultural fears due to SMS mining is not possible. However, in the Nautilus EIS, the potential for conflicts between employees outside the immediately impacted area and the local community due to lack of cultural sensitivity was identified as a potential concern.

An additional social impact identified by Nautilus is the potential for in-migration of people to the local communities directly affected by the project seeking employment. This prompts concern regarding the additional strain on the social and economic capabilities of these communities that must be managed. This relates to the initially discussed distribution of costs and benefits. The objective is to provide benefits as much as possible to the most directly impacted people. Migrant workers could, therefore, potentially undermine that objective as they do not belong to the immediate community.

## **4.5 Environmental Impacts**

There is a large volume of literature that discusses the potential environmental impacts and benefits of SMS mining (see for example Birney et al., 2006; Fouquet & Scott, 2009; Halfar & Fujita, 2002; Herzig, 1999; Scott et al., 2001). However, as there are no SMS mining operations, past or present, these impacts and benefits are theoretical. It is recalled that the environmental pillar of sustainable mining requires responsible environmental management, adherence to standards, and minimization of waste and damage. From a corporate perspective, “a mine must minimize environmental impacts throughout its lifecycle” (Hilson & Murck, 2000). This section seeks to provide a review of the most relevant literature to identify the environmental considerations for SMS mining, as applied to sustainability principles.

Active hydrothermal vent communities contain a high density of unique animal species that are fairly recently discovered and not found anywhere else in the world (Halfar & Fujita, 2002). The zoogeographic characteristics of vent communities vary from region-to-region and site-to-site across the globe. This diversity is illustrated in Table 7.

**Table 7: Zoogeographical characteristics of hydrothermal sites (Coffey Natural Systems, 2008)**

<b>Site</b>	<b>Depth</b>	<b>Dominant Species</b>
Mid-Atlantic Ridge: TAG	3,600 m	Shrimp and anemones
Explorer Ridge	1,850 m	Tube worms, polychates, small gastropods ( <i>Lepetodrilus funcensis</i> and <i>Depressigyra globulosus</i> )
Manus Basin	2,500 m	Gastropods ( <i>Alviniconcha</i> and <i>Ipremeria</i> genera), mussels, tube worms, crabs, squat lobsters, and barnacles

In addition, these communities of animals are contained in the “world’s only fully chemosynthetic ecosystems” (Halfar & Fujita, 2002). It follows that the primary concern for environmental sustainability is the preservation of natural capital through minimization of loss of animal life and destruction of habitat perpetrated by mining operations.

In the heyday of manganese nodule mining, the TUSCH Research Association sought to determine the impacts of nodule mining on deep sea ecosystems (Thiel, 2001). Through the projects undertaken by the association, it was shown that sediments disturbed by mining could enter currents in the water column and be distributed away from the mining block, potentially covering source populations of fauna that would be used for recolonization of the impacted area (Thiel, 2001). An often-mentioned potential advantage of mining SMS deposits is the lack of a thick sediment layer on volcanically-hosted deposits that could generate such a destructive plume (Halfar & Fujita, 2002; Scott et al., 2001; Scott, 2007). Due to the mining process, a localized sediment plume is likely to exist, but it has been posited that this minimal sediment plume would not have a lasting effect on the existing biota, especially as these areas are frequently subject to suspended particulates generated by seismicity and the vent plume itself (Scott et al., 2001). This plume will likely contain high concentrations of sulphide materials which, due to their

density, are likely to redeposit themselves immediately around the site (Herzig, 1999). It has been postulated that resettlement of sediment plumes may smother some of the deep sea fauna (ISA, 2002). However, as mentioned in Section 2.2, large sulphide deposits can form under a sediment cap. Should these deposits be selected as mining targets, there is potential for a sediment plume to become suspended and transported, potentially causing environmental damage by similar mechanisms observed during the nodule experiments (ISA, 2002; Scott, 2007).

Due to the deleterious effects of hot vent fluid on equipment, the most densely populated areas would not be mined as population density of vent species has been correlated to venting activity. Mining would preferentially target less active or inactive deposits for production (Fouquet & Scott, 2009; Jankowski, 2011). Inactive deposits do not contain the unique animals observed at vent sites as these organisms depend on the hot venting fluid for sustenance therefore mining these targets may not pose the same risk to individual species as the potentially impacted fauna are background species sourced from the surrounding ocean (ISA, 2002). However, inactive sulphide deposits have not been studied in as much detail as active sites, and thus these conclusions would need to be confirmed before beginning a mining project (ISA, 2002).

The nature of the SMS mining operation, whether on less active or inactive sites, will inevitably destroy any habitat in the path of the mining vehicle (Halfar & Fujita, 2002). However, active sites have been shown to be ephemeral in nature, with colonies being destroyed by volcanic eruptions that significantly alter the habitat (ISA, 2002). The fact that active sites are subjected to such frequent disturbances has been presented as an advantage by proponents (Halfar & Fujita, 2002), and indeed evidence has shown rapid bacterial recolonization and initial fauna recolonization from larvae within one year (ISA, 2002). The ability of fauna to recover depends on the vicinity of a large population to provide larvae; should there be no such community, “only establishment of protected areas would prevent eradication” of species

(ISA, 2002). Nautilus has proposed to establish temporary reserve areas within its Solwara 1 site as well as maintain a reference site to conserve the fauna and aid in repopulation (Jankowski, 2011).

A final environmental issue to consider involves the water column above the target site, particularly at or near surface where fish, sharks, turtles, and the like make their habitat (Smith, 2010). Care must be taken not to dwell solely on the impacts of the seafloor, but to ensure the preservation of the natural capital in the entire water column. This is reflected in the most recent NI43-101 report prepared by Jankowski (2011) for Nautilus Minerals.

#### **4.6 Summary**

Sustainable mining requires careful evaluation of all the pillars of sustainable development equally. It mandates that “win-win-win” decisions be the primary objective, followed by careful evaluation of any “trade-off” decisions if necessary, all under the auspices of the relevant local, regional, national, or international laws as applicable. These decisions can be categorized together as “go” decisions, assuming any “trade-off” evaluation is determined to be acceptable; “no-go” decisions must be avoided at all costs. For a marine project to be economically sustainable, current market conditions, resource potential, and all costs must be considered (including mitigation strategies and any disaster recovery costs). The capabilities of the selected mining method and technologies will be a key driving factor in determining the economic feasibility of a SMS mining project. Project economic planning should be carried out in a manner that conservatively evaluates the resource (for example, evaluate at \$2/lb. copper instead of \$4/lb.). As illustrated in the projections (see Section 4.2.1), the prices of the primary metals in SMS deposits (Cu, Zn, Au, and Ag) may begin a decline in 2012-2013. This planning will reduce the economic sensitivity of the project to price fluctuations, and help to ensure the economic viability of the project throughout the planned life.

For a marine project to be environmentally sustainable, the primary concern should be to ensure the preservation of natural capital, even though it is accepted that some environmental damage will occur due to mining. In its *Code for Environmental Management of Marine Mining*, the International Marine Minerals Society (IMMS) advocates the use of the precautionary principle. In the *Code*, two definitions of the principle are presented on page three:

1. “The lack of conclusive evidence for a causal relationship between an activity in, or an input to, the marine environment, and the reasonable likelihood that this activity or input may seriously or irreversibly harm the marine environment, cannot be used to postpone action to avoid or minimize such potential harm. The proponent of an activity bears burden of proof that a proposed activity is not seriously or irreversibly harmful.”
2. “In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.”

The adaptation of proven technologies from other industries to SMS mining applications is one method of mitigating environmental risk and ensuring sustainability, as the failure modes of these technologies are well-known and thus potential impacts are easier to identify.

The *Code* also mentions, as one of its operating guidelines, that “biological resource potential and value of living organisms at potential marine mining sites as well as the mineral resource potential and value” be considered, thus prompting the need for three-pillar guided decision-making. When developing an environmental management strategy, there is a clear need for the establishment of biological baselines in order to determine the recolonization potential of the mine site (see ISA, (2002)).

For a marine project to be socially sustainable, the company must secure and retain a “social license to operate” by obtaining informed consent from stakeholders. This can best be achieved through proactive stakeholder engagement, taking care to involve not only the directly impacted stakeholders, but also stakeholders that are involved and interested. As mentioned previously, significant effort must be placed into the identification and engagement of the “new” deep sea mining stakeholders, avoiding merely consulting with stakeholders that would be affected by a conventional mining project. This is imperative, as it will identify the values, needs, and aspirations - essential components in developing a social management strategy. To establish and maintain trusting relationships with stakeholders, it is important that information flow transparently from the proponent to the stakeholders, including the release of non-proprietary information describing the project, socioeconomic benefits, projected mine life, and potential environmental impacts (International Marine Minerals Society, 2011). The flow of information should continue throughout the life cycle through periodic reporting. An additional method that could be used to establish a “social license” is the development of formal agreements between project proponents and stakeholders.

A sustainable SMS mining project encompasses all these pillars and should operate under any relevant laws and legislation based on the jurisdictional area of the proposed operation. There has been significant progress in the development of international regulations for the prospecting and exploration of SMS deposits (see Section 4.3.1.2.2). The autonomy given to the Authority by the Convention allows for changes to be made to the regulations as more knowledge becomes available and as technological capabilities increase. However, there are currently no regulations, draft or otherwise, issued by the Authority governing the extraction of these resources. Thus, any commercial mining of SMS deposits in the near future will likely occur in the exclusive economic zones of coastal states provided the applicable state has developed a legal regime for offshore mineral extraction. To assist with the development of such

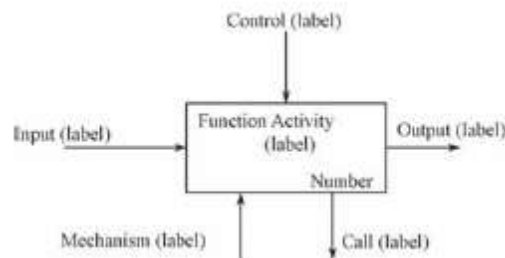
a regime, *The Madang Guidelines*, produced by the South Pacific Applied Geoscience Commission (SOPAC), is a report that provides policy guidelines for coastal states seeking to develop an effective regulatory regime pertaining to the exploration and development of offshore marine mineral resources. Project proponents seeking to operate sustainably have an obligation to ensure that their projects operate under the highest environmental and social standards, even if the applicable legislation is more relaxed. Proactivity by project proponents is an essential component of sustainable mining. Finally, it is vitally important to determine the enforcement capacity of the relevant jurisdictional area. The most robust legislation has significantly diminished utility if there is insufficient capacity to enforce it. Guideline 18 of *The Madang Guidelines* recommends that there be provisions made to “provide adequate human and fiscal resources required for...enforcement activities” (South Pacific Applied Geoscience Commission [SOPAC], 1999). Understanding that any enforcement policy will rely primarily on industry reporting, and to a lesser extent on government inspections, it goes on to recommend that the enforcement policy developed be linked with “activities mandated in the fee regulations...and the environmental policy for offshore waters” (SOPAC Secretariat, 1999).

## **Chapter 5: IDEF0-based Model for Sustainability Assessment of SMS Mining**

### **5.1 Introduction**

It is the objective of this thesis to develop a hierarchical assessment framework that can be employed to determine the sustainability potential of a SMS mining project through all phases of project evaluation studies from scoping through feasibility. Employing sustainability assessment at each phase ensures that sustainability principles are being accounted for and incorporated from the project`s conception, and therefore reduces the risk that unanticipated, potentially prohibitive costs associated with ensuring economic, environmental, and social sustainability is minimized. To be effective, the framework should

be logical, simple to employ, and allow for clear identification of “go-no go” decisions. The IDEF0 (Integration DEFinition language 0) method was selected as a base for the framework. IDEF0 is a function modeling method using a hierarchical, cross-referenced series of graphics and text that has been applied to mining applications such as equipment reliability assessment and mine design and planning (see Djan-Sampson & Daneshmend, (1998) and Morin, (2001)) . The purpose of employing the method is to “obtain understanding, support analysis, provide logic for system adjustment, specify requirements, or support systems level design and integration” (Li, 2009). The system’s fundamental components are boxes and arrows. Boxes detail function activities, and are surrounded by arrows, either entering or exiting the box, based on their type. The five types of arrows are: Inputs, parameters that are transformed or consumed by the function; controls, conditions required for the function to produce correct outputs; outputs, the data or object produced by the function; mechanisms, the means to support function execution; and call arrows, which provide linkages. These properties are shown in Figure 8.



**Figure 8: Basic IDEF0 components (Li, 2009)**

The complete decision-making framework based on IDEF0 for the function *Assess Sustainability of SMS Mining Operation* is illustrated in Figures 8-19. To facilitate the explanation of each diagram, each is immediately followed by explanatory text contained in Tables 10-19. It is important to note that, while the breaking down of functions into smaller functions denotes hierarchy, functions described on the same diagram do not denote sequence. For example, while *Technology Selection (A21)*, *Cost Estimation (A22)*,

and *Profitability Estimation* (A23) are all required in order to perform the *Assess Economic Sustainability* (A2) function, it is not required that the technology selection function be completed prior to beginning work on cost estimation or profitability estimation. It is, of course, important to recognize that estimation of costs will require the results of the technology selection function as an input.

Should a “go” *Final Sustainability Decision* be reached at the scoping study level, a recommendation to proceed to the next study can be made. This can only be accomplished after an engagement process has been completed that includes information derived from the reports generated in the other assessments. If a pre-feasibility study is to be conducted, the assessment process must be employed again, including the identification of any omitted stakeholders, and incorporate the additional level of detail required for a pre-feasibility level study. Similarly, should the project proceed to a feasibility study, one more application of the process is required with maximum possible detail. Thus, it is possible that a project that was determined “go” at scoping may result in “no go” for pre-feasibility or feasibility. The value of employing a sustainability assessment process in tandem with these studies is to identify “show stopping” issues early so they can be corrected or the project abandoned with minimal impact to the company or community.

## **5.2 The A0 Diagram**

In order to ensure that all three elements of sustainable development are assessed equally, the model is designed to be iterative. The iterations are performed after each assessment function and are designed to incorporate any additional costs encountered as a result of environmental or social assessment to be included in the economic assessment. These iterations occur for every level of study. In addition to these iterations, re-assessment within each assessment function is encouraged to attempt to make that pillar abide by the best possible sustainable mining principles before reaching the final decision.

The A0 diagram shown in Figure 11 consists of four functions:

1. Identify Jurisdiction and Engage Stakeholders
2. Assess Economic Sustainability
3. Assess Environmental Sustainability
4. Assess Social Sustainability

Function A0 has three top level constraints, one top level input, and one top level mechanism. Its final output is the *Final Sustainability Decision*.

### **5.2.1 Function Constraints**

The A0 function has three top level constraints and develops one more during subsequent functions.

#### 5.2.1.1 Geography

The *Geography* constraint includes all geographical elements of the proposed project. This includes physical proximity to coastal states, physical proximity of the resource to other resources, climate, and human geographical considerations.

#### 5.2.1.2 Technological Constraints

*Technological Constraints* describes the capabilities and limitations of the technology to be employed in the potential mining project.

#### 5.2.1.3 Market Economics

The economic feasibility of a mining project is constrained, in part, by *Market Economics*, primarily metal prices, as well as the supply-demand state of the metal of interest.

#### 5.2.1.4 Law and Regulation

Any mining operation must operate within the *Law and Regulation* of the relevant jurisdictional area. As this depends on the geographical location of the deposit, this constraint is developed in function A2 (Figure 14).

### **5.2.2 Function Input**

The top level function input is *Resource Definition*. At the scoping level, this input contains a database of all the exploration data, elements of which are illustrated in Table 8. Other inputs should be identified and included as necessary.

**Table 8: Resource definition components**

Assessment Function	
A2 – Economic	A3 – Environmental
Deposit type	Deposit type
Depth	Depth
Material properties of ore/waste	Water column data
Grade/tonnage	Flora/fauna (preliminary)
Deposit size	Other (as necessary)
Other (as necessary)	

As the project moves forward in evaluation and detail, the *Resource Definition* database should be updated with the most detailed information available for use in subsequent iterations of the process.

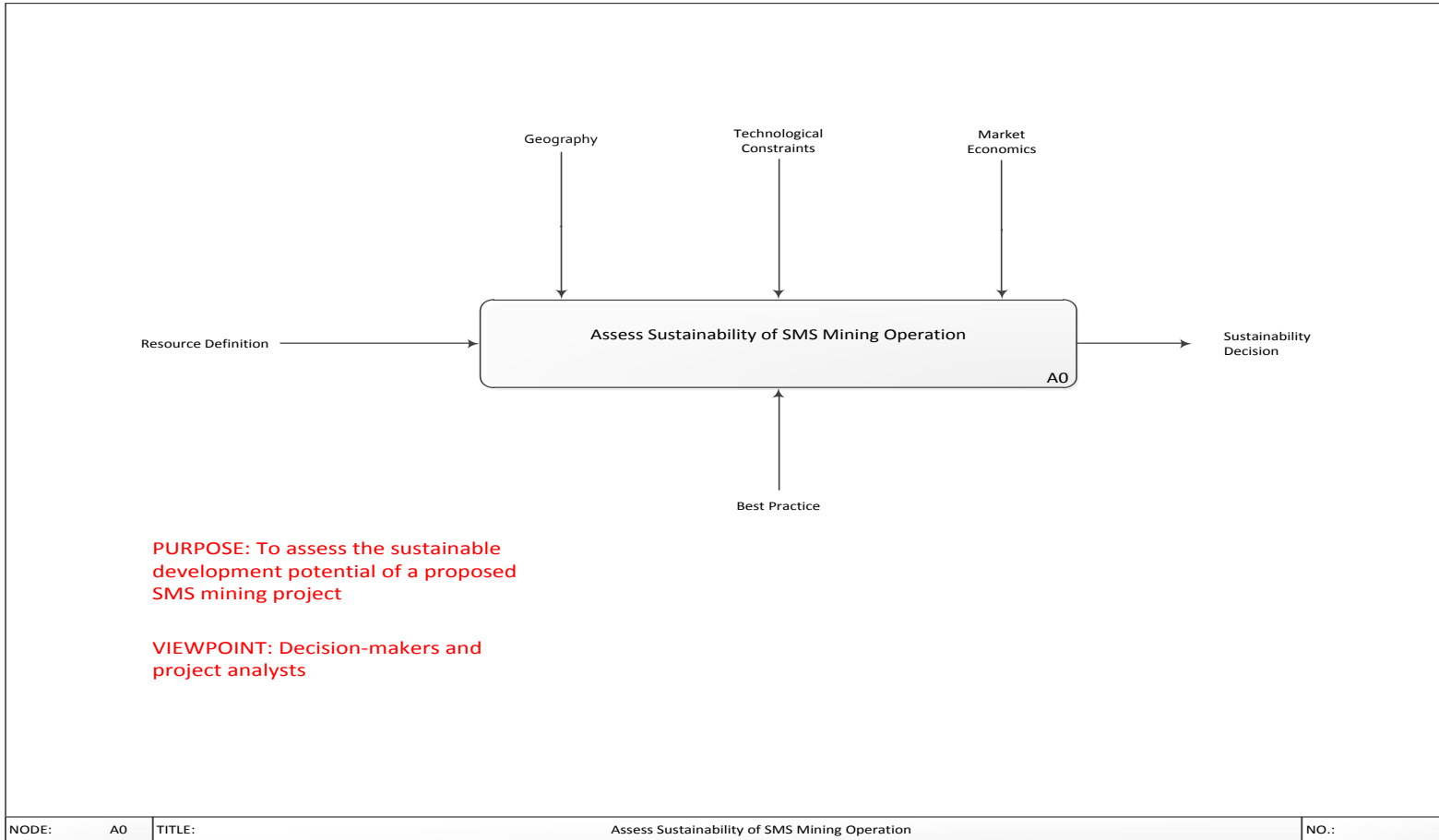
### 5.2.3 Function Mechanisms

The only mechanism employed by this function is the suite of available *Best Practice* materials. This includes not only industry best practice for sustainability assessments, but also a variety of other available tools produced by non-profit and industry groups, for example:

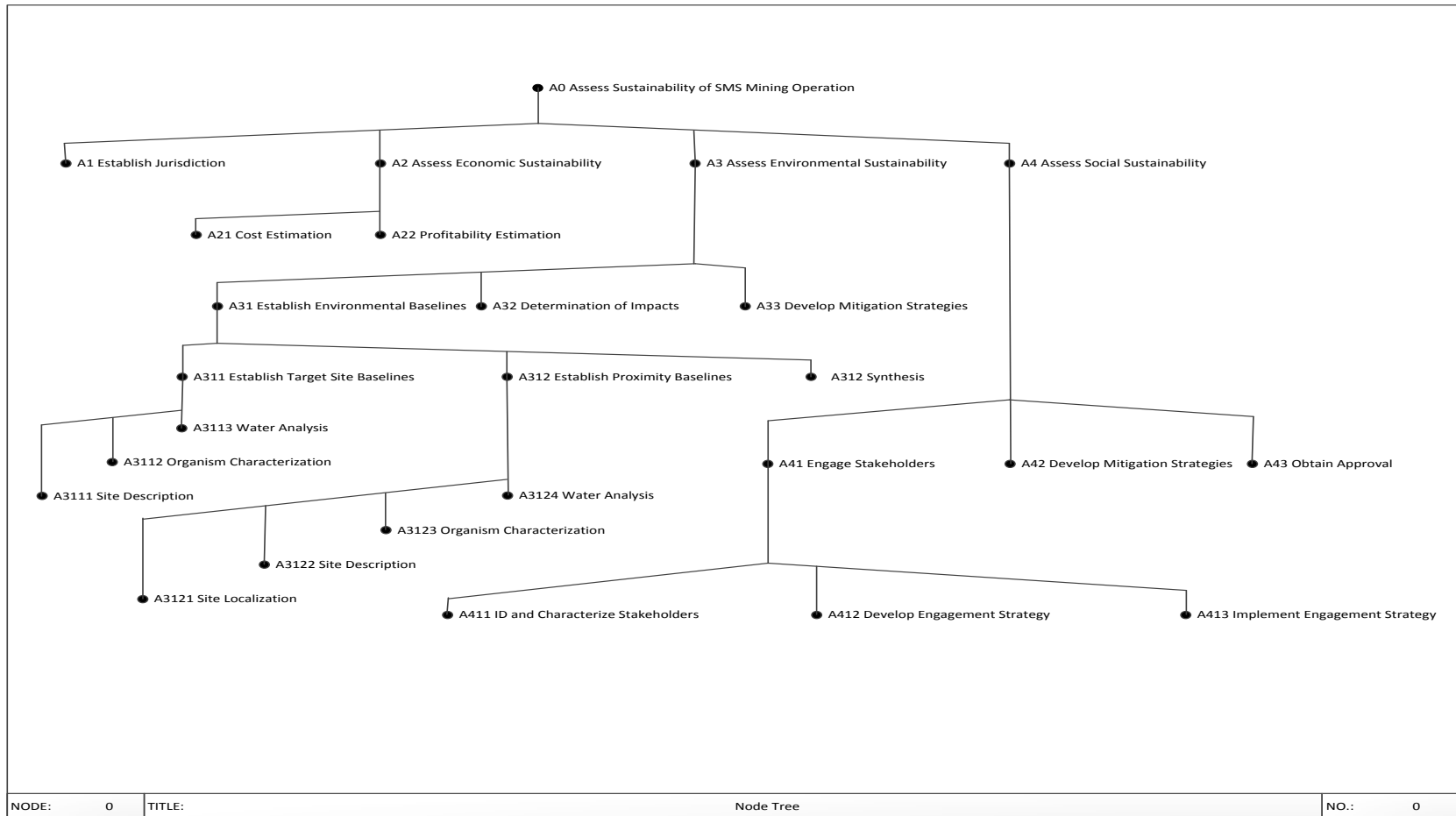
- *Seven Questions to Sustainability: How to Assess the Contribution of Mining and Minerals Activities* by MMSD
- *Mining: Partnerships for Development Toolkit* by the International Council on Mining and Metals (ICMM)
- *The Community Development Toolkit*, a joint publication by ESMAP, The World Bank Group, and ICMM

- The *Code for Environmental Management of Marine Mining* by the IMMS mentioned previously
- The *Framework for Responsible Mining: A Guide to Evolving Standards* published by the Center for Science in Public Participation

One final piece of best practice is law and regulation. Though primarily a constraint based on jurisdiction, operators seeking to contribute to sustainable mining must use the highest legislated standards, regardless of jurisdiction, as a baseline.



**Figure 9: Assess sustainability of SMS mining operation**



**Figure 10: Node tree**

**Table 9: Node index 1/2**

A0 Assess Sustainability of SMS Mining Operation	
A1 Establish Jurisdiction	
A2 Assess Economic Sustainability	
A21 Cost Estimation	
A22 Profitability Estimation	
A3 Assess Environmental Sustainability	
A31 Establish Environmental Baselines	
A311 Establish Target Site Baselines	
A3111 Site Description	
A3112 Organism Characterization	
A3113 Water Analysis	
A312 Establish Proximity Baselines	
A3121 Site Localization	
A3122 Site Description	
A3123 Organism Characterization	
A3124 Water Analysis	
A313 Synthesis	
A32 Determination of Impacts	
A33 Develop Mitigation Strategies	
A4 Assess Social Sustainability	
A41 Engage Stakeholders	
NODE:	TITLE: Node Index 1/2
NO.:	0

**Table 10: Node index 2/2**

A411 ID and Characterize Stakeholders			
A412 Develop Engagement Strategy			
A413 Implement Engagement Strategy			
A42 Develop Mitigation Strategies			
A43 Obtain Approval			
NODE:	TITLE:	Node Index 2/2	NO.: 0

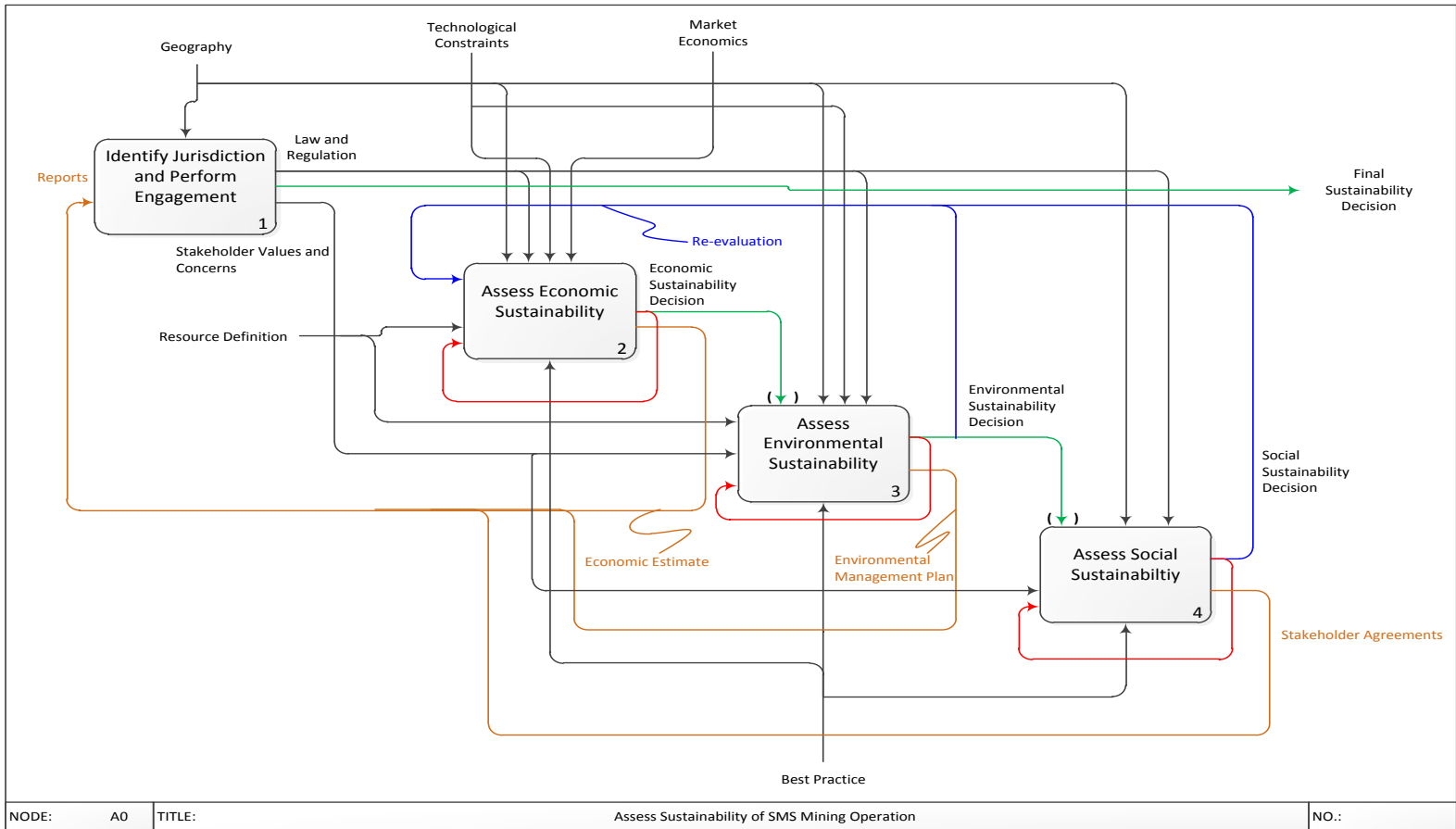
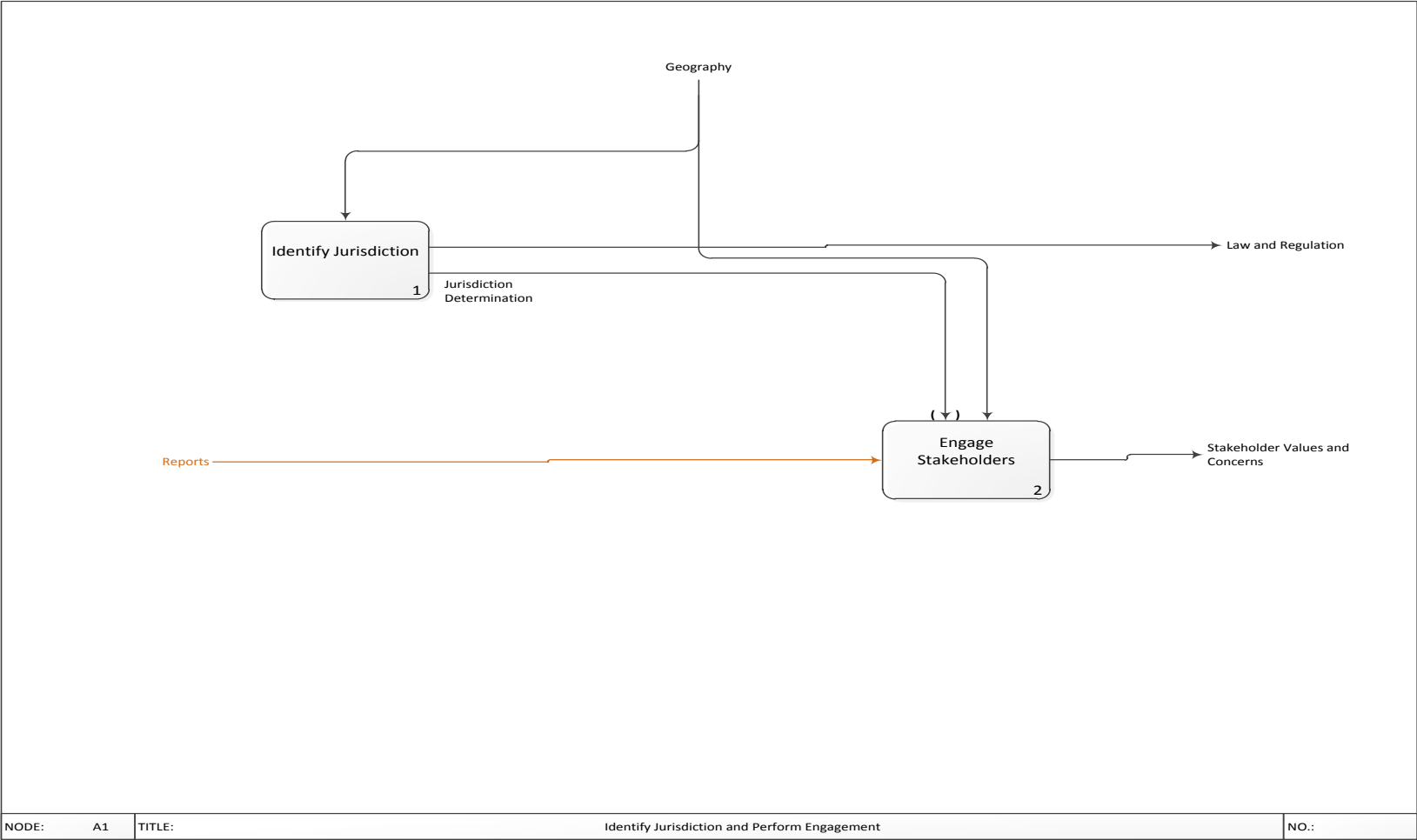


Figure 11: A0 - Assess sustainability of SMS mining operation

**Table 11: A0/T - Assess sustainability of SMS mining operation - text**

	<p>1. Constrained by geography, (1) identifies the jurisdictional area of the project and, subsequently, provides identification of the relevant regulatory entities as well as the applicable law and regulation for SMS mining in that area. Additionally, this function identifies and engages stakeholders, producing stakeholder values and concerns as an output. This ensures consultation and participation from the initial stages of the assessment process.</p> <p>2. Using aspects of resource definition and constrained by geography, law and regulation, technological constraints, and market economics, an economic sustainability assessment is performed. This results in two outputs, a “go-no go” sustainability decision and an economic estimate detailing the results. For subsequent iterations of the model, additional costs incurred are included as input (3O1 and 4O1 to 2I1). To facilitate performing this assessment, best practice sources should be consulted and employed as mechanisms. A “go” decision allows the next assessment to proceed, while “no go” requires re-assessment (2O1 to 2I3) or abandonment of the project.</p> <p>3. Constrained by the economic sustainability decision (a “go” is required), as well as geography, technological constraints, and law and regulation, the environmental sustainability of the operation is assessed using aspects of resource definition as input. This function produces an environmental sustainability decision as well as an environmental management plan. Additional costs to the operation incurred must be input into (2) for the process’ next iteration. A “go” decision allows the next iteration to proceed, while “no go” requires re-assessment (3O1 to 3I1) or abandonment of the project. As with (2), best practice sources should be consulted and employed as mechanisms. If, after re-iteration through (2) the decision remains “go,” the next phase of the sustainability assessment may proceed.</p> <p>4. A “go” decision in (3) is required before the social sustainability assessment may proceed. This function is further constrained by geography and law and regulation. The function consumes aspects of the reports generated from previous assessments (2O2; 3O2) and produces the social sustainability decision and, after the final iteration of the process, a final sustainability decision. If the sustainability decision is “no go,” the re-assessment or abandonment decision must be considered at this phase. As with (2) and (3) above, best practice sources should be consulted and employed as mechanisms.</p> <p>5. Should a “go” decision be reached for the final sustainability decision (1O2), after a final engagement process has been conducted following the final iteration, it can be recommended that the next level of project evaluation be undertaken, and the process be repeated in its entirety.</p>	
NODE: A0/T	TITLE: Assess Sustainability of SMS Mining Operation - Text	NO.:



**Figure 12: A1 - Identify jurisdiction and perform engagement**

**Table 12: A1/T - Identify jurisdiction and perform engagement - text**

<p>1. In (1), based on the geographical location, the law and regulation pertaining to the jurisdictional area of the project is determined.</p> <p>2. Function (2) involves the identification, characterization, and engagement of the stakeholders. This function is constrained by geography and jurisdictional area of the project, and consumes report data as input. The output, stakeholder values and concerns, provides essential input to the (A3) and (A4) functions.</p>		
NODE:	A1/T	TITLE: Identify Jurisdiction and Perform Engagement - Text
		NO.:

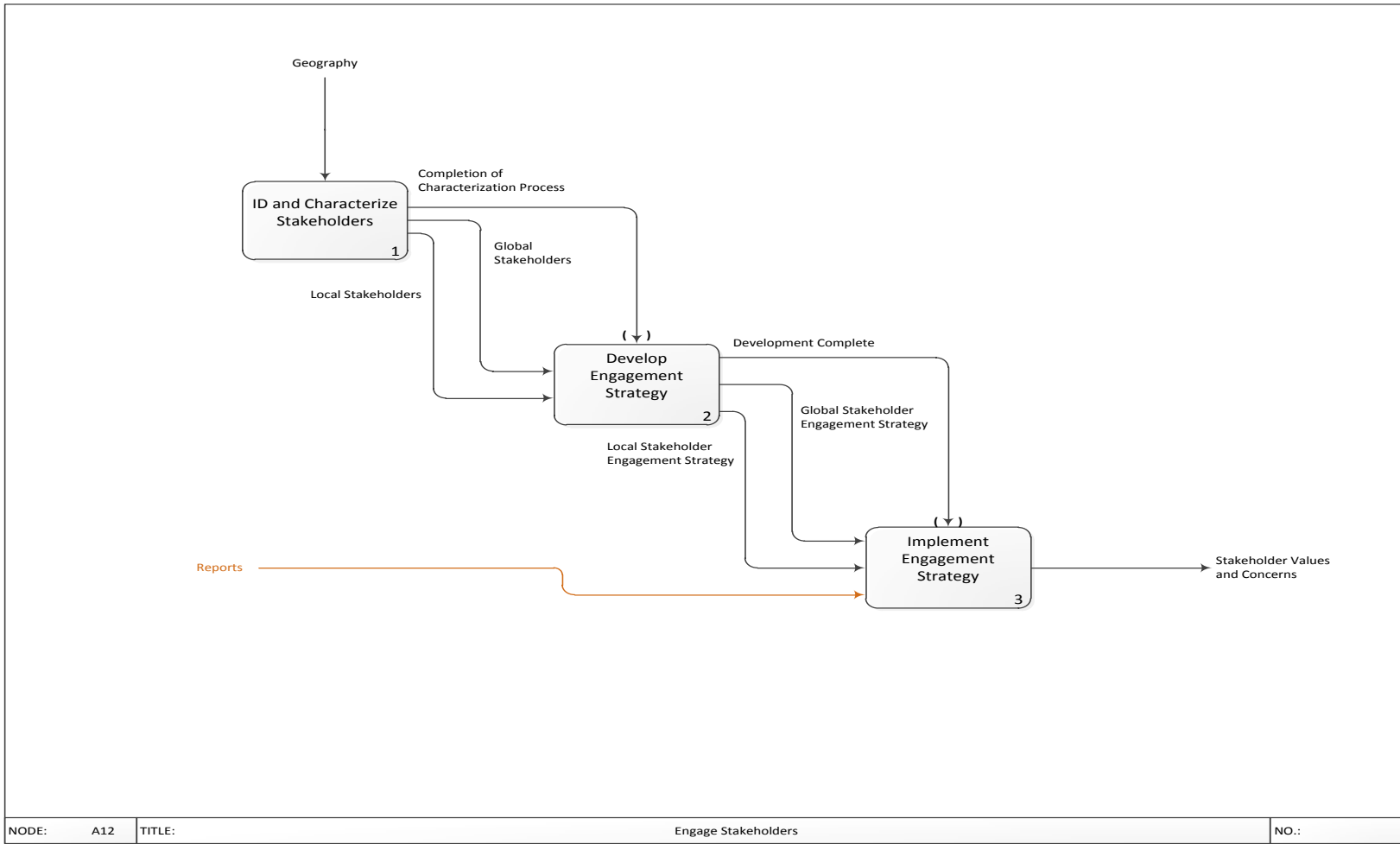


Figure 13: A12 - Engage stakeholders

**Table 13: A12/T - Engage stakeholders - text**

<p>1. In (1), the stakeholders for the project are identified and characterized, constrained by geography. This function outputs a characterization matrix of the stakeholders at the local (country/province/regional) level as well as the global level. These are separated as the engagement processes developed in (2) may have significant differences for each stakeholder category.</p> <p>2. Based on the characterization of the stakeholders, stakeholder engagement strategies are developed in (2).</p> <p>3. In (3), the engagement strategies developed in (2) are implemented. This function uses the non-proprietary information contained in the reports from (A2), (A3), and (A4) as an essential component of the engagement process – it provides the necessary background and transparency for the stakeholders. This function outputs the stakeholder values and concerns.</p>		
NODE:	A12/T	TITLE: Engage Stakeholders - Text
		NO.:

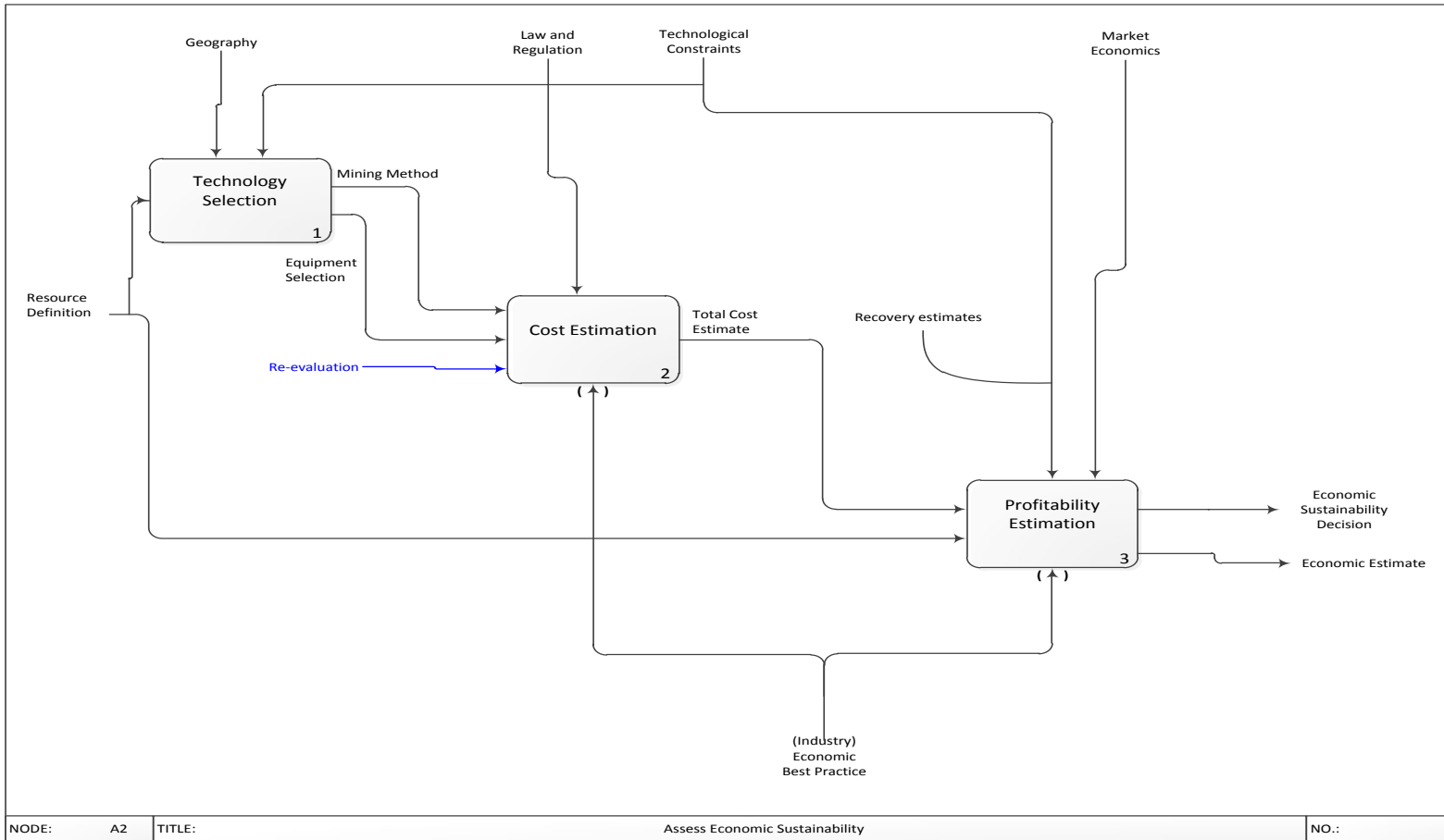
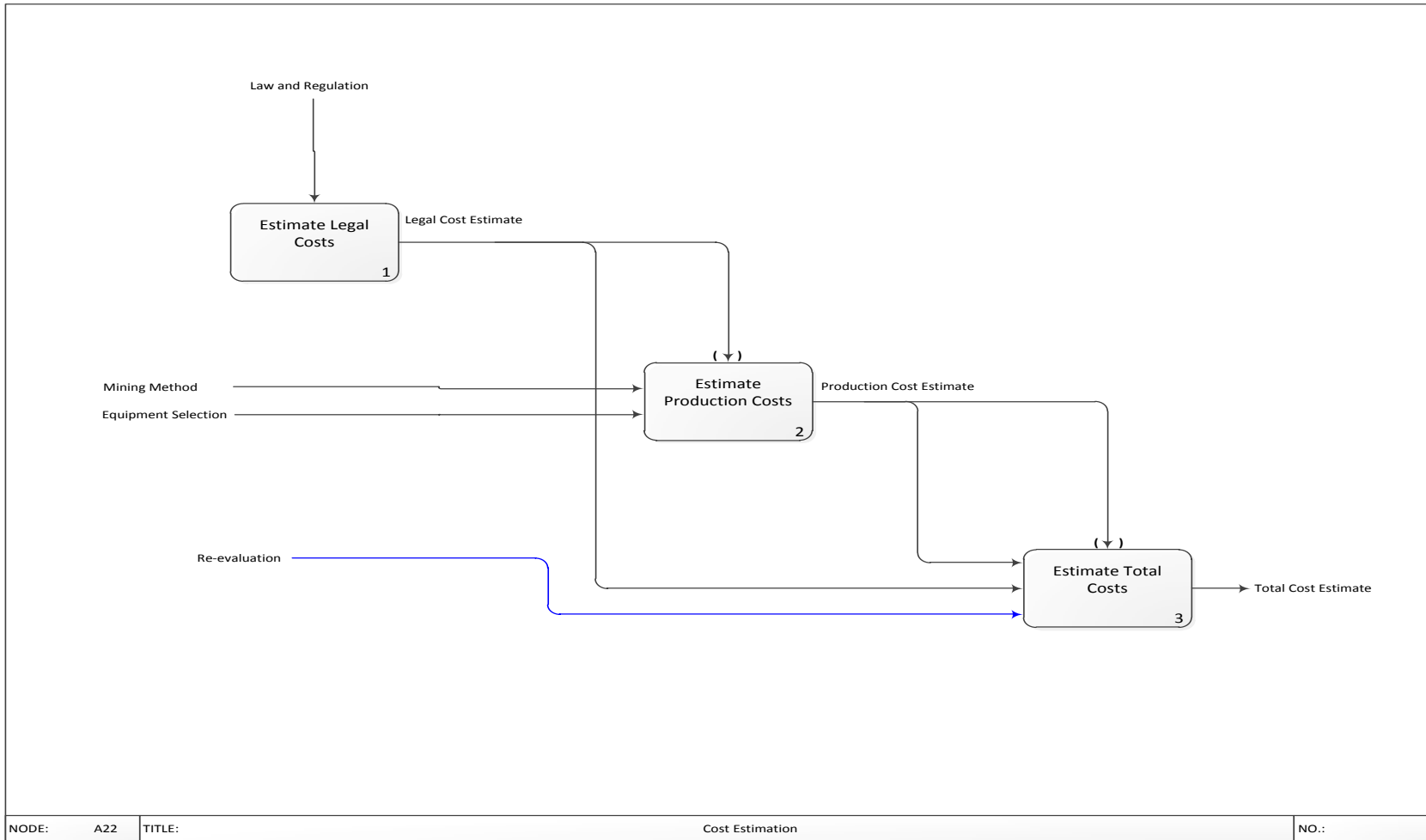


Figure 14: A2 - Assess economic sustainability

**Table 14: A2/T - Assess economic sustainability - text**

<p>1. In (1), the most appropriate technology for the project is selected. This function is constrained by geography (logistical issues due to proximity to shore and climate, for example) and the capabilities of existing technology. This function also requires aspects of the resource definition as input (for example, depth, size, material properties, and continuity of the orebody). The function produces two outputs, mining method and equipment selection.</p> <p>2. In (2), costs incurred by the operation are estimated. This function takes the mining method and equipment selection (1O1 and 1O2) as inputs, as well as any re-evaluation required based on subsequent iterations. This estimation step is constrained by law and regulation. Economic best practice from the industry can be incorporated into this function as a mechanism. The output is a total cost estimate which provides input into the subsequent profitability estimation function.</p> <p>3. Function (3) estimates the profitability of the operation. This is performed by incorporating grade and tonnage information from the resource definition, as well as the total cost estimate (1O1 to 2I1) while being constrained recovery estimates and market economic factors. This function produces the economic sustainability decision as well as an economic estimate. Economic best practice from the industry can be incorporated into this function as a mechanism.</p>		
NODE:	A2/T	TITLE: Assess Economic Sustainability - Text
		NO.:



**Figure 15: A22 - Cost estimation**

**Table 15: A22/T - Cost estimation - text**

1. Constrained by the applicable law and regulation, legal costs pertaining to the operation are estimated (1). The resulting legal cost estimate provides input into the total cost estimate function (3). Once the legal costs have been estimated, the production cost estimate function may proceed (1O1 to 2C1).
2. The production cost estimate function (2) requires mining method and equipment selection information from resource definition as input. The function results in a production cost estimate that is fed to (3) as input (2O1 to 3I1).
3. In (3), the cost estimates from (1) and (2) are synthesized together into a total cost estimate. Additional input (3I3) is determined through subsequent iterations of the decision-making process.

NODE:	A22/T	TITLE:	Cost Estimation - Text	NO.:	
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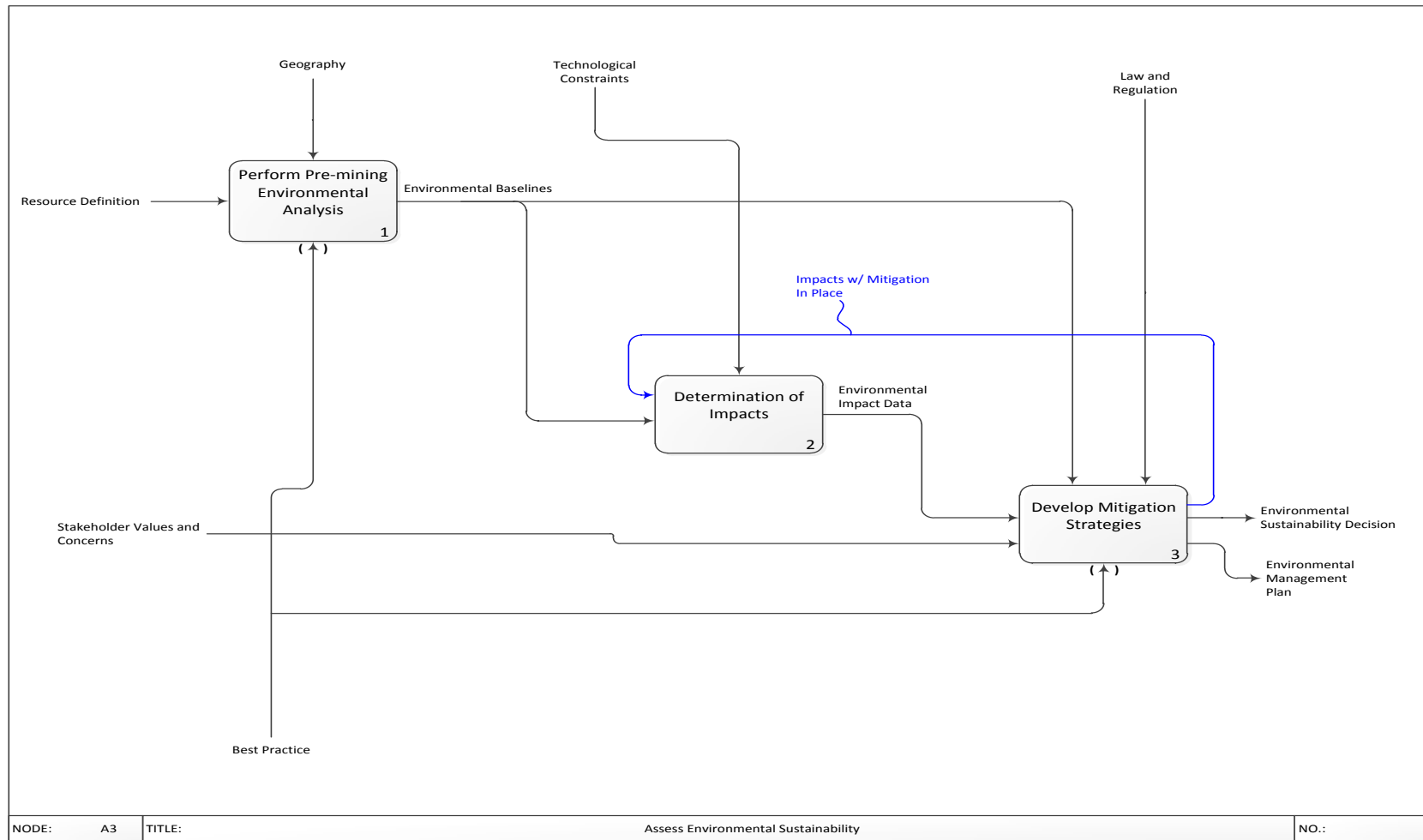


Figure 16: A3 - Assess environmental sustainability

**Table 16: A3/T - Assess environmental sustainability - text**

<p>1. In (1),the pre-mining environmental state of the target site and surrounding area is analysed in order to provide a foundation for the environmental assessment process. The function is constrained by geography and requires aspects of the resource definition as input. The function's output is a set of environmental baselines. Environmental best practice should be employed as a mechanism for this function.</p> <p>2. Function (2) determines the environmental impacts of the mining operation. The baselines determined in (1) are used as input, and the function is constrained by the capabilities of the production technology. The impact data produced provides input to (3). After the mitigation strategies in (3) are developed, (2) should be re-performed to assess the impacts on the environment of the operation with the mitigation strategies in place.</p> <p>3. Constrained by the environmental baselines (1O1 to 3C1) as well as law and regulation and taking the environmental impact data and stakeholder concerns as input, function (3) develops the strategies required to mitigate the environmental impacts. Once mitigation strategies have been developed, function (2) should be performed again to test the strategies' effectiveness. This function produces a report in the form of an environmental management plan as well as the "go-no go" environmental sustainability decision.</p>		
NODE:	A3/T	TITLE: Assess Environmental Sustainability - Text
		NO.:

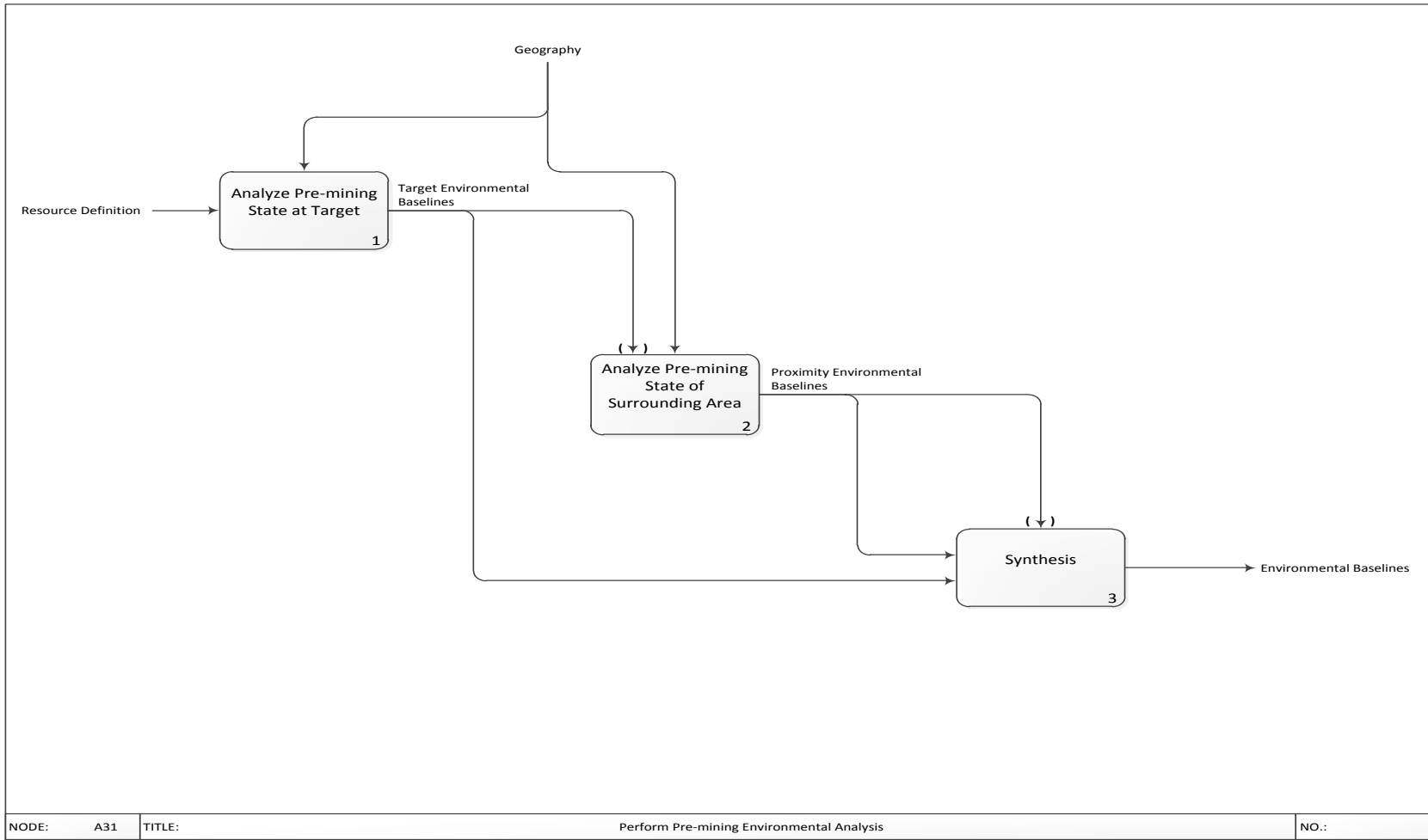


Figure 17: A31 - Perform pre-mining environmental analysis

**Table 17: A31/T - Perform pre-mining environmental analysis - text**

1. Geography and resource definition information are required for the establishment of environmental baselines at the target site.
2. Once the target site baselines have been established, environmental baselines for the surrounding area must be established. This includes the identification and analysis of any nearby deposits as well as ocean currents. This function is constrained by geography.
3. In (3) the established baselines from (1) and (2) are incorporated together, producing the final environmental baselines output.

NODE:	A31/T	TITLE:	Perform Pre-mining Environmental Analysis - Text	NO.:	
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**Table 18: A311/T - Analyze pre-mining state at target - text**

1. In (1), physical characteristics of the target site are described (for example, active/inactive, sedimented, etc.). The site description is required for function (2) to begin.
2. In (2) the organisms at the target site are identified and characterized.
3. A final step in the baseline establishment process is a water analysis. Analyses to be performed include, for example: Temperature, pH, chemical composition, and microbial populations. All three function's outputs are combined, providing the summary of target site environmental baselines.

NODE:	A311/T	TITLE:	Analyze Pre-mining State at Target - Text	NO.:	
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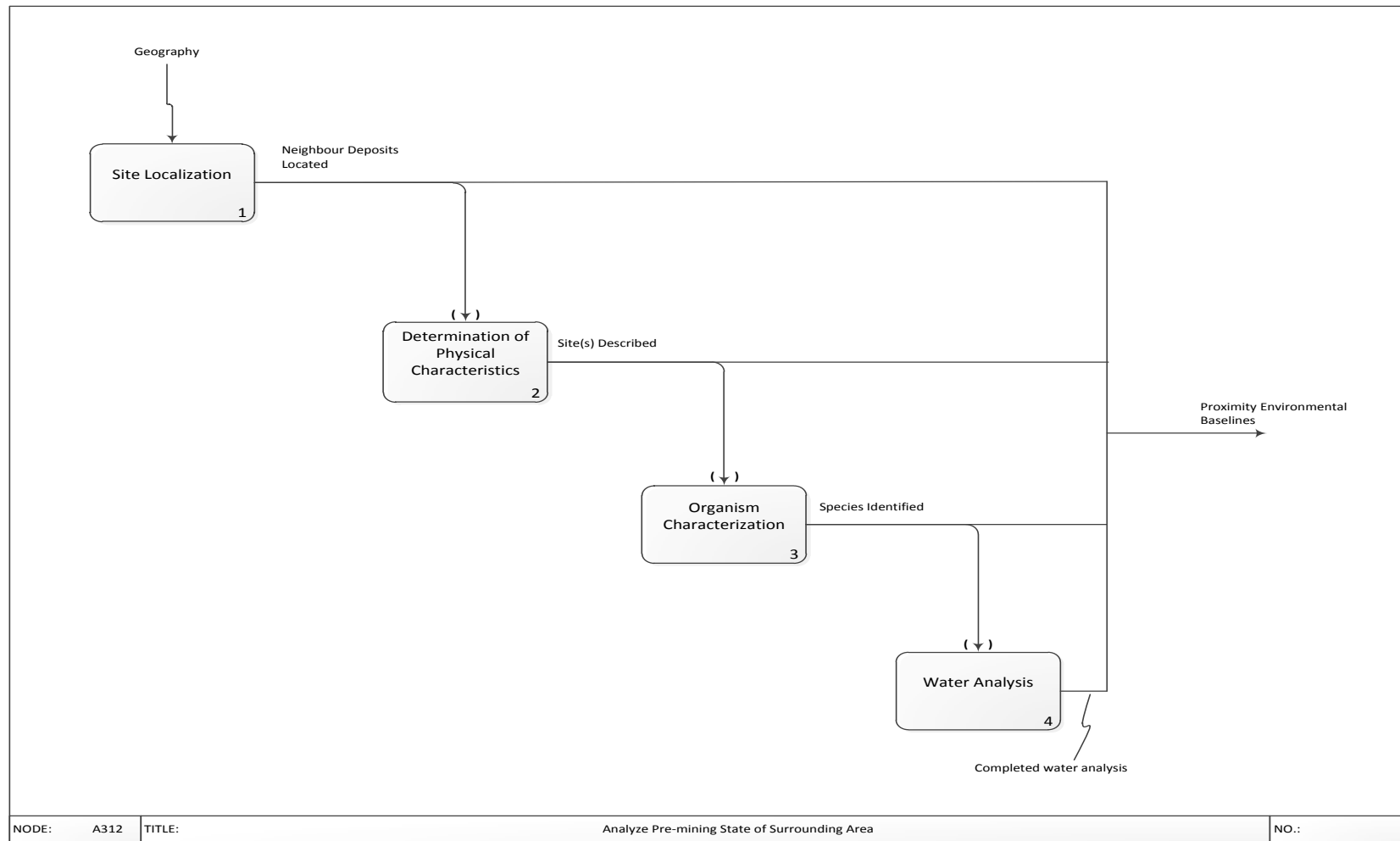


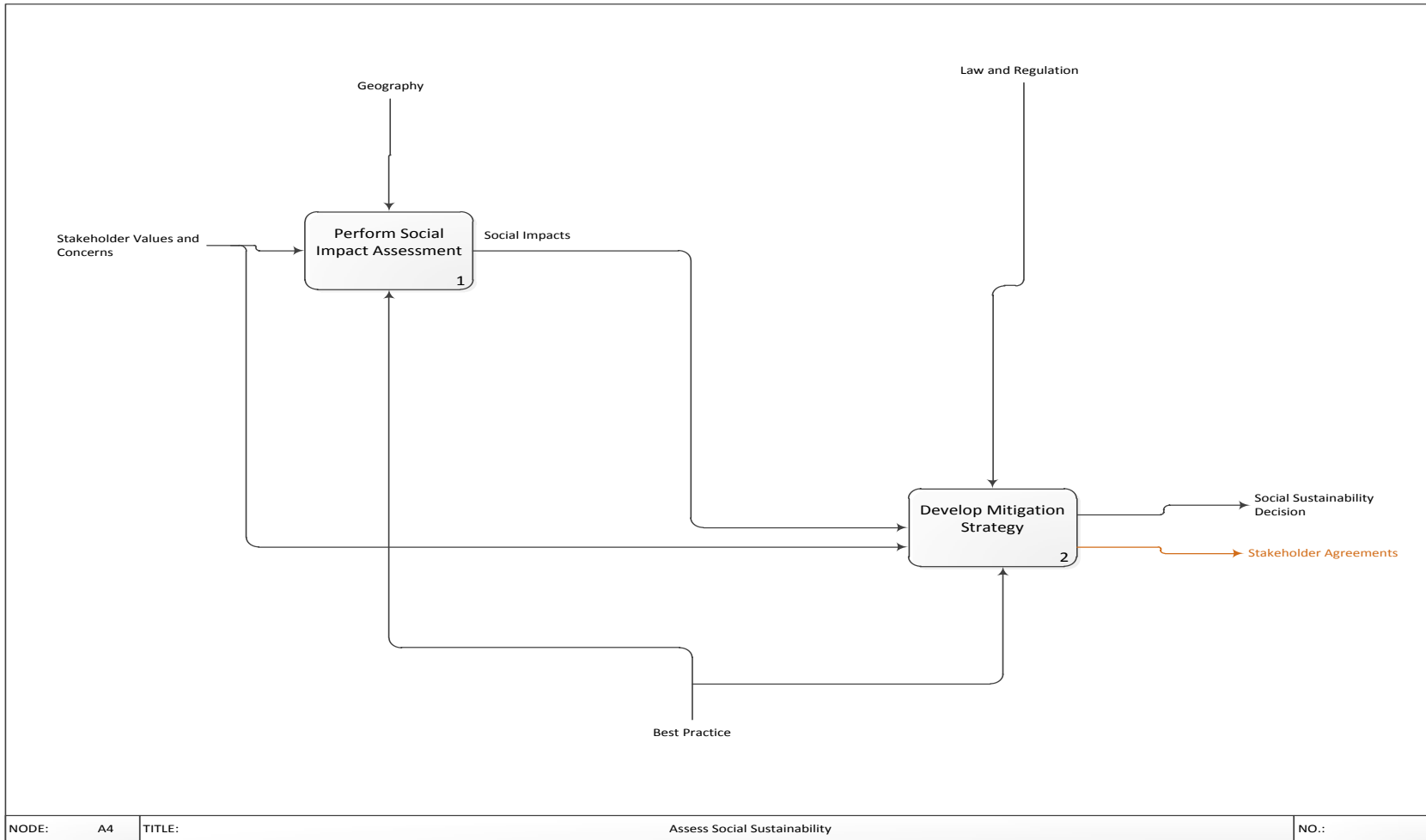
Figure 19: A312 - Analyze pre-mining state of surrounding area

**Table 19: A312/T - Analyze pre-mining state of surrounding area - text**

1. In (1), constrained by the geography, key sites proximal to the target site are located. These sites, should they exist, are to be assessed for ability to assist with mitigation efforts such as the capacity to repopulate the target site or host refugee populations.

2-4. See descriptions of functions 1-3 in diagram A311/T

NODE:	A312/T	TITLE:	Analyze Pre-mining State of Surrounding Area - Text	NO.:
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**Figure 20: A4 - Assess social sustainability**

**Table 20: A4/T - Assess social sustainability - text**

<p>1. Function (1), constrained by geography and incorporating stakeholder values and concerns, determines the potential social impacts the project may have. Best practice should be employed, where applicable, to ensure the most effective social impact assessment is conducted.</p> <p>2. In (2), considering the stakeholder values and concerns and constrained by the law and regulation of the appropriate jurisdiction, a social mitigation strategy is developed. Best practice documents should be employed as mechanisms to facilitate the development of the strategy. This project outputs a set of stakeholder agreements to present to the stakeholders for approval in (1), as well as the social sustainability decision, factors of which must be incorporated into (A2) for the final iteration.</p>			
NODE:	A4/T	TITLE:	Assess Social Sustainability - Text
			NO.:

## Chapter 6: Application of IDEF0 Methodology to Determine Sustainability

This chapter provides an overview of the thought processes required by decision makers to decide whether a proposed SMS mining project is sustainable. It illustrates the steps to be taken and notes where the IDEF0-based assessment tool presented in Chapter 5 is to be applied. Recall that the assessment tool does not produce the "go-no go" decisions, but only serves as a clear, logical guide to be employed to ensure that all aspects of sustainability are assessed equally. In the end, the sustainability decisions themselves must be made, using experience and judgment, by the person responsible for the sustainable mining of the orebody. Sections 6.1 and 6.3 are supplemented by example data from the Nautilus Solwara 1 project.

### 6.1 Initial Resource Definition

In order for a mineral occurrence to become a potential mining target, it is required that the orebody be adequately explored and defined to assess the potential economic viability of the deposit. In this phase, the geographical characteristics of the orebody are identified so as to allow for determination of jurisdiction (see Figure 7) as well as the development of a preliminary stakeholder list. This phase also allows for the introduction of basic environmental data as determined through exploration and research activities, as well as any other orebody characteristics, providing the parameters required for the *Resource Definition* input, as shown in Table 8.

**Example:** Known mineralization in the PACMANUS and SuSu Knolls (to become Solwara 1) areas off the coast of New Guinea were selected for further exploration. On February 24, 2005, a

site visit was conducted and the results compiled in a NI43-101 compliant report prepared by Darryl Clark, Paul Hodkiewicz, and Peter Williams of SRK Consulting. Academic studies indicated the potential for significant mineralization in these areas, with grades in the SuSu Knolls area of 12.8% Cu, 22.0 ppm Ag at the Suzette site and 12.3% Cu, 4.2 ppm Ag at North Su (Clark, Hodkiewicz, & Williams, 2005). Crushing and flotation tests conducted by Rio Tinto from samples obtained in 1998 indicate 90% recovery of Zn and Cu (Clark et al., 2005). At this time, no mineral resource estimates had been made, however the potential for significant mineralization led to a recommendation for further exploration.

In 2008, Ian Lipton of Golder Associates produced the first NI43-101 compliant mineral resource estimate for the Solwara 1 project. This report identifies the depth of the deposit (1550 m on average). It indicates that the deposit is a “stratabound zone of massive and semi-massive sulfide mineralization” with localized venting (Lipton, 2008). Estimates for grade and tonnage were determined for a 4% Cu cut-off grade, and indicate a total indicated resource of 870 kt with 6.8% Cu and 4.8 g/t Au, and a total inferred resource of 1,300 kt with 7.5% and 7.2 g/t copper and gold grades (Lipton, 2008). Metallurgical testing was ongoing at the time of writing of this report. As well, stakeholder engagement processes were conducted beginning in 2007, following the compilation of a comprehensive stakeholder list that included engagement strategies deemed appropriate for each stakeholder group (Coffey Natural Systems, 2008). These strategies included:

- Conversations with key individuals at all stakeholder levels
- Formal and informal presentations and briefings
- Project Awareness presentations to communities

This information, combined with information from published academic literature, would enable a decision-maker to determine the potential sustainability of the project.

## **6.2 Initial Evaluation Level**

If the deposit evaluation results from the exploration program yield a potentially viable mineral deposit, the project evaluation process may proceed. The first step in the evaluation process is a low-detail, low-cost study such as a scoping or order of magnitude study. The purpose of performing these studies, from a sustainability point of view, is to identify the biggest sustainability issues that could, potentially, prevent the project's success. Identifying these potential "deal breaker" issues early is essential, as failing to address them until more detailed studies have been undertaken could result in a "go" decision on sustainability since so much time, money, and effort have been expended on performing detailed studies. . Obviously, this decision would be contrary to sustainability principles, but could occur due to internal company pressures. It is evident that stakeholder identification and engagement is essential at these early stages. It is here, at the initial evaluation level, that the assessment process is performed for the first time. At this level, it should be recognized that there will be many unknown details, but there should be sufficient information to identify the major issues and begin considering mitigation strategies. The known mineral properties of the deposit now provide input into the scoping-level economic sustainability assessment, resulting in an initial concept of mining method and equipment with rough cost estimates. Combined with the grade and tonnage information available, a preliminary sustainability decision can be made by the decision maker.

Environmentally, the information gathered during exploration and research can be used to perform the scoping-level baseline and impact studies. The result of this work will allow conceptual mitigation strategies to be considered and costs estimated, allowing the decision

maker to decide on environmental sustainability. The cost estimates are then incorporated into the economic assessment.

The final step, after re-iteration through the economic assessment, is a scoping-level analysis of the social implications of the project. Any cost incurrences estimated due to conceptualized mitigation strategies are to be incorporated into the economic estimates for the final iteration.

This will allow the decision maker to decide on the social sustainability of the operation and, after final stakeholder consultation, decide on the final sustainability of the operation at the scoping level.

### **6.3 Detailed Project Evaluation**

Should the results of the initial, low-detail studies result in a "go" decision, then the higher costs associated with the conduction of more detailed pre-feasibility and, subsequently if recommended, feasibility studies may be incurred. For each level of study, the assessment process should be conducted, and final decisions carefully considered. It is possible that a "no go" final sustainability decision may result from a more detailed study, despite the fact that, at an earlier phase, a "go" decision was reached. Decision makers are encouraged to not force sustainability decisions at the more detailed levels, but instead should consider alternative mitigation strategies or project abandonment.

**Example:** The most recent NI43-101 report, prepared by Phil Jankowski of SRK Consulting, summarizes details from the Environmental Impact Statement (Coffey Natural Systems, 2008) as well as the Offshore Production System Definition and Cost Study (Blackburn, 2010). Elements of this report can be used to illustrate the information required for sustainability assessments at this level.

Other than the grade/tonnage and deposit type information previously discussed, additional information is provided in this report including (Jankowski, 2011):

- Climate: Mean maximum temperatures of 31°C to 33°C and mean minimum temperature of 23°C. Gale force winds are rare, and the area is not subject to cyclone activity
- Tidal and current descriptions
- The presence of subsea and surface volcanism
- The earthquake potential of both the Solwara 1 project site as well as the Port of Rabaul
- Relevant environmental and other legislation of Papua New Guinea
- Relevant international standards and conventions
- Internal corporate policies
- Voluntary codes and guidelines

This report also details the potential environmental impacts as estimated as a result of independent experts' participation in the environmental impact assessment process. The list of environmental studies conducted is comprehensive, and includes (Coffey Natural Systems, 2008; Jankowski, 2011):

- Benthic habitat assessment
- Bioluminescence

- Existing resource utilization
- Hazard and risk assessment
- Hydrodynamic modeling of dewatering process
- Hydrodynamic Modeling of the seafloor
- Macrofauna survey of active and inactive sites of Solwara 1 site as well as reference site
- Meteorology
- Oceanography
- Noise, light, vibrations
- Sedimentation rates
- Baseline water quality

Any potential impacts and their mitigation strategies must be carefully examined for cost contributions, and these costs must be incorporated into the economic sustainability analysis. A sustainability decision of “go” at this phase may result in the project being considered for an operational phase.

#### **6.4 Operation, Closure, and Post-closure**

During the operation and closure phases, constant monitoring and auditing should be performed internally and externally. This will allow for the validity of initial assumptions and the

effectiveness of mitigation strategies to be assessed and adjusted as needed. This is an essential part of any sustainability program, as encountering new issues is inevitable. A sustainable mining program must be able to adapt, update, and be accountable throughout all phases, including operation and closure.

Monitoring programs, environmental and social, are integral parts of a sustainability program. These must be developed with measureable indicators to ensure not only regulatory compliance, but compliance with sustainable mining. If, due to unforeseen circumstances or changing values, it is noticed that the programs in place to mitigate social or environmental issues are not meeting their objectives, it is incumbent on the project proponent and stakeholders to adjust the mitigation strategies in a manner that produces the desired results.

During operation, these mitigation strategies should be monitored for effectiveness in preventing unnecessary environmental or social impacts. Should an incident occur, the corrective action taken by those responsible must also be monitored to observe the environmental impact of the incident over time and observe the effectiveness of new measures to prevent similar incidents.

During closure and post-closure, a monitoring program to observe and assess the success of rehabilitation efforts must be carried out. Such a program would be in effect until it can be concluded that the environment has been successfully rehabilitated (for example, fauna populations are self-sustaining). There is no definite timeline for a closure and post-closure monitoring program, as each site is different and will recover from impact at different rates. Thus it is imperative that the monitoring program not be ignored or forgotten during this crucial recovery period.

## **Chapter 7: Conclusions and Recommendations**

The demand for metals such as copper, gold, and zinc is increasing and prices are forecasted to remain high through 2013. This demand, combined with the strong prices, will encourage the development of seafloor mineral resources, such as seafloor massive sulphides, in the near future. SMS mining has some unique advantages compared to conventional terrestrial mining, including (a) no development of permanent infrastructure such as roads, power lines, mining camps, etc.; (b) all operations are conducted from a portable research vessel, leaving no technology behind on the seafloor; and (c) low tonnages and short mine lives allow operations to be scheduled or mothballed quickly to respond to price conditions. However, mining SMS deposits contains many unique sustainability issues that are not faced by traditional mining operation, primarily in the environmental, social, and regulatory areas. As sustainability has become an essential component of business planning in the mining industry and stakeholder pressures mount for companies to operate in a more economically, environmentally, and socially responsible manner, it is essential that the unique issues related to SMS mining are considered seriously so that this new aspect of the industry is allowed to develop into a sustainable resource contributor. Continued collaboration between government, researchers, and industry groups is required to further develop a knowledge base of environmental, social, and economic impacts of SMS mining. This database will become extremely important should multiple SMS deposits be mined, as there are many questions surrounding the cumulative impacts of multiple mining operations on the environment.

A major obstacle to the sustainable mining of SMS deposits is the lack of an adequate legal regime. For a project to operate within sustainability parameters, a framework must exist that is (a) specific to the operations being proposed and (b) contains provisions for enforcement. It is

not sufficient to merely copy legislation for terrestrial mining or other offshore operations, as deep sea mining operations have unique concerns and constraints. However, these acts and regulations can form a foundation for a deep sea mining regime. To address the enforcement issue, it is recommended that any legal framework being developed include the establishment of a government office responsible for the hiring and training of deep sea mining inspectors. Any operation must have a representative from this office on board to ensure compliance.

Identifying and confronting the unique sustainability challenges would be simplified with a clear and logical framework that describes the criteria to assess “go-no go” decisions about the sustainability potential of a proposed operation. This thesis outlines a framework to facilitate the decision-making process.

The framework, and the actions required to perform its functions, are intended to be carried out in tandem with project evaluation studies from scoping to feasibility level. To do this, the framework is constructed in such a manner that allows for continuous updating and re-evaluation within study levels, as well as the incorporation of various levels of detail. In doing so, the framework’s functions do not require that all details be known at the scoping phases, but merely that an appropriate level of detail be required to perform a scoping level assessment. For example, the environmental data available at the scoping phase need not have a detailed catalogue of the organisms on site, or detailed water chemistry. It should, however, contain enough information on the potential fauna occupying the site, as well as data on bottom currents – information that would come out of an exploration program. Performing the assessments with this information may yield a “go” sustainability decision after final stakeholder engagement. However, as evaluation levels increase, so does the detail, and the results of the environmental sustainability assessment may yield a “no go” decision. Should this happen, re-evaluation of the

environmental assessment should be undertaken to attempt to move the decision to “go” before abandoning the project.

The hierarchical model presented ensures that no single sustainability pillar becomes neglected or, conversely, given more focus. This is accomplished by forcing the decision-maker to incorporate any additional costs that would be incurred implementing environmental and social impact strategies into the cost estimation function of the economic assessment immediately as they are determined. These costs may adversely affect the economic sustainability assessment, so much so that there is potential for the project to not be economically sustainable as proposed.

While each assessment function produces a sustainability decision as an output, the final sustainability decision is produced through stakeholder engagement. This is done to ensure the decision-makers gain stakeholder approval on the mitigation strategies developed internally for each applicable pillar, before deciding if the operation will contribute positively to sustainable development principles.

Only after all the internal iterations are performed as detailed in Chapter 5, and a “go” decision is produced for the final sustainability decision, can the project be elevated to the next level of study. If more detailed studies proceed, this process should be carried out again, in tandem, to ensure continued sustainability potential of the operation.

As there are no current SMS mining projects in the operational phase, the impacts and sustainability issues facing this new aspect of the mining industry are largely conceptual and have never been tackled before. It is recommended that the IDEF0 model presented in this thesis be further refined as SMS operations come online, and new production technologies are developed that make currently inaccessible deposits potential targets. International and national governments must cooperate with project proponents and stakeholders to ensure that the

sustainable mining of SMS deposits is assured, so that these mineral resources might provide essential raw materials for future generations.

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