Feasibility assessment methods for the economic extraction of seafloor massive sulphide deposits

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by

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Preface

Captain Nemo, from Jules Verne's 'Twenty thousand leagues under the sea', already said it: "In the depths of the ocean, there are mines of zinc, iron, silver and gold which would be quite easy to exploit." However, Captain Nemo didn't exploit these hidden treasures at the seafloor himself, but used the sodium chloride from the seawater to gain enough electric power for his ship the Nautilus. This example illustrates that the concept idea of mining the seafloor already existed back in 1870 when the book by Jules Verne was published. Since the 19th century, many discoveries in the deep-sea have followed. There are still many challenges that have to be faced before it will be economic feasible to exploit the deep-sea for its metals. This thesis report hopes to assist in a better understanding of the challenges in order to make deep-sea mining economic feasible for the future.

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Abstract

The potential emergence of mining seafloor massive sulphide deposits make it necessary to assess the economic feasibility of these deposits. In this thesis it is suggested that a series of calculations can be used to increase the level of confidence from a geological occurrence to an ore reserve. An analysis has been done on uncertainties that effect the economic feasibility of mining seafloor massive sulphide deposits. The uncertainties are divided in topics and analysed. These topics include geology, extraction, transportation, production, shipping, legal, commodity prices, OPEX, CAPEX, environment and discount rate. Each topic has its own uncertainties, which have been categorised into four categories from low uncertainty to extreme uncertainty. Mitigations are suggested to obtain the highest possible level of confidence. The study indicates that some of the uncertainties require more attention than others. The deep-sea mining equipment poses one of the greatest uncertainties. The analysis and evaluation of the parameters involved in the assessment of the economic feasibility have then been used to assess the Nautilus Minerals Solwara 1 project. According to the analysis the Solwara 1 project is economically feasible. From an operation perspective the Solwara 1 project is not feasible as no adequate testing of the deep-sea mining equipment has been conducted.

Abbreviations

CAPEX	capital expenditures
DSM	deep-sea mining
EEZ	exclusive economic zone
EU	European Union
IRR	internal rate of return
LME	London Metal Exchange
NPV	net present value
NSR	net smelt return
OPEX	operating expenditures
PNG	Papua New Guinea
ROV	remotely operated vehicle
SMS	seafloor massive sulphide
TRL	technology readiness level
USD	United States Dollar
VMS	volcanogenic massive sulphide

Contents

1 Introduction **1**
1.1 Thesis introduction . . . 1
1.2 Research questions, aim and hypotheses . . . 1
1.3 The deep-sea mining concept . . . 2
1.4 Economic feasibility . . . 4
1.5 Thesis outline . . . 5

2 Economic feasibility parameters **7**
2.1 Level of uncertainties . . . 7
2.2 Geological resource . . . 8
2.2.1 Seafloor massive sulphide deposits . . . 8
2.2.2 Mineral resource and mineral reserves . . . 10
2.2.3 Geometry and tonnage . . . 12
2.2.4 Deposit density . . . 14
2.2.5 Deposit location . . . 14
2.2.6 Water depth . . . 15
2.2.7 Ore conditions . . . 17
2.3 Economical exploitable . . . 18
2.3.1 Production rate and mine life . . . 18
2.3.2 Extraction method . . . 19
2.3.3 Vertical transport method . . . 19
2.3.4 Production vessel . . . 20
2.3.5 Shipping . . . 21
2.3.6 Legal regimes . . . 21
2.3.7 Stakeholders . . . 22
2.3.8 Mining impact . . . 23
2.3.9 Waste management . . . 24
2.4 Recoverable metal . . . 25
2.4.1 Metal grade . . . 25
2.5 Payable metal . . . 28
2.5.1 Commodity prices . . . 28
2.6 Net smelter return . . . 30
2.7 Operating cash flow . . . 31
2.7.1 OPEX . . . 31
2.7.2 Mineral processing parameters . . . 32
2.7.3 Seawater temperature . . . 32
2.7.4 Sea state . . . 34
2.8 Cash flow after capital . . . 34
2.9 Net cash flow . . . 35
2.10 Net present value . . . 36
2.10.1 Net present value . . . 36
2.10.2 Discount rate . . . 36

3 Economic feasibility assessment **39**
3.1 Geological resource . . . 39
3.2 Economical exploitable . . . 39
3.3 Recoverable metal . . . 39
3.4 Payable metal . . . 40
3.5 Net smelter return . . . 40
3.6 Operating cash flow . . . 40

3.7 Cash flow after capital 42
3.8 Net cash flow 43
3.9 Net present value 44
3.10 Sensitivity analysis 44

4 Economic feasibility case study **47**
4.1 Introduction 47
4.2 Geological resource 47
4.3 Economical exploitable 49
4.4 Recoverable metal 50
4.5 Payable metal 51
4.6 Net smelter return 52
4.7 Operating cash flow 53
4.8 Cash flow after capital 53
4.9 Net cash flow 54
4.10 Net present value 55
4.11 Sensitivity analysis 57

5 Discussion, conclusion and recommendation **59**
5.1 Discussion 59
5.2 Conclusion 60
5.3 Recommendation 62

A Calculations **65**
A.1 Bandwidth metal price history 65

Bibliography **67**

1

Introduction

1.1. Thesis introduction

The mining of deep-sea resources located on the seafloor have been getting considerable attention from both industry and the scientific community over the past years. Deep-sea mining has never been done yet, but there is at least one company, Nautilus Minerals, that claims to be close to starting up the first deep-sea mining project, named Solwara 1 [14]. Since deep-sea mining is a new technology, a lot of research should be done to properly investigate the economic feasibility of deep-sea mining. Many parameters are involved with the assessment on the economic feasibility of deep-sea mining. This thesis aims to get obtain insight in how to assess the economic feasibility on seafloor massive sulphide deposits.

1.2. Research questions, aim and hypotheses

As described in the introduction, a thorough research is required on the assessment of the economic feasibility of the exploitation of seafloor massive sulphides. Without this investigation, there is no say in how economically valuable a deposit is and if it is profitable to invest in deep-sea mining projects on seafloor massive sulphide deposits. Therefore, the main research question for this study is defined as:

- How can a seafloor massive sulphide deposit be assessed on its economic feasibility?

To gain deeper insight into the economic feasibility of a seafloor massive sulphide, the uncertainties are of importance. The following secondary research questions are defined:

- What uncertainties are involved in the economic assessment of a seafloor massive sulphide deposit?
- What additional information or what areas of future research and development are needed to reduce these uncertainties?

The aim of this study is to gain a deeper insight in all the aspects that are involved in the economic feasibility of exploiting seafloor massive sulphide deposits. In order to answer the research questions stated above, the following objectives are described below supporting the aim of this study:

- A description of all parameters involved in the economic assessment of a seafloor massive sulphide deposit.
- An uncertainty analyses on the parameters that are involved in the economic assessment of a seafloor massive sulphide deposit.
- Mitigation on the uncertainties to increase the level of confidence of a seafloor massive sulphide deposit.
- An economic value calculation with an increasing level of confidence of a seafloor massive sulphide deposit.

1.3. The deep-sea mining concept

In deep-sea mining a distinction is made between three types of metalliferous ore deposits: seafloor massive sulphide deposits, manganese crusts and polymetallic nodules. Seafloor massive sulphide deposits are mainly located at volcanic active areas. Depending on the location of these seafloor massive sulphide deposits, the deposits can differ in their metallic composition. Manganese crusts are found throughout the global oceans on the flanks and summits of seamounts and ridges and are mainly of interest because of their high grade and thus economic potential of cobalt. Polymetallic nodules are balls of ore of golf to bowling ball size and consist primarily of manganese. In this thesis, only seafloor massive sulphide deposits are within the scope of this thesis because of their expected economic feasibility.

Deep-sea mining of seafloor massive sulphide deposits has never been done yet. Therefore, there are a lot of unknowns in mine planning and equipment selection. In order to be able to assess the economic feasibility of exploitation of seafloor massive sulphides, the concept of Nautilus Minerals Project Solwara 1 is used. Where possible, more general applications and calculations are used, for example the water depth or the tonnage of seafloor massive sulphide deposits.

Nautilus Minerals, a Canadian company with offices in Australia, Papua New Guinea, Tonga and Fiji, is leading the world in the quest to develop seafloor mineral deposits. Nautilus was granted the first mining lease in January 2011 for such deposits at the prospect known as Solwara 1. The environmental permit for Solwara 1 was awarded in December 2009. Nautilus developed a production system using existing technologies adapted from the offshore oil and gas industry, dredging and mining industries to enable the extraction of these high grade seafloor massive sulphide systems on a commercial scale [14].

The concept of Nautilus is to use seafloor mining tools to excavate the material from the seafloor in benches. The excavated material will be pumped as a slurry to the production support vessel via a riser and lift system. The mined product will be dewatered at the surface and then transferred to cargo barges for transportation to shore for stockpiling. The ore will subsequently be loaded into bulk carriers for transportation to a mineral concentrator for processing and delivery to the customer concentrate smelter market [14]. A diagrammatic representation of the production process flow and associated process flow diagram are presented in Figure 1.1.

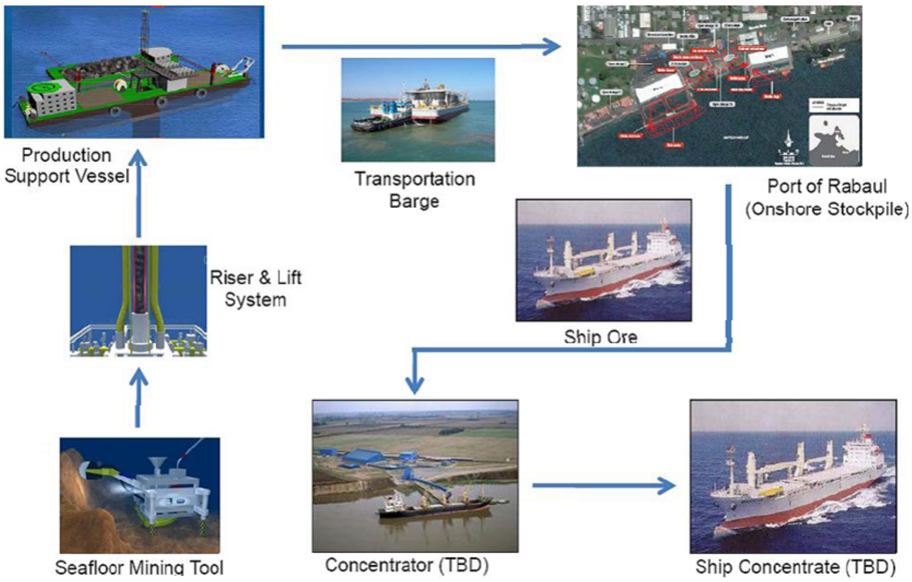

Figure 1.1: Seafloor mining system process flow [14].

Nautilus pursues a seafloor mining configuration that utilises three distinct machine designs. The drivers for this are similar to equipment optimisation on land based mining projects where the machine flexibility required to establish and 'clean' benches is in conflict with the optimisation required to maximise machine productivity. The current approach for the seafloor mining system is analogous to many surface mining systems, where it is common for a more flexible and mobile machine to prepare the site which is usually followed by a separate, dedicated high production system. Surface ore collection can be either integrated or laid in wind-rows behind the production machine for another collection system to follow behind. Because of the topography of the mine site with its relatively steep slopes and the numerous chimneys that cover the mine sites, three different subsea mining machines, namely the auxiliary miner, the bulk miner and the gathering machine will be utilised to extract the ore from the seafloor. Each of the machines is configured differently and performs different mining tasks [14].

The mine plan Nautilus has developed maximises the net present value from the Solwara 1 deposit. Mining will follow a standard open mining approach with machines designed for each of the main functions:

- Site establishment
- Cut
- Gather and transport
- Clean-up

Fragmentation of the ore will be by mechanical cutting using drum and pick technology developed for the mining and dredging industry. The mining equipment will use tracks as the main mode of locomotion over the seafloor and mining benches. Site establishment work requires spud stabilisation. Gathering of the cut ore is achieved by using mechanical gathering to a suction mouth. The ore is then pumped to the subsea lift pump [14].

The equipment from Nautilus Minerals, used in this thesis, have not completed any performance tests. Therefore, the equipment used for the extraction on the seafloor scores a 3 out of 9 on the technological readiness level in the Ecorys report [25] about the technology analysis of deep-sea mining (DSM). This score means that the equipment is on an experimental proof of concept level, imposing some additional level of uncertainties. Although the equipment is at this level, a level where there are additional uncertainties, it will be used in this thesis for the extraction of ore from seafloor massive sulphide (SMS) deposits. Technology readiness levels [TRLs] are a type of measurement system used to assess the maturity level of a particular technology [41]. Each technology level of a particular project is evaluated against parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest, see Figure 1.2.

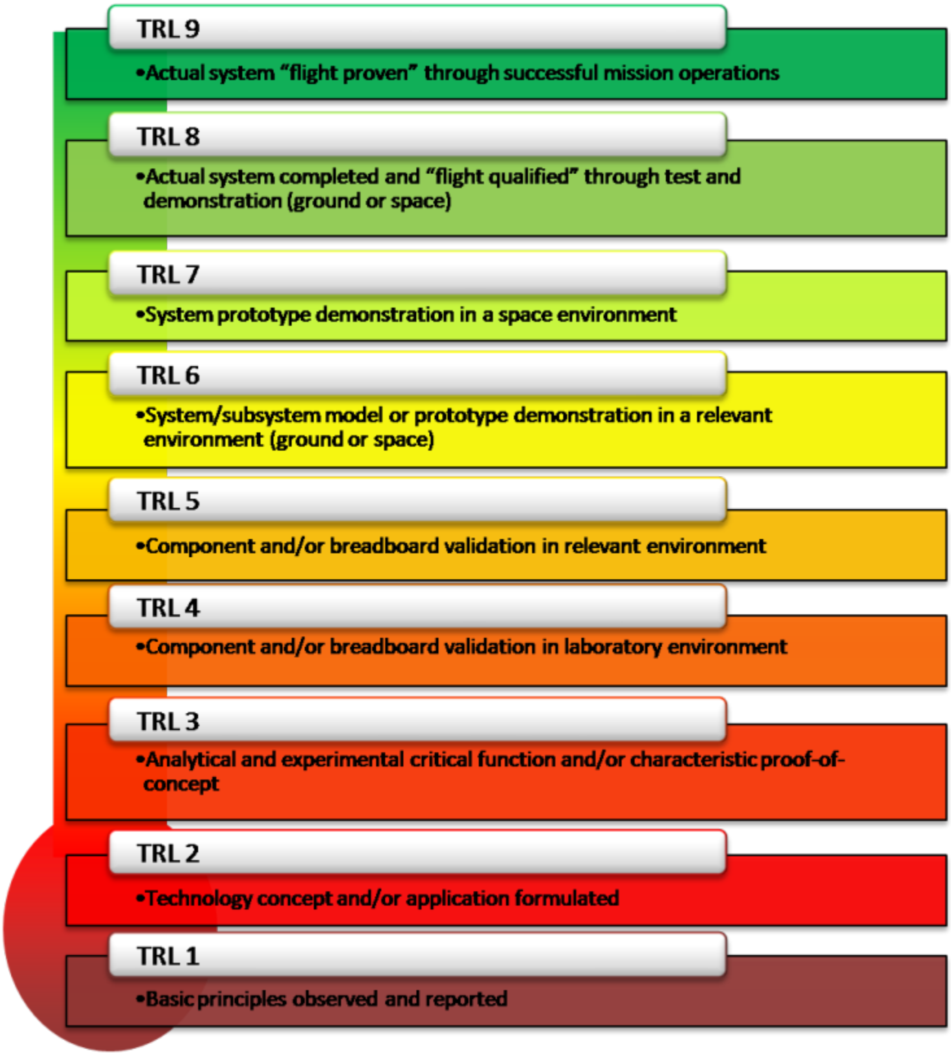

Figure 1.2: Technology readiness levels [41].

1.4. Economic feasibility

The economic feasibility can be assessed by a series of calculations that increase the confidence level. Each step in this series increases the level of confidence, see Figure 1.3.

Ten levels of confidence are defined. The lowest level of confidence is the geological occurrence, where little information is known about the deposit. The revenue is high, as relative small expenses have been made. By increasing the expenses, and thus lowering the revenue, the level of confidence is increased. Each level in the level of confidence scale involves expenses. The expenses are required to gather more information. A level higher than the geological occurrence is the geological resource. To get to this level, geological information is required. Parameters involved in this level of confidence have both geological as geographical properties. Economical exploitable is the next level of confidence. Here, information on the life of mine and production rate are required. The fourth level is recoverable metal. Important information for this level of confidence is the metal grade of the ore body. Extra expenses to gather information on commodity prices can lead to a higher level of confidence, payable metal. To get to the net smelter return level of confidence, expenses should be made to gather information on smelting fees, penalties, refining charges, freight charges and insurance costs. The net smelter return is also a measure of value of ore. The next level of confidence is operating cash flow. Parameters of this level of confidence are the operational expenses and all parameters that are involved or influence the operational expenses. The eighth level of confidence involves all capital expenses, cash flow after capital. With the cash flow after capital and the taxes and interest, the net

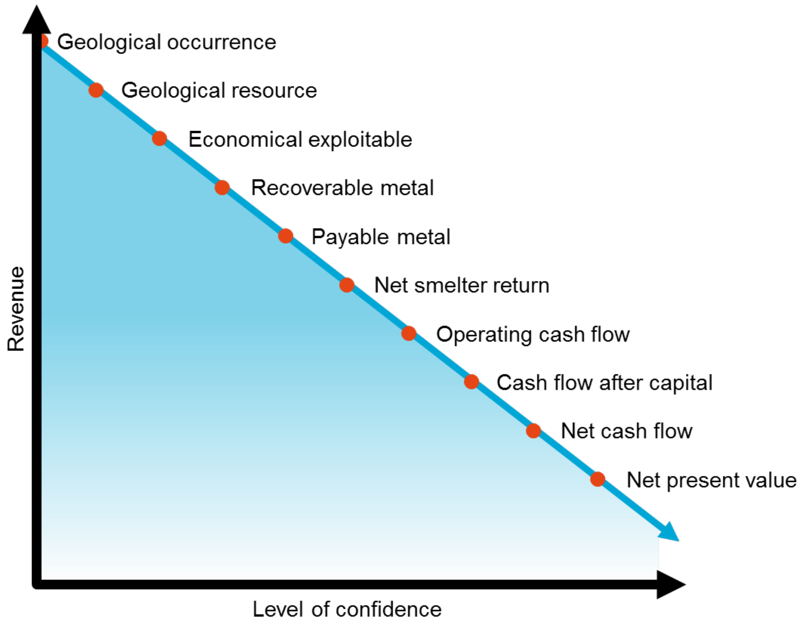

Figure 1.3: Increasing level of confidence for a geological occurrence to a net present value of a seafloor massive sulphide deposit. With an increasing level of confidence comes greater expenses and thus a lower revenue.

present value can be obtained. The highest level of confidence is the net present value that involves the time value of money with a certain discount rate.

All these levels in the level of confidence scale have parameters involved in determining their level. When a geological occurrence is discovered, not all other parameters are known. First estimates can be made on the assessment of the economic feasibility of exploitation of seafloor massive sulphides.

1.5. Thesis outline

The thesis can be divided into four parts, see Figure 1.4. The first part, the economic feasibility parameters, explains the level of confidence and describes the parameters involved in deep-sea mining and analysis them raking them with a level of uncertainty. The second part, the economic feasibility assessment, evaluates the impact of the parameters described in the first part using calculations. The project of Nautilus Minerals is used as a case study in the third part, to apply the analysis and economic impact assessment from part one and two. The thesis closes with a discussion, conclusion and recommendation on the findings of the thesis.

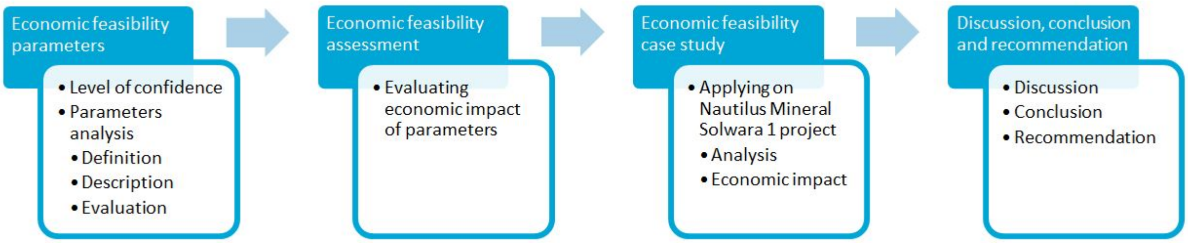

Figure 1.4: Overview of the thesis outline.

2

Economic feasibility parameters

2.1. Level of uncertainties

The parameters that are involved with the economic assessment pose uncertainties. For some parameters, there can be multiple uncertainties involved or uncertainties that are intertwined with other parameters.

When a geological occurrence is discovered, all uncertainties are present to their fullest extent. In order to get the assessment to a higher level of confidence, the uncertainties have to be mitigated or terminated. Mitigation or termination of an uncertainty costs money as it involves obtaining information and/or research and development. There will be an economic trade-off for mitigation and termination of uncertainties. With a mitigation, there is always a level of uncertainty present, despite being smaller before the mitigation. After termination of an uncertainty, the uncertainty is no longer threatening the project. As an example, drilling will give a more certain overview of the outcrop of an SMS deposit, but it will be an expensive undertaking.

Quantifying the uncertainties would be ideal. However, due to the amount of uncertainties and new terrain of deep-sea mining, an extensive amount of assumptions on the uncertainties would be required, making the reliability of the quantifications not useful for an economic assessment of a seafloor massive sulphide deposit. Therefore, all uncertainties will be classified using impact and likelihood, see Table 2.1. An uncertainty is first analysed on its impact: extensive, severe, moderate, minor. The impact can vary for all the parameters. The impact on uncertainties involved with metal grade, differ from those involved in legal regimes. Therefore, a substantiated guess on the impact is presented with a justification of the analysis. After the impact, an uncertainty is analysed on its likelihood, the state or fact of something's being likely. There are four classes: remote, unlikely, likely and frequent. As for impact, the likelihood can vary for all uncertainties and a substantiated guess on the likelihood is presented. The impact and likelihood give a classification for the uncertainty, *'A1'* to *'D4'*, see Table 2.1. This classification can determine if mitigation is required to continue the project or that the project should be abandoned. Each classification has its own colour, illustrating the uncertainty:

- Green, low uncertainty. Acceptable level of uncertainty. Further analyses or mitigation not required.
- Yellow, medium uncertainty. Represent a manageable level of uncertainty. Mitigation measures required.
- Orange, high uncertainty. Extensive uncertainty mitigations must be immediately implemented.
- Red, extreme uncertainty. Stop activities unless mitigations have been implemented and the uncertainty is reduced to a lower level.

A first classification of the level of uncertainty is needed to determine if mitigation is required, as stated above. The project can only continue if all uncertainties have a low level of uncertainty. It this thesis, some mitigations have, even after mitigation measurements, not a low level of uncertainty. For these uncertainties are extra mitigation measurements required.

Table 2.1: Uncertainty classification using impact and likelihood, with colour indication.

	Likelihood			
Impact	**Remote**	**Unlikely**	**Likely**	**Frequent**
Extensive	**A4**	**B4**	**C4**	**D4**
Severe	**A3**	**B3**	**C3**	**D3**
Moderate	**A2**	**B2**	**C2**	**D2**
Minor	**A1**	**B1**	**C1**	**D1**

Now that each uncertainty has its own classification, it should be determined if an uncertainty is added or multiplied. Depending on the uncertainty level, either one can contribute a greater uncertainty to the project. The adding and multiplication also refers to the impact on the calculations that are done when assessing the economic feasibility of a seafloor massive sulphide deposit.

2.2. Geological resource

2.2.1. Seafloor massive sulphide deposits

Another name for SMS deposit is polymetallic sulphide deposit. The main ore forming group of minerals in as this deposit is the sulphide group, hence the name sulphide deposit [47]. SMS deposits form through hydrothermal circulation, see Figure 2.1. Hydrothermal circulation requires three components: a heat source, a permeable medium and a fluid.

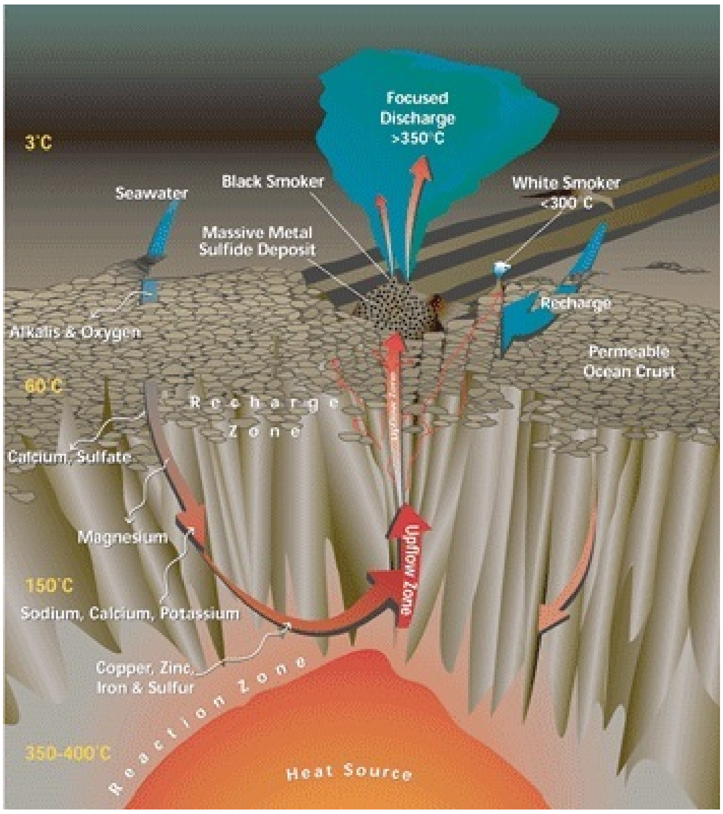

Figure 2.1: Hydrothermal activity with the hydrothermal circulation components: a heat source, a permeable medium and a fluid [35].

The circulation starts with the intrusion of a heat source into an oceanic crust or subsea continental crust. The heat source causes a deep convective circulation of seawater around the heat source [35]. The radius of a circulation is more or less five kilometre. The temperature of fluids that discharge on the seafloor increases with time from the ambient temperature to a maximum of around the 350°C and then decreases gradually to the ambient temperatures in a time scale of 100 to 10,000 years [47]. The majority of sulphide and sulphate mineralization occurs during the so called waxing stage of hydrothermal activity. Reaction between relative low temperature, temperatures lower than 150°C, host rock with downward percolating seawater cause to precipitate seawater SO_4^{2-} as disseminated gypsum and anhydrite in the host rock. Reactions of the precipitate seawater with higher-temperature rock at depths during the waxing stage cause the transformation of this seawater to metal- and H_2S-rich ore-forming fluids. These metals and sulphide sulphur are leached from the host rock. The previously formed gypsum and anhydrite are reduced by Fe^{2+}-bearing minerals and organic matter, providing additional H_2S. Reactions between ore-forming fluids and cooler rock in the discharge zone cause alternation of rock and precipitation of some ore minerals in the stockwork ores. Mixing of the ore-forming fluids with local seawater within unconsolidated sediments and/or on the seafloor causes precipitation of primitive ores with the black ore mineralogy, sphalerite, galena, pyrite, barite and anhydrite[35]. These black vents are called black smokers [51]. Reactions between these primitive ores with later and hotter hydrothermal fluids cause transformation of primitive ores to mature ores that are enriched in chalcopyrite and pyrite [35]. The majority of massive sulphide accumulation occurs during the mature stages of the system, as the higher temperatures can leach more metals from the host-rock. Young or immature hydrothermal vent systems contain white smoker [32].

At hydrothermal sites where the fluids are expelled trough vents where they are mixed with seawater to precipitate, the main proportion of the sulphide deposit consists of a lens of massive sulphides. This lens can form a small hill on the seafloor and is called a mound, which mainly consists, as the name implies, of sulphide minerals. Chimney structures that vent clouds of precipitated particles grow on these mounds. Two types of chimneys can be distinguished based upon the colour of their smoke: white smokers and black smokers, spoken of earlier. These chimneys grow as a result of minerals which precipitate as a result of the mixing of hydrothermal fluid and seawater. These chimneys tend to collapse when they become inactive and the debris of the collapsing chimneys forms a talus around the hydrothermal field. Underneath the sulphide lens a stockwork zone may develop. Stockwork is a term used to describe the geometry of multiple cross-cutting veins with blocks of host-rock in between. This zone is sometimes called the sulphide stinger-zone and the geometry of the fractured host-rock is called a breccia [24]. A schematic diagram is given in Figure 2.2.

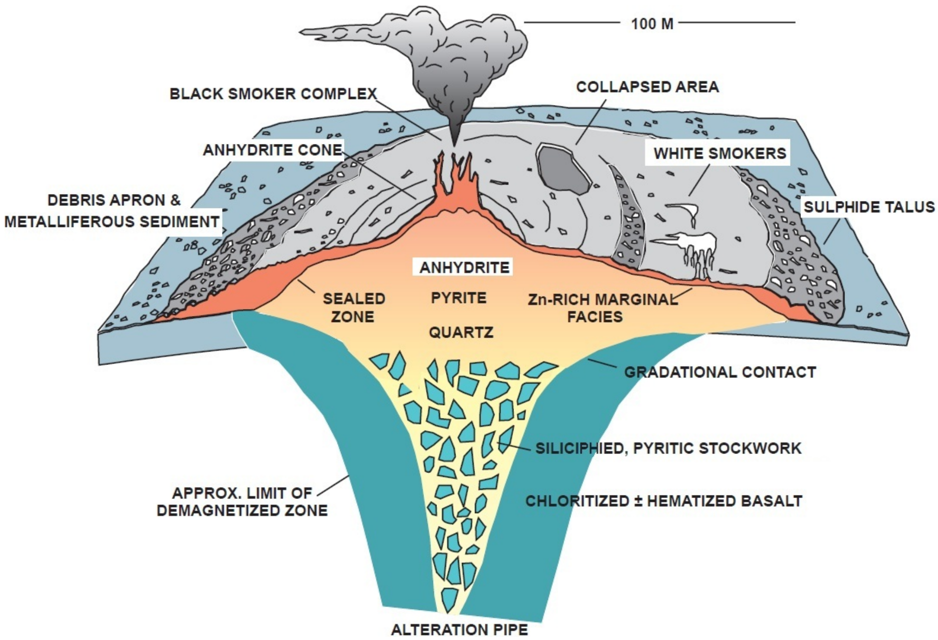

Figure 2.2: Schematic diagram of the modern TAG-deposit on the Mid-Atlantic Ridge. This represents a classic cross section of a seafloor massive sulphide deposit, with concordant semi-massive to massive sulphide lens underlain by a discordant stockwork vein system and associated alteration halo [24].

Seafloor massive sulphide deposits can be either active, with continued hydrothermal activity required to build on existing deposits, or inactive. With rapid switching in activity of deposits, the distinction between active and inactive deposits is not always clear, complicating the definition of active and inactive areas [27].

Hydrothermal vent systems on the modern seafloor have been found in diverse volcanic and tectonic settings at water depths ranging from about 1,500 to 5,600 metre. Although massive sulphide deposits have been found at water depths as shallow as 1,500 metre, there may be import physical limitations to the depths at which massive sulphide deposits might form. In shallow water, the pressure at the seafloor is insufficient to prevent boiling of hydrothermal fluids. At 350°C, these solutions will begin to boil if the hydrostatic pressure drops below 160 bar, 16 MPa, which is equivalent to about 1,600 metre of water depth [12, 13]. In response to boiling, a portion of dissolved metals will be deposited as disseminated or vein mineralization beneath the seafloor [21].

All hydrothermal vent systems need a heat source that provides the energy needed for the fluid to circulate through the rock [32]. Heat can be derived from several sources such as magmatism, exothermal chemical reactions and decay of radioactive elements. Unsurprisingly, all known hydrothermal vents are found at locations with high magmatic activity. Most of these sites are located at mid-ocean ridges (65%) and in back-arc basins (22%) and to a lesser extend at volcanic island arcs (12%) and at intraplate volcanoes (1%) [28]. Figure 2.3 shows an overview of the tectonic settings in which hydrothermal vent sites have been found.

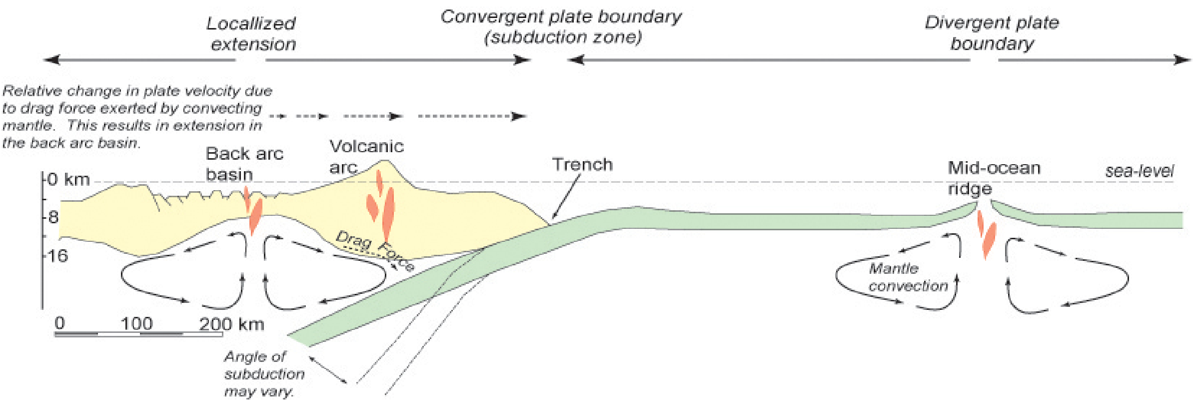

Figure 2.3: Schematic diagram showing the tectonic setting in which seafloor massive sulphides are found [49].

A second parameter influencing hydrothermal activity at the seafloor is the spreading rate, which is the speed at which the two plates move apart, which in turn is related to the magmatic activity in the area. Fast spreading ridges only permit short periods of hydrothermal venting at one location, entailing smaller deposits, while at slow spreading ridges the venting can be sustained for a long period of time leading to the growth of substantial deposits [60].

A mid-ocean ridge is a location where two plates of oceanic crust move apart and new oceanic crust is formed by the influx of mantle material, see Figure 2.3. Most mid-ocean ridges, such as the Mid-Atlantic Ridge, are barren without sediment, but about 5% is covered with sediments [28]. These sediments can have a profound effect on the metal and mineral grade and the mode of occurrence of the deposit. The sediments are an effective metal trap and protect the minerals from weathering.

A back-arc basin can develop behind subduction zones. At subduction zones, one plate subducts below another plate, see Figure 2.3. As this setting matures, the subducting plate sinks with a shallow angle, which gradually turns into a steeper angle. This movement, also called slab-rollback, creates space between the subducting an overriding plate. This space is filled with the influx of hot mantle material and as a result, a new spreading centre can develop the so-called back-arc basin.

2.2.2. Mineral resource and mineral reserves

A mineral resource is a concentration or occurrence of material of intrinsic economic interest in or on the earth's crust in such form, quality and quantity that there are reasonable prospects for eventual economic extraction. Mineral Resources are further sub-divided, in order of increasing geological confidence, into:

- Inferred
- Indicated

• Measured

Inferred Mineral Resource is that part of a mineral resource for which tonnage, grade and mineral content can be estimated with a low level of confidence. It is inferred from geological evidence and assumed but not verified geological/or grade continuity. It is based on information gathered through appropriate techniques from locations such as outcrops, trenches, pits, workings and drill holes which may be of limited or uncertain quality and reliability. A low level of confidence corresponds to high uncertainty. All geological uncertainties need at least to be classified high.

Indicated resources are simply economic mineral occurrences that have been sampled (from locations such as outcrops, trenches, pits and drill holes) to a point where an estimate has been made, at a reasonable level of confidence, of their contained metal, grade, tonnage, shape, densities, physical characteristics. An reasonable level of confidence corresponds to medium uncertainty. All geological uncertainties need at least to be classified medium.

Measured resources are indicated resources that have undergone enough further sampling that a competent person, defined by the norms of the relevant mining code, has declared them to be an acceptable estimate, at a high degree of confidence, of the grade, tonnage, shape, densities, physical characteristics and mineral content of the mineral occurrence [16]. An reasonable level of confidence corresponds to low uncertainty. All geological uncertainties need at least to be classified low.

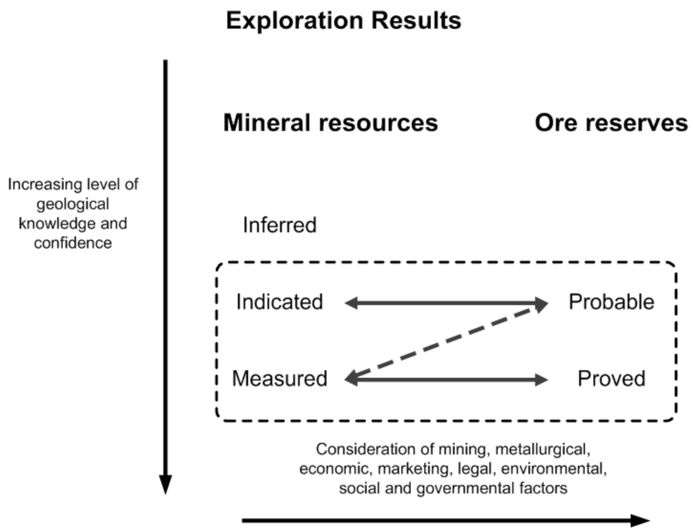

Figure 2.4: Exploration results according to the JORC, 2012 [16].

Mineral reserves are resources known to be economically feasible for extraction. Reserves are either:

• Probable

• Proved

A Probable Ore Reserve is the part of indicated, and in some circumstances, measured mineral resources that can be mined in an economically viable fashion. It includes diluting material and allowances for losses which may occur when the material is mined. A Probable Ore Reserve has a lower level of confidence than a Proved Ore Reserve but is of sufficient quality to serve as the basis for decision on the development of deposit. All uncertainties, not limited to the geological, to correspond to a medium uncertainty level.

A proven ore reserve represents the highest confidence category of reserve estimate. The style of mineralization or other factors could mean that Proved Ore Reserves are not achievable in some deposits. All uncertainties, not limited to geological, to correspond to a low uncertainty level.

Generally the conversion of resources into reserves requires the application of various modifying factors, including [16]:

- mining and geological factors, such as knowledge of the geology of the deposit sufficient that it is predictable and verifiable; extraction and mine plans based on ore models; quantification of geotechnical risk essentially, statistical and variography to ensure the ore is sampled properly
- metallurgical factors, including scrutiny of assay data to ensure accuracy of the information supplied by the laboratory, this required because ore reserves are bankable
- economic factors
- environmental factors
- marketing factors
- legal factors
- political factors
- social factors

2.2.3. Geometry and tonnage

Geometry is the collective term for properties of size and shape. An SMS deposit can be measured in volume, cubic metres, outcrop area, square meters or tonnage, metric tonne. Size is a term that can cause confusion because it can be used to describe the size of the outcrop or the size of the deposit in tonnes. Another important factor in geometry is the spatial distribution of the deposits. The spatial distribution describes the distance between outcrops that may or may not, depending on the distance, be part of one and the same deposit. Geometry and tonnage are one of the most important factors in the assessment of the economic feasibility of a seafloor massive sulphide deposit, because the amount of ore in combination with the metal price determine the revenue.

Determining the geometry and tonnage of an SMS deposit is a great challenge, as major uncertainties are involved with the exploration of these deposits. Estimating the outcrop is already challenging because of the possible coverage by sediments and the gradual transition to non-sulphides at the edges of the deposit. Obtaining the volume includes assumptions for the vertical extent of the deposit, as assumption for the extent is different for every sulphide deposits. Geophysics can be used to obtain the vertical extent of the deposit. The most accurate and highest confidence way to get the vertical extent is drilling. Using the mean density of an SMS deposit, obtained from drilling or by estimation, makes it possible to calculate the third property: tonnage [29].

Outcrop information is relevant and important for mine planning. Transport on the seafloor or from the seafloor to the water surface pose great engineering challenges. Estimating the size of an outcrop creates economic uncertainties, because the determination of the outcrop in an early stage is very challenging, as limited information is available without drilling. There is a wide variation in the outcrop size as demonstrated in Table 2.2.

Table 2.2: Outcrop size estimates of SMS deposits by Hannington et al. [29].

Outcrop size [m^2]	Total number of deposits	Number of MOR	Number of BAB	Other
100	19	17	-	2
300	2	-	1	1
1,000	3	1	-	2
3,000	6	3	1	2
5,000	11	7	3	1
15,000	5	1	3	1
30,000	5	2	1	2
50,000	5	4	-	1
90,000	1	-	1	-
100,000	1	1	-	-
150,000	2	1	-	1
300,000	1	1	-	-

Tonnage estimates of SMS deposits vary from a few tonnes to over 94 million tonnes of ore material. Reliable tonnage estimates are very rare, as drilling information is required for accurate tonnage determination of massive sulphide occurrences. The tonnage of SMS deposits can be compared to the tonnage found for volcanogenic massive sulphide (VMS) deposits on land. The average tonnage for ancient VMS deposits are generally larger than those for typical seafloor massive sulphides Hannington et al. [29]. Figure 2.5 shows the comparison of SMS deposits and VMS deposits up to 3.3 million tonne. Four larger SMS deposits were indicated by Hannington et al. [29], one of 9, two of 10 and one of 94 million tonne of ore material. The same trend in tonnage can be noticed between the SMS and VMS deposits. However, a total of 63 SMS deposits are documented with reliable tonnage estimates, compared to 868 VMS deposits that are documented by Mosier et al. [44]. It is expected that in the future many more SMS deposits will be discovered.

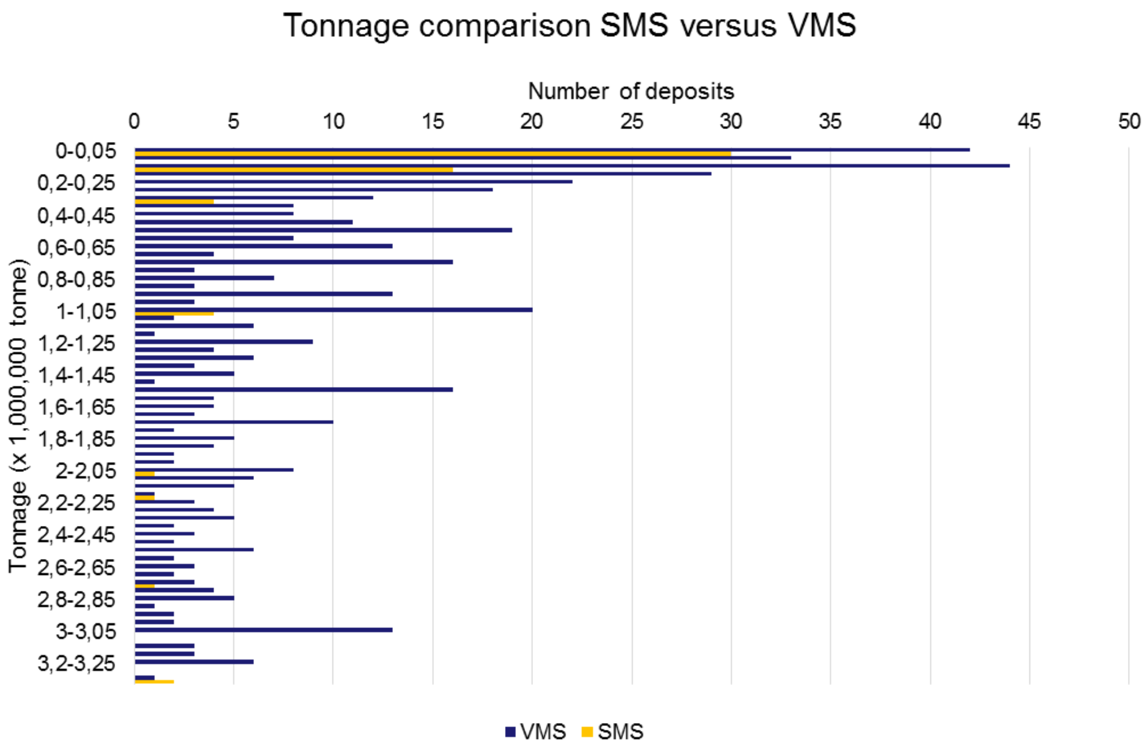

Figure 2.5: Tonnage comparison of SMS deposits versus VMS deposits [29, 44].

Minor VMS deposits do not contribute enough to the total tonnage and are therefore not included in published reserves, as documented by Mosier et al. [44]. That results in strong bias of the VMS deposit tonnage [32]. Like outcrop size estimations, uncertainties in tonnage estimates increase the level of uncertainty. The highest level of uncertainty *'D4'* is awarded to the uncertainty as the impact will be extensive and the likelihood is frequent. Without drillings, it is very certain that mistakes on tonnage estimations will be made.

The spatial distribution creates multiple scenarios for the mine plan. When a single sulphide deposit is economically feasible for exploration, it will not be dependent on possible surrounding sulphide deposits. However, a single sulphide deposit is not economically feasible for exploration, it could become economically feasible for exploration if one or multiple surrounding deposits are considered and added to the mine planning. The distance between these surrounding deposits will be an important factor since it will determine if the seafloor tools can move on the seafloor to the next deposit or that they have to be taken to surface, transported and lowered onto the seafloor again. There will be an economic trade-off for transport of the exploitation tools on the seafloor or the hoist up, ship and hoist down scenario.

The uncertainties involved in the geometry can be summed up as the sediment coverage and gradual transition for the outcrop, vertical extent for the volume and density for the tonnage. Since deposit density will be discussed in another paragraph, it will not be further analysed here. The mitigation for all the uncertainties is extensive drilling. Despite that drilling is a very good mitigation method for these uncertainties, the drilling is an economic expensive undertaking, with engineering challenges. The highest level of uncertainty *'D4'* is awarded to the uncertainty as the impact will be extensive and the likelihood is frequent. Without drillings, it is very certain that mistakes on tonnage estimations will be made. The impact of the distance to the level of uncertainty is moderate and unlikely, since estimations of the distance can already be made in an early stage. After drilling, an exact distance can be given, resulting in

Geometry	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Sediment coverage	**D4**	**A3**	Multiplied
Gradual transitione	**D4**	**A3**	Multiplied
Vertical extent	**D4**	**A3**	Multiplied
Distance between deposits	**B2**	**A1**	Added

2.2.4. Deposit density

The density of a deposit is required to assess the tonnage of that deposit. In the starting phase of a project, the density can only be obtained from physical samples by drilling. Since drilling can only be done on a limited amount of outcrops, little is known about the average density of SMS deposits. The density distribution within an SMS deposit is heterogeneously spread through the ore body [32].

Information is available on the outer surface of the East Pacific Rise deposit. The outer surface of this deposit consists of sulphide chimneys, hydrothermal crust and sediments. The surface has a very low density in the order of 1-2 g/cm^3 [18]. For the Solwara 1 and 12 project by Nautilus Minerals, the dominant sulphide interior has a density of 4.4 g/cm^3, while the exterior is lighter with a density of 2-3 g/cm^3 [38]. For the Okinawa Trough, the density is between 3.6-5.5 g/cm^3 [32].

The density of the main sulphide body can be estimated with a a severe impact and a likelihood that is likely. This results in a high level of uncertainty, or *'C3'*. The range is roughly 3.6-5.5 g/cm^3. The exterior is less important compared to the interior body in terms of density. Mitigation would be extensive drilling of the SMS deposit, resulting in high expenses and a medium level of uncertainty, or *'B2'*, as it is unlikely but not remote that the density is changes. The same level of uncertainty is applied for the density assumption.

Deposit density	**Uncertainty**	**Mitigation**	**Added/Multiplied**
SMS deposit density assumption	**C3**	**A2**	Multiplied
Homogeneity of density within deposit	**C3**	**A2**	Multiplied

2.2.5. Deposit location

The location of an SMS deposit is directly related to the distance to shore or to harbour. This distance is required for the economic assessment of the transport costs of the sulphide ore to land. Besides distance, the location determines other parameters like climate conditions, sea state and legal regime. It is likely that the location is limited by weather conditions.

To get a better understanding of where SMS deposits are most likely to be situated, a map of the global distribution of hydrothermal vent fields can be used, as shown in Figure 2.6. Hydrothermal vent field are associated with seafloor massive sulphide deposits [32]. The legal regime, the Exclusive Economic Zone, is also indicated in this map. It should be noted that not all hydrothermal vent fields necessarily contain a sulphide deposit. This means that not all locations indicated on the map are of interest for the exploitation of SMS deposits.

The distance between the deposit location and a harbour ranges between several to thousands of kilometres. An estimation of this distance would be 50 – 7,500 km from SMS deposit to the harbour. The distance to the harbour can be extended, if the harbour that is closest to the deposit is not chosen for unloading the ore.

The European Union (EU) want to secure their supply of raw materials, as it is critical for EU manufacturing industries and their competitiveness. The EU sees deep-sea mining as a way to provide in their need to secure their raw material supply [57]. As a result of this aim, this could potentially mean

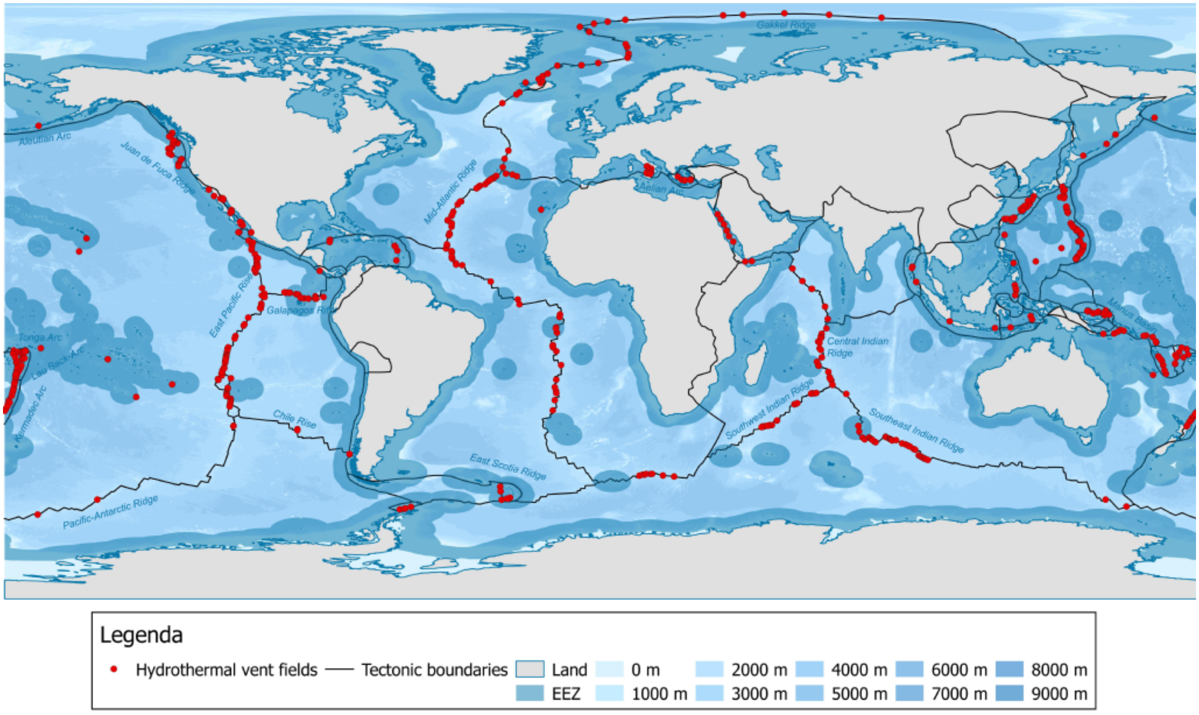

Figure 2.6: Global distribution of hydrothermal vent fields including the Exclusive Economic Zones. The InterRidge v3.3 database [1] was used to construct this map.

that thousands of kilometres could be added to the distance between harbour and deposit. For example when the location is in the Pacific Ocean and the ore needs to be shipped to the port of Rotterdam.

The distance to harbour can be measured exactly and, on itself, is not an uncertainty. The discovery of a geological occurrence goes hand in hand with determining the location. The distance can pose uncertainties about the shipping time, due to weather conditions and sea currents. These uncertainties are discussed in another paragraph, hence the deposit location is given an *'A1'* for uncertainty level. No mitigations are required for the deposit location.

The operator, or miner, doesn't necessarily have to be the producer of the metal. In the case of Nautilus Minerals, the ore is shipped to a harbour in China and Nautilus has nothing to do with the ore anymore [14]. Although there aren't any uncertainties left for the miner, there still is one for the producer. When the ore is in the harbour, it still needs to be transported to the processing plant for further processing. Not all harbour have processing plants or processing plants in the vicinity. This transport could make it possible to choose a different harbour because of the long distance the ore would need to travel over land in order to get to the processing plant. There are no uncertainties involved, in terms of transport on land. The uncertainty of choosing a harbour without access to a processing plant is considered as a severe impact, as extra transport over water is needed, and the likelihood is considered likely, resulting in a uncertainty level of *'C3'*. Mapping all available harbours worldwide with access to a mineral processing plant that can deal with seafloor sulphide ore can mitigate this uncertainty to the a remote likelihood resulting in a level of uncertainty of *'A3'*.

Deposit location	**Uncertainty**	**Mitigation**	**Added/Multiplied**
SMS deposit location	**A1**	**A1**	Added
Harbour selection with accessible processing plant	**C3**	**A3**	Added

2.2.6. Water depth

Water depth describes the distance between the seafloor and water surface. The distance is in metres. It is not the absolute distance, but the average distance to the top of the deposit or to the coverage if the deposit is covered by sediments. The distance for multiple locations of the deposit, when a deposits that stretch over a larger areas with different water depths, is averaged. The water depth is a factor influencing the exploitability of SMS deposits. Deposits situated at great water depths are more difficult to exploit in comparison to deposits that occur at shallow water depths.

As a result of the greater water depth, equipment is exposed to greater water pressure. The pressure will require more rigid design of the equipment in order that it will not fail under these high pressure conditions. This design and greater pressure will bring great technical and engineering challenges compared to operation with lower pressure environment.

There is limited information available about the water depth of SMS deposits, as it is expected to discover many more seafloor massive deposits. Hydrothermal venting, that is associated with SMS deposits [32], can be the solution to this information gap. Instead of only taking the limited information about existing SMS deposits, all hydrothermal vent fields are taken into account when analysing the water depth. Hydrothermal venting occurs over a large range of water depth. From shallow, low temperature vents like hot springs in coastal environments and offshore extension of sub-aerial systems to the very deep trough and mid ocean ridge settings.

The majority of the mid ocean ridge sites are distributed at the 2-3.5 kilometre depth, whereas arc volcano sites are generally situated at shallower depths, see Figure 2.7. Back-arc spreading centre rifts are found at a wide variety of water depths. Hydrothermal venting is possible at very shallow systems, but due to the temperature decrease and lower pressure, metal-depleted deposit types are formed. SMS deposits have been found in water depths as shallow as 1,500 m. This makes settings with a water depth lower than 1,500 metre, mostly associated with arc volcano settings, not interesting for exploitations [32]. If Figure 2.7 is considered for the depth of SMS deposits, then it can be assumed that most of the SMS deposits will be between 1,500 and 4,000 metre. However, since discovering deeper SMS is a greater challenge, the assumed depths should be taken as a first indication.

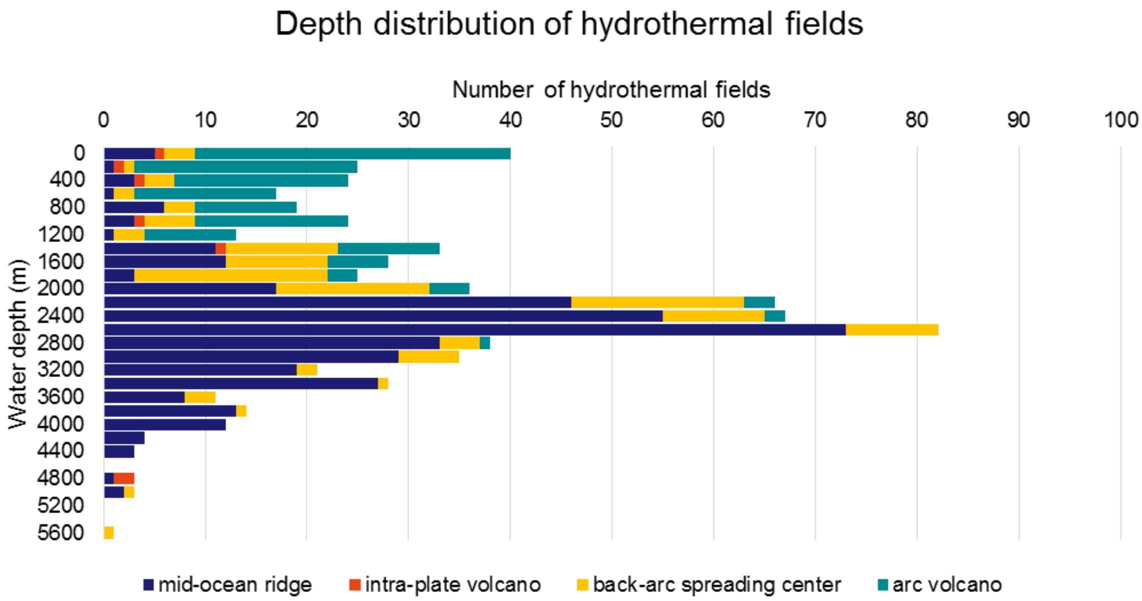

Figure 2.7: Depth distribution of hydrothermal fields [1].

The impact of measuring a dipping orebody, by dipping seabed or by dipping of the orebody itself, is considered minor and the likelihood as unlikely, or *'B1'*. Because of the low uncertainty, no mitigation is required. Although, a mitigation could be assessing the whole deposit depth using remotely operated vehicle (ROV) or other equipment. This would decrease the likelihood to remote, or *'A1'*. An increased depth would have a multiplied effect on calculations.

Water depths over 1,500 metre pose great engineering challenges towards the extraction tools and transport equipment that will be used during the exploitation of SMS deposits. There is a multiplied uncertainty for extraction tools because of inaccessibility of the environment in that they operate.

Downtime will be longer in the deep-sea than it would be on land. This poses a severe impact with a frequent likelihood, or *'D3'*. The impact on the calculations would be multiplied. There is no way to decrease the water depth of the deposit. A mitigation should be found in the design of the seafloor tools used. The impact would stay the same, but the likelihood would decrease to likely or unlikely, *'C3'* or *'B3'*. The impact of the water depth will increase energy consumption of both extraction and transportation tools. The energy will need to be transported over a longer distance. Although the increased energy consumption would have a great impact on the feasibility, the level of uncertainty is minor and remote, as the extra energy required can be calculated up front of the operation.

Longer vertical transport will result in a longer exposure to the elements of the sea, which can increase the level of uncertainty. The extra water depth will increase the level uncertainty, but no level of uncertainty can be indicated, as that will depend on which comparison is made. A comparison between 1,500 metre and 6,000 metre water depth will most definitely result in an extensive impact, as 3,000 metre and 3,100 metre will not change the impact. The extra length cannot be mitigated, but extra rigid design and testing of the equipment will decrease the likelihood of the uncertainty.

Water depth	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Dipping orebody	**B1**	**A1**	Multiplied
Longer downtime with increased water depth	**D3**	**B3**	Multiplied
Increased energy consumption with increased water depth	**A1**	**A1**	Multiplied

2.2.7. Ore conditions

The ore conditions describe the state of the ore in terms of porosity, grains size, grain geometry and if the ore is wet or dry. When the ore is recovered from the seafloor, it is wet with salt seawater. The effect of this seawater on the ore should be investigated as ore with salt water in combination with oxygen could lead to chemical reactions dissolving base or valuable metals. The impact could be severe as the amount of metal that could be extracted from the orebody would be less than anticipated for. The likelihood is likely. Mitigation is laboratorial research in the effects of seawater and oxygen on sulphide ore from seafloor massive sulphides. The results would lead to an uncertainty level with a remote minor impact, or *'A1'*.

Porosity is a measure of void space in the ore and is a fraction of the volume of the voids over the total volume of the ore. The porosity in a seafloor massive deposit depends on the location within the deposit [33]. Mixing between the upwelling hydrothermal fluid and cold seawater is regarded as a major cause of sulphide precipitation and will probably strongly influence the porosity of the top layers of the deposit [20]. Cross-section of chimneys illustrate high porosity [33]. The effect of the porosity is unknown. For mineral processing it would probably only effect the grinding, as it will be to small after grinding to be porous. The large surface area caused by the pores could have an effect on the chemical reactiveness of the ore. This uncertainty could have a negative influence on the amount of metal that could be extracted from the ore body, therefor it is a multiplied effect. The impact could be severe with a likelihood that is likely, resulting in *'C3'*. To mitigate this uncertainty, laboratorial research on the effect of the porosity should be further investigated, lowering the likelihood to remote and minor impact, or *'A1'*. As the porosity is unknown, drilling of a deposit is required to determine the porosity of this deposit. The porosity would need to be estimated resulting in a likely and moderate impact, or *'C2'*. The impact will stay moderate but the uncertainty will be remote after mitigation, or *'A2'*.

The grain size and geometry are controlling factors for the extraction and metallurgy of the metals. Very fine-grained grained minerals that are complexly inter-grown with each other are harder to separate than large regularly ordered grains that have discrete boundaries. The small grain size and complex intergrowth of sulphides with gangue minerals in SMS type deposits provides difficulties for the extraction of the desired metals. Their fine-grained nature and complex intergrowth are the result of the fast precipitation of the minerals as the result of the rapid change in conditions that the hydrothermal fluid encounters when mixing with seawater in chimneys [33].

The grained difficulty of the minerals is correlated to the energy that would would increase when the difficulty increases. Exact data on the grain size of the minerals is scarce and is mainly restricted to qualitative terms such as fine-grained or coarse-grained. Crawford et al. [18] reports that 93% of the material is within the 1 to 10 micrometre range. Data from the Explorer Ridge and East Pacific Rise gives grain sizes between 1 to 600 micrometre for the minerals pyrite, chalcopyrite and sphalerite with an average between 22-37 micrometre [32]. Important to note is that this material was all surface-sampled material. Within the mound, hydrothermal reworking results in coarser-grained recrystallized material. No quantitative data on recrystallized material was found. The risk involved with the parameter is limited to the extraction and metallurgy. To mitigate these uncertainties, scrutiny of drilling core data by a laboratory is needed.

Ore conditions	Uncertainty	Mitigation	Added/Multiplied
Reactiveness of wet ore	C3	A1	Multiplied
Effect of porosity	C3	A1	Multiplied
Porosity estimation	C2	A2	Added
Grain size estimation	C2	A2	Added
Grain geometry estimation	C2	A2	Added

2.3. Economical exploitable

2.3.1. Production rate and mine life

Production rate and mine life play a large role in determining the projects economic feasibility. There is a mutual interdependency between production rate and mine life. A higher production rate typically allows for lower operating costs, while the subsequent shorter mine life maximizes the net present value of ore extraction. However, a higher production rate requires a greater capital cost as larger equipment and infrastructure is required.

Estimation of production rate can be done using multiple models. One of the models uses the present value ratio in order to find the optimal production rate, Wells' theory [62]. Another method that can be used is the model of Taylor [58]. Taylor [58] developed a theoretical model, Taylor's Rule, which is a rule of thumb that can be used as a first indication of mine life, see Equation 2.1. With this mine life and the tonnage, the production rate can be calculated, see Equation 2.2. With an assumption on the operating days, it is possible to come up with a system of equations.

$$\text{life} = 0.2\sqrt[4]{\text{tonnage}} \tag{2.1}$$

$$\text{production} = \frac{\text{tonnage}}{\text{life} \times \text{operating days}} \tag{2.2}$$

The method of Wells for determining production rate and mine life, with use of the present value ratio, results in more unknowns in the parameters and variables [62]. Therefore, Taylor's rule is a good first indication of the production rate but has its downsides for deep-sea mining [58]. A downside is that very deep, flat ore bodies where production is limited by hoisting limits of shafts. This is a major downside for deep-sea mining as hoisting over a large distance is always the case. But this also poses an upside, the maximum production rate is equal to either the Taylor's Rule or the production rate of the vertical transportation method. A quick calculation: 390 tonnes with for example a copper grade of 10% and a copper price of 5,000 US dollar per tonne would result in a revenue of 195,000 US dollar per day. As shown in this simple example it already seems that it is not feasible for extraction so Taylor's Rule should be adjusted for deep-sea mining. A suggestion is to reduce the life time of the mine by half so the production rate and revenue are doubled, see Equation 2.3.

$$\text{life} = 0.1\sqrt[4]{\text{tonnage}} \tag{2.3}$$

The level of uncertainty predicting the life of mine has an extensive impact and a frequent likelihood, or *'D4'*. All design of the equipment is based on these figures. Using Taylor's Rule can mitigate the level high, with extensive impact an unlikely likelihood, or *'B4'*. For the the life of mine, the same reasoning holds. Both are multiplied.

Production rate and mine life	Uncertainty	Mitigation	Added/Multiplied
Predicting production rate	D4	B4	Multiplied
Predicting life of mine	D4	B4	Multiplied

2.3.2. Extraction method

The extraction method for deep-sea mining is currently unknown. Possible extraction methods could be cutting, scrapping, blasting, laser cutting, grabbing and fragmentation, techniques that are currently used in land mining operations. At this moment, Nautilus Mineral is planning to use the cutting method for extraction [14]. In this thesis, the method from Nautilus will be taken as an example for the extraction method, however, in the future, a different method might be preferred.

Three seafloor mining tools are designed for the extraction method of Nautilus. A drum cutter for the bulk, an auxiliary cutter for the precision and a collector to collect the loose ore. All machines are designed and manufactured by Soil Machine Dynamics in the United Kingdom. According to Ecorys [25] the technology readiness level of this technique is at the level of experimental proof of concept. It scores a 3 out of 9 on the level of readiness scale. Although the cutter heads are successfully applied today on cutter suction dredgers, there is no record of any experiments to test the behaviour of such cutter-heads to cut SMS deposits and the behaviour at significant ocean depths. At the same time, ocean crawlers with cutter suction heads are used today for marine diamond mining in a shelf environment up to 150 metre water depth. This has an effect on the uncertainties and their impact and likelihood. Describing all uncertainties that are involved with the machinery, is out of scope of this thesis and will not contribute in a better understanding or economic assessment of a SMS deposit.

Due to the level of readiness of the concept of the extraction tools it is estimated that the impact will be extensive and the likelihood will be frequent, or *'D4'*. Mitigation would be through testing of the equipment so the likelihood can be brought down to unlikely, or *'B4'*. The uncertainty is multiplied as extra downtime that could be a consequence and is multiplied in the calculations. The same analysis is used for the production rate, equipment operability, erosion rates, downtime and interface with riser and lift system. All are multiplied except for the interface between the riser and lift system. It is expected that this could be resolved by engineering the equipment in such a way that it will work without it continuing to have effect on the interface.

The hyperbaric effect on the extraction tools and method is unknown. The impact is extensive as the energy needed for the extraction could increase a great deal. The likelihood is frequent as there is no knowledge what will happen under hyperbaric conditions. The level of uncertainty is therefore *'D4'*. After studying the hyperbaric effect thoroughly, the impact will be moderate and the likelihood will become unlikely, or *'B2'*.

Transporting sufficient energy to the seafloor over a distance of more than 1,500 m will pose great engineering challenges. Although transport over these distances are already achieved for remote operated vehicles, the energy requirements for the seafloor extraction tools are expected to be much more. Due to the level of readiness of the concept of the extraction tools it is estimated that the impact for the energy transport will be extensive and the likelihood frequent, or *'D4'*. Mitigation would be through testing of the equipment including the energy transport system so the likelihood can be brought down to unlikely, or *'B4'*. The impact of the energy transport will be added.

Extraction method	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Concept of extraction tools	**D4**	**B4**	Multiplied
Production rate	**D4**	**B4**	Multiplied
Equipment operability	**D4**	**B4**	Multiplied
Erosion rates	**D4**	**B4**	Multiplied
Downtime	**D4**	**B4**	Multiplied
Interface with riser and lift system	**D4**	**B4**	Added
Hyperbaric effect	**D4**	**B2**	Multiplied
Sufficient energy on the seafloor	**D4**	**B4**	Added

2.3.3. Vertical transport method

Vertical transportation of excavated ore is a critical step in the mining sequence of deep-sea mineral deposits. Vertical transport is the vertical transportation of an ore from the seabed to surface. Both mechanical transportation methods, such as continuous line bucket and batch cable-lifting, and slurry-based methods, like air lift and hydraulic pump, have been proposed to bring the ore to the surface. The production efficiency of the vertical transportation system depends on several components such as the particle concentration in the slurry, riser friction factor and/or chosen lifting system [8]. At this moment, Nautilus Minerals has designed a slurry-based system with hydraulic pumps. The subsea lift pump is supplied to Nautilus by GE Hydril. In this thesis, the method from Nautilus will be taken as an example for the vertical transport method, however, in the future, a different method might be preferred. The choice of the method also dictates necessity to have auxiliary systems: e.g. hydraulic transport required dewatering and return of the waste water, while transporting in semi-open buckets eliminates such a necessity.

The riser and lift system from Nautilus is used for the vertical transportation of the ore. The subsea mining tool, the collector, gathers all of the ore and pumps this as a slurry to the subsea lift pump. The subsea lift pump pumps the slurry through the riser, basically a pipe, to the sea surface.

According to Ecorys [25] the technology readiness level of this technique is at the level of experimental proof of concept. It scores a 3 out of 9 on the level of readiness scale. The similarity of the conceptual riser system with systems currently applied in deep-sea oil and gas drilling make this system promising for deep-sea mining. The system is capable to transport rock cuttings as a slurry over large vertical distances of several kilometres and this can be seen as an experimental proof of concept. However, with the technology concept defined, the behaviour of the system should be investigated in a series of experiments and field tests. One of the uncertainties involved in this technique is the energy efficiency and the method that is used to transport energy to the seabed. Another uncertainty is the impact of the hydrodynamic loads due to underwater flows resulting in vortex induced vibrations and reducing the fatigue life on the riser pipe [37]. With bad weather, the riser could be damaged. Removing the riser pipe in bad weather would be a major operation. This technique could likely only be used at a calm sea state. Therefore, other alternative should be investigated for a more future proof vertical transport method. Due to level of readiness of the concept of vertical transport it is estimated that the impact will be extensive and the likelihood will be frequent, or *'D4'*. Mitigation would be through testing of the equipment so the likelihood can be brought down to unlikely, or *'B4'*. The uncertainty is multiplied as extra downtime that could be a consequence and is multiplied in the calculations. The same analysis goes for the production rate, equipment operability, erosion rates, downtime and interface with seafloor tools and production vessel. All are multiplied except for the interface between seafloor tools and production vessel. It is expected that this could be resolved by engineering the equipment in such a way that it will work without it continuing to have effect on the interface.

Transporting sufficient energy to the seafloor over a distance of more than 1,500 m will pose great engineering challenges. Although the transport over these distances are already achieved for remote operated vehicles, the energy requirements for the vertical lift pumps is expected to be much more. Due to level of readiness of the concept of the vertical transport equipment it is estimated that the impact for the energy transport will be extensive and the likelihood frequent, or *'D4'*. Mitigation would be through testing of the equipment including the energy transport system so the likelihood can be brought down to unlikely, or *'B4'*. The impact of the energy transport will be added.

Vertical transport method	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Concept of vertical transport	**D4**	**B4**	Multiplied
Production rate	**D4**	**B4**	Multiplied
Equipment operability	**D4**	**B4**	Multiplied
Erosion rates	**D4**	**B4**	Multiplied
Downtime	**D4**	**B4**	Multiplied
Interface with seafloor tools and production vessel	**D4**	**B4**	Added
Sufficient energy on the seafloor	**D4**	**B4**	Added

2.3.4. Production vessel

The production support vessel is at the centre of a deep sea mining operation, supporting the surface and subsea mining operations. Operationally, the production support vessel is similar to many of the vessels used for deep-sea oil and gas drilling, dredging, or transportation industries. Its purpose is to supply a large deck space and a stable platform from which the mining operations are controlled.

Depending on the extraction method and the vertical transport method, the production support vessel can have different deck layouts. In this thesis the Nautilus equipment are used as the assumed techniques. The production support vessel would not need a crane or an A-frame for the hoisting of ore, but only for the hoisting of the seafloor production tools and the riser and lifting system. With regards to the economic feasibility, the production vessel is not expected to have any uncertainties of interest.

2.3.5. Shipping

The shipping and transport describes the transportation of the ore from the production support vessel to shore. This transport can either be done by large cargo bulk carriers or by smaller barges that commute between harbour and production support vessel. The infrastructure is out of scope of this thesis. However, there are some uncertainties that influence the economic feasibility. One of the uncertainties is the reactiveness of the wet ore when it is transported to shore. During the transport, the ore can react with the oxygen causing a reduction of the metal grades. The impact can be severe as the grade is of great importance to the whole operation. The likelihood is likely. Research is required to come up with solutions to prevent or delay this reactions in the ore. The level of the uncertainty is for now *'C3'*, but after mitigation is unknown.

Shipping and transport	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Reactivity of the ore	**C3**	-	Multiplied

2.3.6. Legal regimes

There are multiple legal regimes in the seas and oceans, see Figure 2.8:

- Territorial Sea
- Contiguous Zone
- Exclusive Economic Zone
- Continental Shelf
- High Seas
- The Area

These legal regimes are described in the Law of the Sea Convention. Two of these regimes are important from a deep-sea mining perspective: Exclusive Economic Zone and The Area.

The exclusive economic zone (EEZ) is a maritime area beyond and adjacent to the territorial sea, see Figure 2.8. Its breadth is 200 nautical miles from the baselines from which the territorial sea measured and comprises both the water column, subsoil and seabed. The coastal state has sovereign rights for the purpose of exploring, exploiting, conserving and managing the living resources of the water column, seabed and subsoil of the EEZ. The non-living resources rights are exclusive in the fullest sense and import no requirement for coastal states to share access, let alone any benefits from the exploitation [52]. A coastal state has three types of jurisdiction in the EEZ:

- The establishment and use of artificial islands, installations and structures
- Marine scientific research
- The protection and preservation of the marine environment.

The Area is the deep seabed beyond national jurisdiction, see Figure 2.8. It consists of the seabed and the subsoil thereof. The superjacent water column is governed by the regime of the High Sea. The Area has no defined borders of its own, in contrast to the other maritime regimes, but they are determined by exclusion. The Area starts where the continental shelf ends. The Area and its resources are declared the common heritage of mankind. This principle has four elements:

- No state can claim or exercise sovereignty or sovereign rights over any part of the Area or its resources, nor can any state or juridical or natural person appropriate any part.
- The Area may only be used for peaceful purposes.

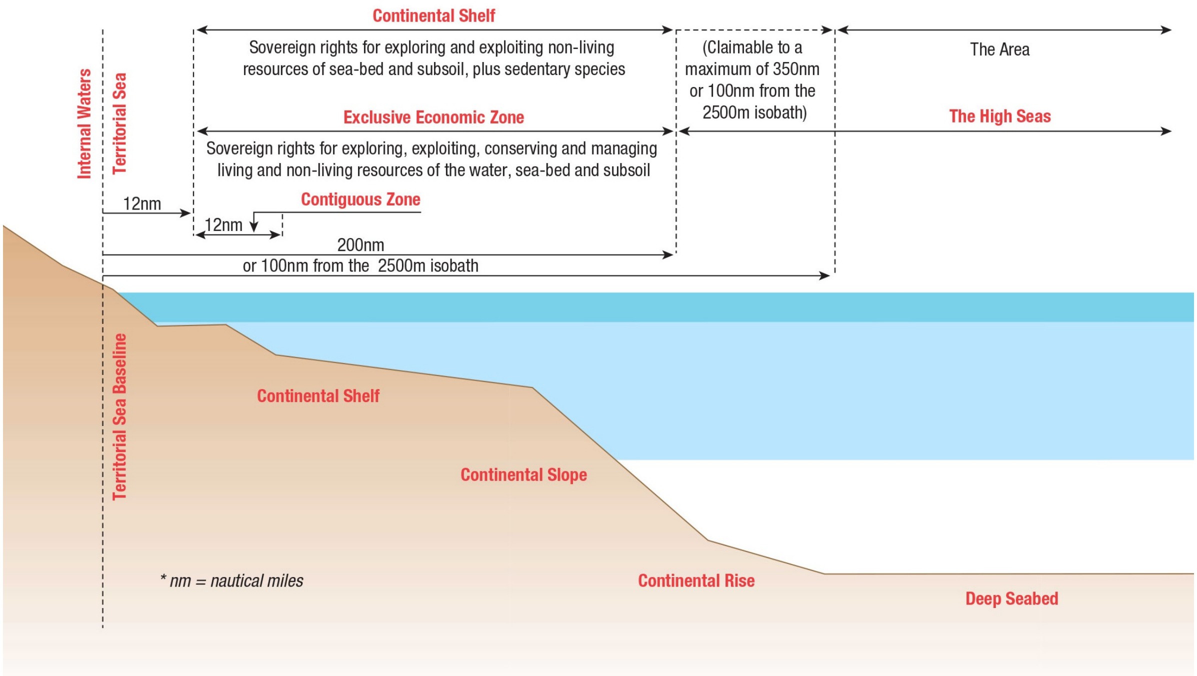

Figure 2.8: Overview of legal regimes in the sea and ocean, explaining the Exclusive Economic Zone and The Area [6].

- Activities in The Area shall be carried out for the benefit of mankind as a whole.
- The Area is regulated by the International Seabed Authority.

The EEZ and The Area pose two different scenarios for deep-sea mining. Rules and regulations are more clear within the EEZ, than they are for The Area. Many of the hydrothermal vent fields, that are associated with sulphide deposits, are located within the EEZ, see Figure 2.8. Although the regulations might be more clear within the EEZ, every coastal state has its own regulation resulting in multiple scenarios from a legal point of view for the EEZ. This multiple scenario for the EEZ increases the level of uncertainty depending on the coastal state the deposit is part of. The overall uncertainty would suffer an extreme impact and be unlikely. Mitigation for the EEZ would contain very close monitoring of the legal evolvement of a state and perform a through stakeholder analysis, reducing the impact to severe, or *'B3'*.

As no state can claim sovereignty over The Area, it is not said that no state will do so after a deep-sea mining project has commenced close to the EEZ of that state. Therefore, a likely extensive impact is assumed for exploitation within The Area, or *'C4'*. The mitigation for The Area would be to get support of a strong neighbouring state. Even with this strong ally, the likelihood will only change to unlikely and not remote.

Legal regimes	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Deep-sea mining in the EEZ	**C3**	**B3**	Added
Deep-sea mining in The Area	**C4**	**B4**	Added

2.3.7. Stakeholders

A stakeholder is an individual, group or organization, who may affect, be affected by or perceive itself to be affected by a decision, activity or outcome of a project [42]. Project stakeholders are entities that have an interest in a given project. There are multiple categories of organizations involved in deep-sea mining projects:

- International and national governmental organizations
- International and national non-governmental organizations

- Research organizations
- Industrial organizations

In every category there are organizations which are involvement in deep-sea mining projects. Mining, in this case deep-sea mining, affects a wide array of individuals, groups and organizations. Vice versa, these stakeholders affect the mining project, therefore it is necessary to do a stakeholder analysis. A thorough stakeholder analysis is considered to be essential to modern mining projects, regardless if the project is on land or at sea. A stakeholder analysis starts with identifying those stakeholders that are directly and indirectly affected by the project. After these stakeholders, stakeholders whose interests determines them as stakeholders are analysed. Underestimating their potential influence on project outcomes may pose risks. Stakeholder analysis should assist in this prioritization by assessing the significance of the project to each stakeholder group from their perspective, and vice versa. It is important to keep in mind that the situation is dynamic and that both stakeholders and their interests might change over time, in terms of level of relevance to the project and the need to actively engage at various stages. Identifying stakeholder representatives and consulting with and through them can be an efficient way to disseminate information to large numbers of stakeholders and receive information from them reducing the uncertainties to the project.

Stakeholders can pose threats and uncertainties to the deep-sea mining operation and deep-sea mining project. To what extent should be investigated by means of a stakeholder analysis. The levels can differ from a low to an extreme level uncertainty. Mitigations may be different for every stakeholder that is involved. A note should be made about stakeholders but no level of uncertainty after mitigation can be given. Depending on the type of stakeholder, uncertainty should be added or multiplied in calculations. An example for added is extra research that would be required for this stakeholder and example for multiplied is changing mining method that would be required.

Stakeholders	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Stakeholders	**D4**	-	Added/Multiplied

2.3.8. Mining impact

Mining impact covers all mining operations that are performed on the seafloor. When exploiting the seabed, all hydrothermal vent chimneys will be removed and flattened so the ore is easily accessible for deep-sea mining tools. After abandoning the mine site, a flat gap will be left at the seafloor. Hekinian et al. [30] reported physical chimney growth of 40 centimetres over 5 days at some locations in the East Pacific Rise. However, this is only for active hydrothermal fields. Furthermore, it is unknown how long recovery of the associated ecosystems of hydrothermal vent fields and whether recolonization would occur at all.

The removal of habitat by deep sea mining using deep-sea mining tools could have a negative impact on local fauna. Possible impacts of deep-sea mining tools could be:

- Sessile organisms, aquatic animals that are not able to move about, are impacted directly by mining machinery and processes since they cannot migrate away.
- Motile organisms, animals that are able to move, could migrate away from mining areas due to environmental disturbance, but may not avoid all impacts caused by the deep-sea mining tools.
- Increase smothering and clogging of filter feeding organisms, like crabs etc., as a result of exposure to sediment plumes.
- There is likely to be some direct bathypelagic fish mortality caused by all mining operations, as well as further impacts as a result of a decline in food sources.
- Potential spills of hydraulic fluids in case deep-sea mining equipment uses hydraulics.

Part of the mining impact is the operational noise impact. Deep-sea mining tools will create underwater ambient noise, as will support vessels situated at the sea's surface. Most deep-sea species experience relative silence in the environments they inhabit so any introduced noise will likely represent a substantial increase on ambient sound levels [9]. Studies on deep sea fish reveal that some species appear to communicate using low sound frequencies of <1.2 kHz [53] and it is thought that other benthic species may use sensitive acoustic systems to detect food falls of up to 100 m away [56]. Marine mammals such as whales are known to use sound for communication and navigation.

Another part of the mining impact is the operational light impact. The operation light impact is the impact that light has on the environment, above and underwater. Mining activities operate 24 hours a day, 365 days a year. This mining activity will increase light levels in the deep-sea as a result of operating deep-sea mining tools. The benthic environment is dark and organisms are adapted to these low light conditions [9]. Herring et al. [31] reported that deep-sea shrimp species have been blinded by lighting on scientific research equipment which visited the area for only a few hours. If increased light levels persisted for some time, this could damage organisms and result in migration away from the mined site.

The uncertainty from the mining impact is that the level of impact is uncertain. It is not known to what extent the mining will impact the environment. There are no precedents that can be used as an example. Therefore the highest impact level is awarded to this mining impact uncertainty. The likelihood is set to the highest level too. To mitigate the mining impact, thorough investigation is required to a broad extent. After mitigating, the level of uncertainty is difficult to predict. In order to perform deep-sea mining, a low level of uncertainty would be required, so mitigation should bring the level down to a low level of uncertainty. The uncertainty will have an added value, because the mitigation will be research that requires fixed costs.

Mining impact	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Mining impact	**D4**	**low**	Added

2.3.9. Waste management

Waste management can be divided in four categories: dewatering waste, side cast sediment, sediment released during the mining process and tailing disposal.

Dewatering waste may contain fine sediment and heavy metals which are resuspended when discharged into the water column [14]. Aggregations of suspended particulate matter and settlement of sediment could cover a wide area depending on currents and discharge volume, physically changing the seabed topography. Sediment plumes would smoother habitats and flora and fauna and, depending on their origins and composition, could result in the exposure of benthic communities to heavy metals and acidic wastes [61]. The release height of dewatering discharge may help to mitigate to some degree the impact of sediment plumes in the water column [8]. If released close to the seabed, models suggest that the plumes should be confined to deep water and not move into the upper water column due to differences in water density [9]. However it is difficult to model this system without extensive plume data, upwelling and current information [39]. Dewatering waste could stop the whole operation, making it the highest level of uncertainty, or *'D4'*. Research on plume dispersion is a way to mitigate this uncertainty to unlikely and moderate impact, or *'B2'*. As more research is required, added fixed costs would be applicable.

Side casting sediment waste on the seafloor minimises the need for transport to the surface or land based storage, but would nonetheless lead to major physical alterations and smothering of the benthic habitat. In side casting sediment the mining zone is cleared of sediments. The sediment is transported to the edges or further away from the mining zone, so it will not interfere with the mining operation. This is however not always necessary. Some deposits could have no sediment coverage and are exploitable without the need of side casting the sediments. This time of waste management is not considered to be an uncertainty to deep-sea mining operations.

For sediments that are released during the mining process it is likely to be impossible to restrict impacts of sedimentation or the release of metals to a local mining area due to current movements and the unconstrained nature of the oceans. Depending on the scale of mining, impacts could spread between ocean basins, far away from original mine sites and could lead to disputes as impacts spread from territorial to international waters or vice versa [55]. Sedimentation could stop the whole operation, making it the highest level of uncertainty, or *'D4'*. Research on sedimentation is a way to mitigate this uncertainty to unlikely and moderate impact, or *'B2'*. As more research is required, added fixed costs would be applicable.

Subsea tailing disposal is an optional parameter that only occurs when mineral processing is done offshore. This parameter has both a legal and environmental groundwork that go hand in hand. The basic subsea tailing disposal design comprises a tailings line to a de-aeration or mixing chamber, with seawater intake line, and discharge to a location at depth allowing gravity flow of a coherent density to the final sedimentation area. This system of disposing tailings in a subsea environment can place mine tailings at locations and depth constraining environmental impact [17, 23].

From a legal perspective, disposal of tailings in a subsea environment is addressed in two agreements of international application. The first is the 1982 Law of the Sea Convention. This law requires states to adopt laws and regulations to prevent, reduce and control dumping. These laws may not be less effective than global rules and standards [2]. The second agreement is the 1972 London Convention and 1996 Protocol. The London Convention and the Protocol are instruments of global application to all marine waters. The objective of the 1972 London Convention is to prevent the pollution of the sea by the dumping of waste and other matter that is liable to create hazards to human health, to harm living resources and marine life or to interfere with other legitimate uses of the sea [4]. In 1996 the Protocol was adopted. Under the Protocol, it is forbidden to dump anything whatsoever in the sea, unless it is expressly permitted. The Protocol, which has been signed by about forty states, supersedes the Convention between those parties that are also party to the Convention [4, 34].

For offshore mineral processing, the disposal of mine waste in a subsea environment would be a necessity. Depending under which country the mining company operates, it has to fulfil the requirements stated in the 1996 Protocol. Even without having to adapt to this Protocol, it will be a great challenge to prove that the subsea tailings disposal is not a hazardous to human health or harms living resources of marine life. The additives used in mineral processing for dense medium separation and froth flotation, like xanthate, copper sulphate and sodium cyanide, can be toxic to very toxic for marine life. This gives two possible scenarios, the first where no subsea tailing disposal is done and no additional legal requirements are needed or the second where there is subsea tailing disposal and very strict legal regulations have to be implemented in the mine planning. The first pose no additional risk to the economic feasibility of an SMS deposit. The second scenario involves a great risk factor for the economic feasibility of an SMS deposit, because of the extra uncertainties that are involved with requiring a permit to commence subsea tailing disposal. In this thesis it is assumed that processing offshore will not be possible.

As seafloor tailing disposal is not a possibility, in this thesis, the tailings have to be stored in a land based tailing pond. A tailing pond is basically an area with a dam that can hold the tailings. It is preferred to have the tailing pond close to the processing plant, so less freight costs for the tailings have to be paid. The ability to build a tailing pond should be investigated thoroughly as a tailing pond will contain toxic tailing elements. The uncertainty involved with the tailing pond is the location selection and the design of the tailing pond. The later should not pose a big uncertainty as there is years of experience of designing tailing ponds. The location selection for the processing plant should consider the toxic tailings when selecting a location. Mitigation of this uncertainty is selecting a country with stable and reliable government. The level of uncertainty before mitigation is considered medium, severe impact and unlikely, or *'B3'*. After mitigation the level is considered moderate impact and remote, or *'A2'*. The costs of tailing management will would go up per tonne, so multiplication is chosen as an effect for this uncertainty.

Waste management	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Plume dispersion	**D4**	**B2**	Added
Sedimentation	**D4**	**B2**	Added
Tailing pond design	**A1**	**A1**	Added
Location selection tailing pond	**B3**	**A2**	Added

2.4. Recoverable metal

2.4.1. Metal grade

The metal grade in combination with the amount of ore can determine the amount of metal that is present in the ore. The grade is expressed in percentage or in parts per million. Another expression for parts per million is grams per tonne. The metal grade is key to determining the value of an SMS deposit, since it tells how much of valuable metal is present within the deposit.

The composition of SMS deposits is highly variable. Not all elements contained in the sulphide ore are of commercial interest. Some elements, like arsenic, are considered a penalty element. Copper, zinc and lead are elements that make an SMS deposit attractive for exploitation. Valuable metals such as gold and silver are trace components of the sulphides but can be highly enriched in some deposits, making them very attractive for exploitation.

The geochemical composition of seafloor massive sulphides is not only variable on a regional scale, but also varies at the deposit or even on hand-specimen scale. As a result of this heterogeneity, the sampling of black smoker chimneys, which commonly show high concentrations of copper, might not be representative of the bulk composition of the deposits. Many published grades of seafloor sulphide deposits are strongly biased due to sampling of chimneys, which are easier to recover than sub-seafloor mineralisations. Unfortunately, with the exception of a few deposits that have been drilled through the Ocean Drilling Program or by commercial or scientific projects, little is known about the interiors of most seafloor massive sulphides deposits. Due to lack of information about the important subsurface component of deposits, it is difficult to estimate the resource potential of most seafloor massive sulphide deposits.

To resolve this lack of information, VMSdeposits can be compared with seafloor massive sulphide deposits. Volcanogenic massive sulphide deposits are based on land and can have a similar origin as seafloor massive sulphide deposit. Figure 2.9 is a comparison between the mean metal grade in an SMS deposit and the statistical information known about VMS deposits for three base metals: copper, zinc and lead. The same is done for silver, Figure 2.10, and for gold, Figure 2.11.

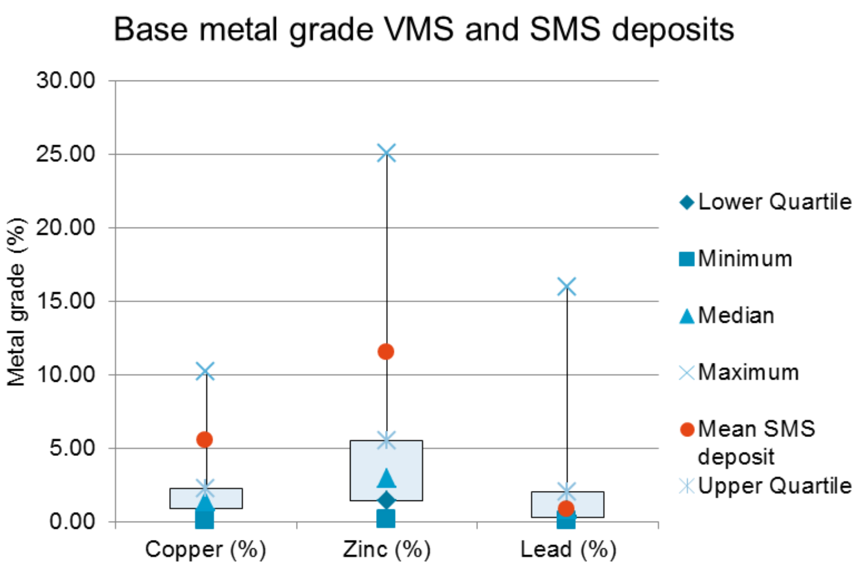

Figure 2.9: Metal grade of copper, zinc and lead in boxplots with the mean of known SMS deposits [1].

From the comparisons made between VMS and SMS deposits it can be stated that SMS deposits have a higher metal grade on average. Only for lead, the metal grade appears to be equal between both deposit types.

These graphs can give a first estimate or interpretation of what can be expected when an SMS deposit is found. However, they provide limited information to assess the economic feasibility of an SMS deposit. When used to assess the economic feasibility, the level of uncertainty should be considered as extreme. The impact is extensive and the likelihood frequent, or *'D4'*. The metal grade can be determined using core drillings. This will have a level of uncertainty of unlikely and moderate impact, or *'B2'*.

Metal grade	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Metal grade	**D4**	**B2**	Added

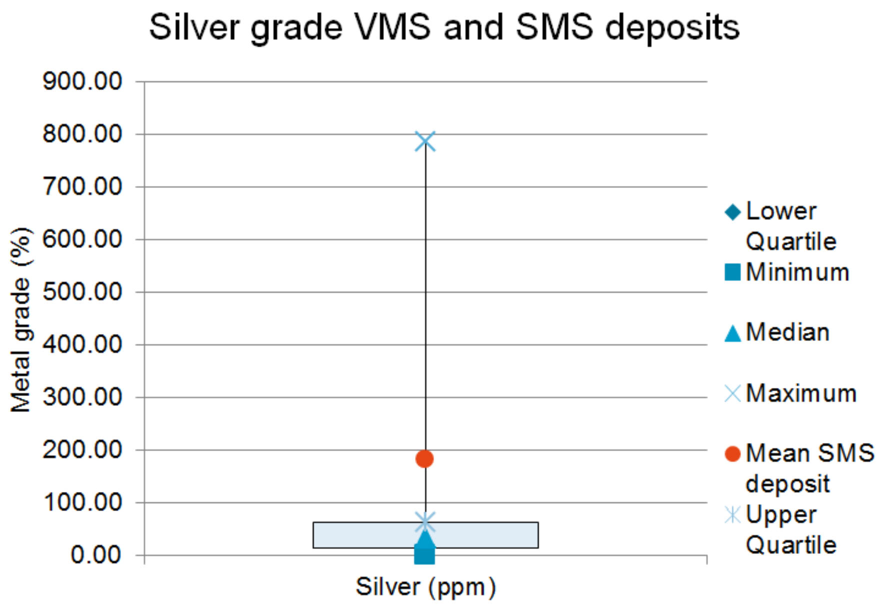

Figure 2.10: Metal grade of silver in boxplots with the mean of known SMS deposits [1].

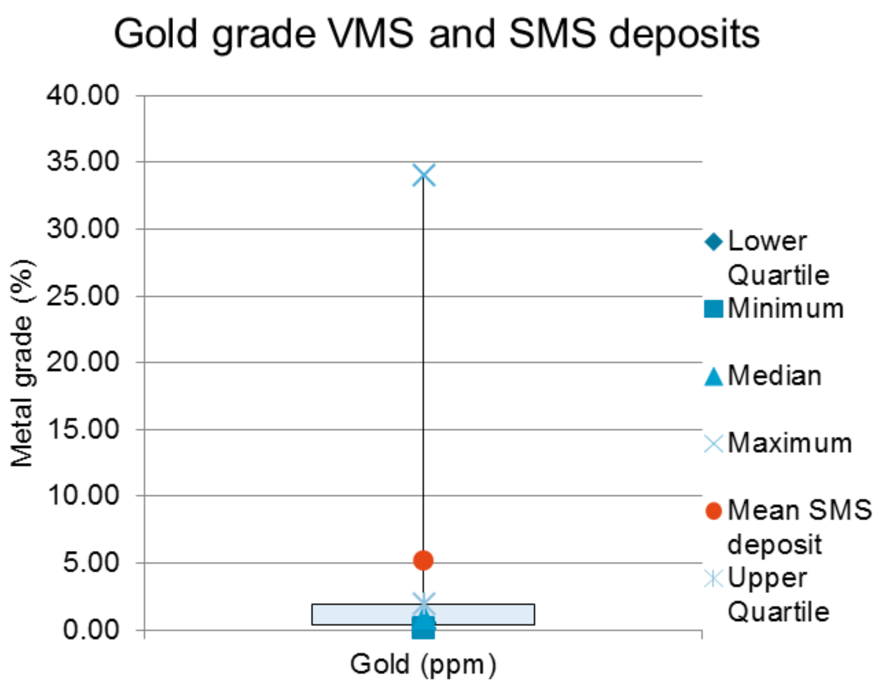

Figure 2.11: Metal grade of gold in boxplots with the mean of known SMS deposits [1].

2.5. Payable metal

2.5.1. Commodity prices

Seafloor massive sulphide deposits contain multiple metals: base and valuable metals. Base metals considered to add value to an SMS deposit are copper, lead, nickel and zinc. Valuable metals considered are gold and silver. This totals to six different commodity prices that should be considered in assessing the economic feasibility of an SMS deposit. In this thesis two, copper and gold, are briefly discussed. The commodity price is the most important determinant of revenue. Future metal prices are notoriously difficult to forecast accurately, but attempts should be made.

There are four different ways to determine the metal commodity prices. The first is the producer price. The producer sets the price taking into account costs, potential markets and levels of competition. This was common metals like aluminium, molybdenum, cobalt and nickel. The second is the negotiated price. The price is determined by direct negotiation between buyer and seller. This is common in long-term contracts for ore, metal concentrates or metal products. The third way for determining the commodity price is independent pricing. The price is determined by sources that are neither buyer nor seller of metals. Prices are averages of prices actual transactions between producers, consumers and metal traders. Examples of metals are magnesium, titanium, iridium, aluminium and uranium. The fourth way is commodity exchanges. The two biggest and most well-known metal exchanges are the London Metal Exchange (LME) and the CME Group. The prices are determined by transactions of dealers who are representatives of metal buyers, seller and metal traders. The trade is done in spot, present or forward and in future prices. The LME trades in the metals aluminium, cobalt, copper, molybdenum, lead, nickel, tin, zinc and steel products. The CME Group trades in the silver, gold, copper, platinum, palladium and steel products [22].

Copper is used across a wide range of sectors and industries. This explains the direct link with economic activity in those sectors and industries as well as indirectly with the overall economic activity. The sectors and industries of copper are:

- Manufacturing sectors
- Installation sector
- Energy sector
- ICT sector
- Construction sector
- Medical sector

The copper price has experienced some major peaks and lows over the past decennia. This is one of the reasons why it is more relevant to track the long-term price trend than the short-term movements. The highest price, adjusted for inflation, was recorded in 1966 at 11,334 USD per tonne. The price then trended downward, reaching a low of 2,052 USD per tonne in 2002, before it starts moving up again. It fell back briefly after the collapse of Lehman Brothers in late 2008, but then soared to high levels, peaking at 9,284 USD per tonne in 2011. An important reason behind the uptrend in the copper price since 2002 is the very strong demand for copper from China, which needs the metal to facilitate its industrialisation and urbanisation process [15].

On average, the prices of all base metals strengthens in the first four months of the year. This is followed by six months of volatility before it strengths again during the last two months of the year. This price trend is called the seasonal movement. The seasonal movements in copper price are an interesting phenomenon, but are not a guarantee for copper prices in the future. The seasonal movement of the copper price is not of interest to deep-sea mining projects that produce and sell copper over a longer period of time.

Next to these macro impacts on the copper price, there are some other forces micro that affect the price of copper. For example, between January and August 2014 the price came under pressure from many factors that were not directly of a fundamental or cyclical nature. In early March that year, the copper price was hit by a sharp downward correction following the collapse of the Chinese company Chaori Solar, which failed to meet its corporate bond obligations. In response to this default, stakeholders began to worry more about Chinese economic growth and future demand of copper. Around June that year, fraudulent practise came to light in the Chinese port of Qingdao, where the same shipment of copper had been used as collateral in a number of financing deals. This made stakeholders nervous about the future liquidity of the market [15].

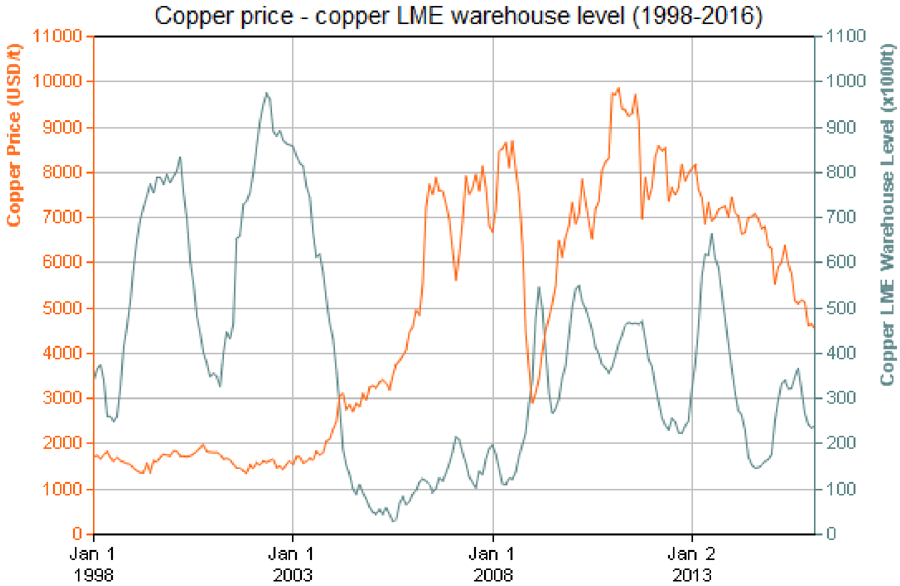

Figure 2.12: Copper price and copper LME warehouse level from 1998-2016 [3].

Commodity exchanges have warehouses where a physical supply of metal is stored. In this case the copper supply is the total available for purchase in these warehouses on a particular day. Traders know this supply and also know of any constraints on supply, like smelter or mine shutdowns. Thus they know as much as possible about the market and bid or ask a price on that basis. The correlation coefficient between copper stocks and price is anti-correlated, see Figure 2.12. Similar results are there for other base metals [22].

These macro and micro effects on the price of copper make predicting the copper price have a level of extreme uncertainty, or *'D4'* with extreme impact and frequent likelihood. As mitigation measurement, a bandwidth for the copper price can be established for which the project is feasible. It can then be calculated, with all price history data available, what the possibility is that the target bandwidth is met. For example, the project is only feasible if the price of copper is higher than 5,000 USD per tonne. With respect to the historic price data over the past ten years it can be calculated that the price of copper was within the bandwidth for 89.3% of the time, see Appendix A.1. This means that the project would be feasible to operate for 89.3% of the life time of the mine with the copper price within the bandwidth. If the historic price data is taken over the past twenty years, the price of copper would be within the bandwidth for 44.8% of the life time of the mine. This illustrates that even with a bandwidth and historical data the impact could be extensive, but with a likelihood of unlikely, resulting in a uncertainty level of *'B4'*. This level of uncertainty can be lowered by taking a broader bandwidth. Mitigation of this uncertainty would be to make a robust plan where the project would be feasible at an as low as possible copper price. The same level of uncertainties are applied to the volatility of the copper price.

Gold is used in the jewellery, technology and investment sectors and industries. Furthermore, it is used by central banks and other institutions. Gold is not linked with the overall economic activity, like copper is. The demand for gold differs strongly compared to the demand for copper. Where copper is used on a day-to-day basis, over the past 5 years, more than half of the demand for gold was for jewellery, 51%, see Table 2.3.

In the late 1990s, the central banks began selling their gold supply and therefore the gold price decreased. Hedging of gold by gold producers during the same period effectively increased the supply because hedging effectively selling gold that is not yet mined. However, producers have decreased hedging activity since about 2000. Terrorist activities in 2001-2002 may have cause investors to protect the value of their portfolios with gold causing an increase in price [22]. The more recent price increase and decrease cannot be explained by the increasing inflation or by the need for portfolio protection.

Table 2.3: Gold demand over the past 5 years in tonne and percentage [World Gold Council, 2015]

Gold demand	5-year average [tonnes]	5-year average [%]
Jewellery	570.3	51%
Technology	98.3	9%
Investment	328.3	29%
Central banks and other institutions	117.1	11%
Total	1,114	100%

Other forces such as sovereign debt, the level of economic uncertainty or the low oil price may be the cause of the price variation, as shown in Figure 2.13.

Figure 2.13: Gold price from 1990-2016 [3].

The prediction of the gold price has a level of extreme uncertainty, or *'C4'* as the impact is extreme and the likelihood is likely. The same mitigation measurement as for copper price, using a bandwidth and historical data, could be implemented. This mitigation results in a medium or high level of uncertainty depending on the bandwidth that is chosen. The same levels of uncertainties are applied to the volatility of the gold price.

Commodity prices	Uncertainty	Mitigation	Added/Multiplied
Future commodity prices	D4	B4	Multiplied
Volatility of commodity prices	D4	B4	Multiplied

2.6. Net smelter return

The processing plant, that will process the sulphide ore from mined seafloor massive sulphide deposits, will use flotation to produce a concentrate that has a grade of 25-30% copper. This copper is transported to a smelter where pure copper is made. Unless the deep-sea mining company owns the smelter, the sale of concentrate is governed by a smelter contract. The payment received by the mine is often called the net smelt return (NSR). The NSR is a measure of value of ore. NSR is defined as the proceeds from the sales of mineral products after deducting off-site processing and distribution costs [26]. In sulphide deposits, containing copper and nickel, the NSR usually corresponds to about 56-60% of the gross value of the metal contained in the ore. This value drops to around 40% for ores with significant quantities of lead or zinc. The presence of gold and silver in the ore will generally increase these percentages. The NSR serves two main purposes. The first is to provide a common denominator for the comparison of assays from polymetallic deposits. The second is to create a healthy awareness of the economic factors which determine the value of ore. Both purposes serve this thesis. To obtain the NSR, a NSR model can be used that contains the following parameters:

- Payable metals. For copper, usually 1.0 or 1.4 units less than the copper contained in the concentrate. A unit is one percentage point. Thus, a 1.0 unit deduction in a concentrate grading 25.0% copper would mean that (25.0-1.0)/25.0 or 96% of the contained copper would be paid for.
- Smelting fees. In currency per dry tonne of concentrate.
- Penalties. Imposed by the smelter if the concentrate that is delivered holds unduly high concentration of certain substances that are not favourable for the smelter.
- Refining charges. In cents per pound of payable metal. In this thesis in cents per pound of payable copper.
- Freight charges. In currency per wet tonne of concentrate.
- Insurance costs, marketing expenses and physical losses of concentrate during transportation.

All these parameter have multiple other parameters and can either be industry, market or some other type of dependency. All parameters needed for obtaining the NSR pose uncertainties as they are unknown. The impact is considered to be severe to moderate. Smelting fees, penalties and refining charges are considered severe, as they are multiplied. The freight charges and insurance are fixed costs and the impact is considered to be moderate. The likelihood is, up front, likely and after checking with suppliers, smelters etc. to be remote, but with the same impact.

When producting a concentrate there are two extra products: by products and co products.The by products are a secondary metal produced in the mining and processing of another metal and usually not importent to the viability of the mine. These could be gold or silver in a copper concentrate. The co products are metals that are mined and produced together with the main metal. The have an important role in the viability of a mine. These could be lead and zinc that are usually produced together.

In the case of seafloor massive sulphide deposits, the concentrate will consist of a mixture of copper and gold. Because of the uncertainties and expensive extraction in deep-sea mining, gold and silver will probably need to be co-products instead of by-products. This will have its effect on the type of smelter of refinery contract. The impact on the level of uncertainty is considered to be severe, as it is considered that the valuable metals will contribute greatly to the value of SMS deposits. The likelihood is likely. Making contracts with smelters and refiners give more certainty. The impact stays the same, but the likelihood will decrease to remote.

Net smelter return	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Smelting fees	**C3**	**A3**	Multiplied
Penalties	**C3**	**A3**	Multiplied
Refining charges	**C3**	**A3**	Multiplied
Freight charges	**C3**	**A3**	Added
Insurance costs	**C3**	**A3**	Added
Valuable metals co or by product	**C3**	**A3**	Multiplied

2.7. Operating cash flow

2.7.1. OPEX

The operating expenditures (OPEX) is the sum of mining, beneficiation and administration. Beneficiation is the process which removes the gangue minerals form the ore to produce a higher grade product and a waste stream. Examples of parameters that influence the OPEX are labour costs, consumables, power, water, exploration and evaluation costs, mine development adjustments, third-party smelting, refining and transport costs, by-product deduction costs, administrative and distribution expenses, closure provision, severance charges, currency gain and losses [10].

The OPEX can be expressed in two ways. The first is the OPEX per day of the whole mining operation, this is in financial accounting the way to express the OPEX. The second method is the

OPEX per tonne. This gives an insight what the operational costs are for one tonne of concentrate. With this second method it is easier to compare operations and calculate the economic feasibility of mining operations. The OPEX per tonne is obtained by taking the OPEX per day and divide that by the amount of concentrate that is produced that day.

Most of the operating expenditures for deep-sea mining have to be estimated. Although this is also done for mining operations on land, because of the extra's that are required in deep-sea mining, this poses an uncertainty. The impact of these estimates can be extensive as they are multiplied in the calculations. The likelihood of this uncertainty is frequent. Mitigation is possible with the use of simulations. The process can be simulated and the expenditure can be obtained from these simulations. The impact will decrease to moderate or minor depending on the what part of the OPEX is wrongly interpreted. The likelihood will be remote as many scenarios could be simulated.

Operating expenditure	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Estimating OPEX	**D4**	**A2**	Multiplied

2.7.2. Mineral processing parameters

Mineral processing parameters is a collection of multiple parameters that are involved in the treatment and refinement of the sulphide ore into ore grinding, ore concentrate, ore refinement and metal. A simplification of these parameters gives the energy that is required for size reduction and other treatment, the wear of equipment, labour, consumables that are used for the mineral processing of the ore and efficiency of the equipment. Equipment involved in the mineral processing are semi-autogenous mills, ball mills, sieves, hydrocyclones, froth floatation cells, filter presses and more.

In this thesis, the Nautilus Mineral setup for treating the ore is used. After extraction from the seabed, the ore is transported to the surface. At the surface the ore is saturated with salted seawater. Before transport or processing, the ore should be dried using sieves. There is an option now to treat the ore offshore on a vessel or platform, or to transport it to shore so it can be processed on land. The last option is chosen in this thesis since offshore processing of sulphide ore only makes sense if waste management would allow the tailings to return to the seabed. The toxicity and environmental regulations make returning the tailings to the seafloor with current knowledge not feasible. Therefore, it is assumed that all the ore is transported to shore after drying it on the production vessel.

Each of the processing steps has its own uncertainties. It is however not the aim of this thesis to go into the details of possible uncertainties in mineral processing. That would be impossible since there is no elaborated plan for the mineral processing. As there is not sufficient material for testing mineral processing equipment, there is no data available to start designing an optimal processing plant. Examples from sulphide ore processing plants can be used to have a first indication on the design of the plant. The level of uncertainty is considered to be moderate, as designs in processing plant for sulphide ore is are straight forward. It is the optimization of the processing plant that poses an extensive impact. The design optimisation included all kinds of uncertainties like recovery rates, size reduction ratios, drying efficiency and more. Every unit of copper or gold counts when mineral processing the ore. The likelihood for the the plant design is considered likely. The optimization of the plant is considered likely. Mitigation for both uncertainties is acquiring sufficient test material for plant design and optimization. Both uncertainties have after mitigating a level of minor impact and unlikely likelihood.

Mineral processing parameters	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Plant design	**B2**	**A1**	Added
Plant optimization	**B4**	**A1**	Multiplied

2.7.3. Seawater temperature

The temperature of the seawater is directly correlated to the OPEX, as the impact of the seawater temperature influences operations that can be or can or can't be done at some temperatures, for example freezing temperatures. The seawater temperature can be defined in three different stages: surface temperature, the water column between surface and seafloor temperature and temperature at the seafloor.

The surface seawater temperature is not the most important factor for deep-sea exploitation, however, when the sea is frozen a lot of challenges would need to be faced, for obvious reasons. It is expected that exploitation is limited to areas where the sea temperature is never lower than the temperature at which the sea forms ice, since the operational risk would increase enormously when exploitation would take place at areas where the seawater can freeze.

The temperature of the seawater between surface and seafloor is expected to decrease with water depth see Figure 2.14. On certain points a thermocline occurs, at which the temperature will decrease more rapidly. The average seawater temperature is between 2 and 4°C [46]. It is not expected that this relative small difference of temperature poses an additional risk to the exploitation operations.

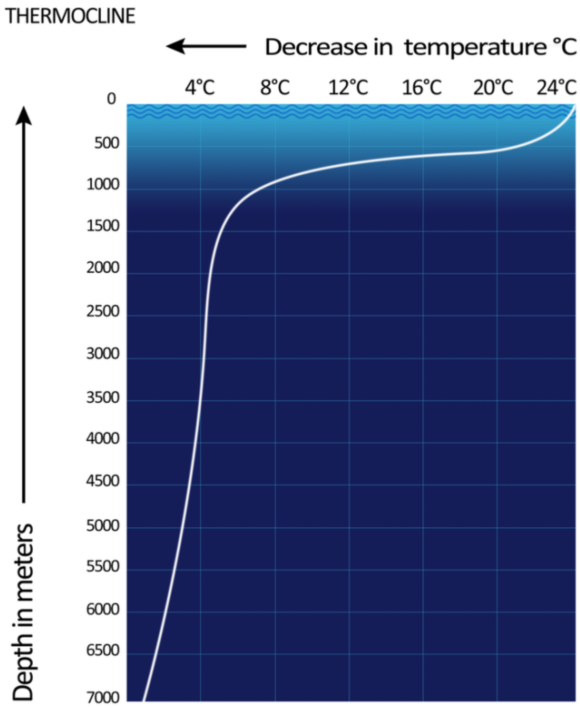

Figure 2.14: Decrease of seawater temperature with water depth for an area with warm seawater [50].

The seawater temperature at the seafloor is not only dependant on water depth, but also on the presence of active hydrothermal vent fields. The seawater temperature from a hydrothermal vent can rise to 350°C [32]. Due to environmental restrictions, because of the fauna present at hydrothermal vent fields, it is not expected that exploitation will be taken place at locations where hydrothermal vents are active. Therefore it is not expected that huge temperature differences in the seawater will occur at the seafloor that would result in uncertainties.

There are no direct uncertainties involved with the seawater temperature. The range of the temperature is too small to pose any risk to the engineering of the equipment used for extraction or vertical transport. The only uncertainty somewhat related to the seawater temperature would be lose drifting iceberg from colder areas towards the mining site. For obvious reasons, this is not an uncertainty for all locations of SMS depots. In areas where lose icebergs are able to disturb mining operations the impact is extensive as operation will need to be interrupted and target are not met. The likelihood is however remote. Therefore the level of uncertainty is high, or *'A4'*. This uncertainty could be mitigated, by investing the ice drift in the area of the mine site beforehand and if necessary install early ice detection measurements, to a low level of uncertainty, or *'A1'*. This uncertainty will be highly unlikely to none existing in tropical waters.

Seawater temperature	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Lose/Drifting icebergs	**A4**	**A1**	Multiplied

2.7.4. Sea state

The sea sate is the general condition of the free surface on a large body of water, with respect to wind waves and swell at a certain location and moment. The sea state directly correlates to the OPEX, as the impact of the sea state influences the operability of the vessels and equipment used offshore. The sea state varies with time as the conditions can change. The sea state is expressed in the Douglas sea and swell scale from 0 to 9, were 0 has calm characteristics and 9 has phenomenal characteristics [7], see Table 2.4. The sea state is an impact on the workability of the tools used for both the exploitation on the seafloor and the infrastructure towards and at the sea surface. Today's vessels are not capable of working under all sea state conditions.

Table 2.4: Sea state level with wave height and characterisation [7].

Sea state level	Wave height [metres]	Characteristics
0	0	Calm
1	0-0.1	Calm
2	0.1-0.5	Smooth
3	0.5-1.25	Slight
4	1.25-2.5	Moderate
5	2.5-4	Rough
6	4-6	Very rough
7	6-9	High
8	9-14	Very high
9	>14	Phenomenal

The sea state can either be assessed by an experienced observer or through instruments like weather buoys, wave radar or remote sensing satellites. Waves can be generated in different ways:

- A floating structure which is moving
- The interaction between wind and the sea surface
- Astronomical forces or tides
- Earthquakes or subsea landslides

The wind can reach speeds of more than 33 metres per second. Besides causing waves, wind causes aerodynamic forces on a structure at the sea surface. The wind speed can be measured with a anemometer or by observation. Because the wind is not constant, the aerodynamic force, or drag, is not constant either.

The sea state is closely related to the climate and current location of the SMS deposit. SMS deposits in sheltered water will assumingly have an overall average lower sea state level in comparison to Mid-Atlantic ridge locations that lay in the middle of the ocean in full exposure to the elements like currents and wind. The location of the geological occurrence determines what the sea state of that location can be. If the sea state is such that offshore working will be challenging, then a higher uncertainty classification should be accounted for. On beforehand, the sea state isn't known, so it is assumed to be highly uncertain, with a severe impact and likely likelihood, or *'C3'*. Mitigation by investigating the sea state throughout a longer period can help prevent downtime due to bad sea state conditions, resulting in a low level of uncertainty with remote likelihood and moderate impact, or *'A2'*.

Sea sate	Uncertainty	Mitigation	Added/Multiplied
Unpredictable sea state conditions	C3	A2	Added

2.8. Cash flow after capital

The capital, or capital expenditures (CAPEX), is defined as development, construction, indirect costs like engineering and management, contingencies, start-up, inventories, working capital, inflation cost, replacement and sustaining capital and closure costs. CAPEX estimates will generally need to consist of:

- Initial preproduction cost of constructing a new mining company,
- On-going cost of replacing worn out equipment throughout the productive life of the operation.

One of the positive aspects of deep-sea mining is the fact that a mining company is not bound to a single location. This results in a reduction of CAPEX since the initial preproduction costs of constructing a new mining company is spread over multiple mining projects. Although the initial preproduction costs are spread over multiple mining projects, there are some initial costs that can't be spread over multiple projects like purchase of a mining license.

According to Baurens [10], the degree of accuracy of preproduction capital expenditure can vary in the region of plus or minus 30%, depending of a stage of the project. Contingency allowances of 8 to 12% are typically applied to the estimates of surface capital expenditure, with somewhat higher allowances applied to the estimated cost of capital mine development. The estimates for deep-sea mining operation are possibly higher because of the complexity of working offshore. Equipment, like the production vessel, vertical transport system and seafloor exploitation tools, has a limited economic life and works fall out of use, therefore an annual depreciation charge must be considered as part of the cost. Depreciation provides for the recurring expenditure on necessary replacements and for the complete redemption of the related capital expenditure before the inevitable closure sets in. An annual depletion charge is calculated to redeem the previous purchase or the exploration cost of the mineral property. Together, depreciation and depletion may be considered capital costs [10].

Predicting or calculating the CAPEX has its uncertainties. As deep-sea mining equipment needs to be newly developed and build is the expenditure not fixed. Examples from the Nautilus tools can be observed as they were anticipated to be cheaper [14]. The uncertainty of correctly predicting the CAPEX is considered to be a fixed added cost. The level of uncertainty obtained from the severe impact, as all the extra costs need to be made mostly in advance of the project, making the project reliable on possible third party contributors. The likelihood is frequent, resulting in *'D4'* as the level of uncertainty. Mitigating measurements are strict contracts with suppliers. Even with these measurements, there is still a likely likelihood and severe impact, or *'C3'*.

The contingency allowances are considered to be the same as on land. As they are presented in a percentage, they don't pose an extra uncertainty to deep-se mining. The impact of the contingency is considered to be severe as mining operations have to be delayed or stopped if the allowances are not correctly estimated. The likelihood is considered likely. A higher allowance estimate can mitigate this uncertainty to a medium level of uncertainty, where it is unlikely and moderately on impact. Although it is a percentage and thus multiplied, it is considered a fixed costs. It is assumed that the depreciation costs for deep-sea mining are the same as for other off-shore equipment. Therefor the depreciations cost are not an extra uncertainty in deep-sea mining operations. The level of uncertainty for depreciations has a moderate impact and unlikely likelihood. No mitigations required.

Capital expenditure	**Uncertainty**	**Mitigation**	**Added/Multiplied**
Predicting CAPEX	**D4**	**C3**	Added
Contingency allowances	**C3**	**B2**	Added
Depreciation costs	**B2**	**B2**	-

2.9. Net cash flow

Tax is a financial charge or other levy imposed upon a taxpayer by a state or the functional equivalent of a state to fund various public expenditures. Royalty tax is a tax that is unique to the natural resources sector. It has a variety of forms, sometimes based on measures of profitability but more commonly based on quantity of material produced or its value [48].

Regulations governing the levels of taxation applicable to the exploration and exploitation of SMS deposits companies vary from jurisdiction to jurisdiction and are depend in what legal regime the SMS deposits is situated. Taxes usually applied can be summarized like this [10]:

- Income tax: 25-35%
- Withholding tax on dividends, loan interest and services: 10-20%

- Royalty: 2-4%

Since the cash tax payable are invariably a significant component of the valuation, it is a task which must be undertaken with a degree of care [36]. The tax and royalties are not considered as uncertainties. There is, however, a level of uncertainty in the amount of tax and royalties. Some countries have a less stable government or laws that may change over time. The impact of those events would be severe and unlikely, or *'B3'*. A stable country will decrease the likelihood to remote, or *'A3'*.

Royalties and taxes	Uncertainty	Mitigation	Added/Multiplied
Royalties and taxes	A1	A1	Multiplied
Changes over time	B3	A3	Multiplied

2.10. Net present value

2.10.1. Net present value

Time value of money dictates that time has an impact on the value of cash flows. A cash flow today is more valuable than an identical cash flow in the future because a present flow can be invested immediately and begin earning returns, while a future flow cannot. Cash flows of nominal equal value over a time series result in different effective value cash flows that makes future cash flows less valuable over time [11]. Net present value (NPV) is determined by calculating the costs and benefits for each period of an investment. After the cash flow for each period is calculated, the present value of each period is achieved by discounting its future value, using the discount rate, at a periodic rate of return. NPV is the sum of all present values of incoming and outgoing cash flows over a period of time, see Equation 2.4. NPV is an useful tool to determine whether a project or investment will result in a net profit or a loss.

$$NPV(i,N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \tag{2.4}$$

Where t is time of the cash flow in years, i the discount rateand R_t the net cash flow in US dollars per year. As time, discount rate and net cash flow are part of other parameters, the net present value has no uncertainties of its own.

2.10.2. Discount rate

The discount rate is used to determine the present value of future cash flows. There are no guidelines that hold the board, even though this is a key factor driving the end result of the net present value. The major areas of difference rest on assessments of cost of capital, political risk and project development risk.

The cost of capital depends on the mode of financing that is used: cost of equity, cost of debt or a combination equity and dept. The cost of equity is the return that stockholders require for a company. The cost of debt is the effective rate that a company pays on its current debt. The cost of equity consists of a risk free rate of return and a premium assumed for owning a business. These premiums are an additional factor that has to be paid extra on top of the risk free rate. Depending on your location, this premium can vary, see Table 2.5. For deep-sea mining the rating will be even higher, but might have a link premiums on land that is closest to the mine site.

The level of uncertainty in costs of capital are extreme. As there is no precedent, it not sure what to expect from the cost of capital. The impact is however severe as the whole project is leaning on capital. The likelihood will be likely, resulting in a level of uncertainty of *'C4'*. A strong partner can help mitigate this uncertainty a less likely uncertainty level of *'B4'*.

The political risk discount factors are even more subjective. This is due to the uniqueness of every company in its aggregate exposure to generic country risk and to more specific project-related risk. In addition, most investors will be pricing political risk in different contexts, depending on their own portfolio spreads, ability to hedge, and even the requirements for a particular country exposure. One of the key elements that equity markets consider most important in determining the success or failure of the vital development phase is the security of tenure. The security of tenure within The Area poses an

Table 2.5: Average of the total risk premium for different locations in the world [19].

Location	Average of Total Risk Premium [%]
Africa	12.35%
Asia	9.65%
Australia and New Zealand	8.25%
Caribbean	11.23%
Central and South America	11.50%
Eastern Europe and Russia	10.39%
Middle East	8.42%
North America	6.00%
Western Europe	7.93%

uncertainty. A mining company can, with backup from a nation, set claims to certain area's in the seas and oceans. These claims are registered and bought at the International Seabed Authority (ISA). The ISA is an intergovernmental body that was established to organize, regulate and control all mineral-related activities in the international seabed area beyond the limits of national jurisdiction. It is an organization established by the Law of the Sea Convention. This Law of the Sea Convention is however never signed by the United States of America and some other countries, like Peru and Kazakhstan [2, 52]. It is likely, when an area is claimed near the border of the EEZ of another country, that this would lead to a dispute between both countries, making the security of tenure extreme uncertain over a longer time period. There are examples of modern day oilfields that are even within the EEZ boundaries of countries that lead to dispute between countries [59]. The impact of an international dispute could result in extensive damage and shutdown of the deep sea mining project. Hence, the security of tenure for deep sea mining projects within The Area is classified as *'D4'*, an extensive impact and frequent likelihood. There are multiple ways to mitigate this uncertainty. The first is to select the country that is closest to the site of the mining project with its national border. However, as stated earlier, this is no guarantee for success. A second option would be to select a country with good international relations within the area where the project is situated. Although this creates a challenge if the location is in the middle of the Atlantic Ocean since the closest country is 2,000 km away an many countries surround the ocean. A third option would be to select a country with a strong navy and high commitment to securing its raw materials. This seems a very radical measurement, but the example used of China earlier about the international dispute about oilfields, proves that this measurement works. The only thing these mitigations can achieve is reducing the level of uncertainty to unlikely, ore *'B4'*.

Next to the cost of capital and political risk there is the project development risk or technical risk. The technical risks can be divided in reserve risk, completion risk and production or equipment risk. The reserve risk is determined by both nature and quality of ore-reserve estimates and reflects the possibility that actual reserves will differ from initial estimates. The completion risk reflects the possibility that a mining project will not make it into production as anticipated because of cost overruns, construction delays or engineering design flaws. Production risk reflects the possibility that production will not proceed as expected as a result of production fluctuations caused either because of problems with equipment or extraction processes or because of poor management. As all sub-sea equipment scores a 3 out of 9 on the technological readiness level in the Ecorys [25]. See extraction method and vertical transport method for more explanation about the uncertainty.

Discount rate	Uncertainty	Mitigation	Added/Multiplied
Cost of capital	**D4**	**B4**	Added
Security of tenure within The Area	**D4**	**B4**	Added
Technical risk	**D4**	**B4**	Multiplied

3

Economic feasibility assessment

3.1. Geological resource

When determining the economic feasibility of a seafloor massive sulphide deposit a series of calculations are required. The basis of the economic value of a sulphide deposit is the deposit itself. The grade and tonnage determine the amount of valuable metal which is present. In the case of seafloor massive sulphide deposits, like stated in the deep-sea mining concept in the beginning of this thesis, it will be likely that a single deposit will not be economically feasible. Therefore, multiple deposits in the vicinity of one another will be combined as one big sulphide deposit. In order to do that, the total amount of metal that is present needs to be determined, see Equation 3.2. Combined with the total tonnage, see Equation 3.3, the overall grade of the metal can be determined, see Equation 3.4. But first the amount of metal per deposit needs to be determined, see Equation 3.1.

$$\text{metal [tonne]} = \text{tonnage of deposit [tonne]} \times \text{metal grade [\% or ppm]} \tag{3.1}$$

$$\text{overall metal [tonne]} = \sum \text{(metal [tonne])} \tag{3.2}$$

$$\text{overall tonnage [tonne]} = \sum \text{(tonnage of deposits [tonne])} \tag{3.3}$$

$$\text{overall metal grade [\% or ppm]} = \frac{\text{overall metal [tonne]}}{\text{overall tonnage [tonne]}} \tag{3.4}$$

3.2. Economical exploitable

To assess the economic exploitability of an SMS deposit, the life time of mine and the production rate needs to be established. The adjusted Taylor's Rule is used to get a first indication of both parameters. The life of mine, in Equation 3.5 and Equation 3.6, is in years. The tonnage is in tonnes. The production rate is calculated per day.

$$\text{life [year]} = 0.1 \sqrt[4]{\text{tonnage [tonne]}} \tag{3.5}$$

$$\text{production [tonne/day]} = \frac{\text{tonnage [tonne]}}{\text{life [year]} \times \text{operating days [day/year]}} \tag{3.6}$$

3.3. Recoverable metal

To calculate the recoverable metal, the flowchart as illustrated in Figure 3.1 can be used. The feed in combination with the concentrate or tailing can determine the other, tailing or concentrate. The metals in the tailing are considered lost metals. By establishing the grade in the concentrate and in the tailing, the efficiency can be determined using Equation 3.7.

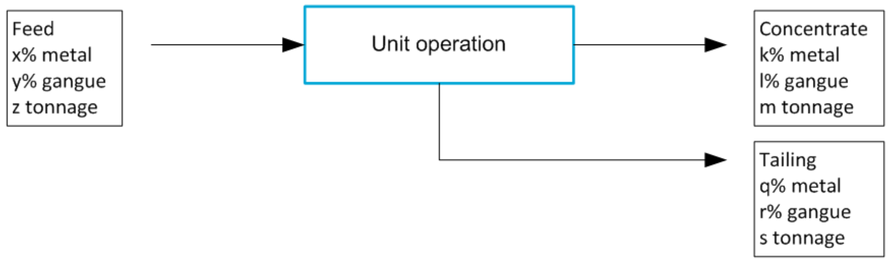

Figure 3.1: Recoverable metal calculation [Wills]

$$\text{recovery efficiency [\%]} = \frac{k \text{ [\%] } metal \times m \text{ [tonne]}}{x \text{ [\%] } metal \times z \text{ [tonne]}} \times 100 \tag{3.7}$$

3.4. Payable metal

The payable metal depends on what is specified in the contract with the smelter. The payable metal can be calculated using Equation 3.8.

$$\text{payable metal grade [\%]} = \frac{\text{metal grade [\%]} - \text{unit deduction [-]}}{\text{metal grade [\%]}} \tag{3.8}$$

An example of a term could be that the buyer shall pay for 96.65% of the final copper grade, subject to a minimum deduction of 1.0 unit at the official LME grade a settlement copper quotation averaged over the quotational period. Now the payable copper would be (30-1)/30= 96.67%, but because of the contract the buyer shall only pay 96.65%. If the copper concentrate would be 25%, the payable copper would be (25-1)/25=96%.

3.5. Net smelter return

To establish the net smelter return, first the following parameters need to be determined:

- Smelting fees
- Penalty elements
- Refine costs
- Freight charges
- Insurance

The NSR is then determined by subtracting all of these costs from the revenues, see Equation 3.9. These cost can either be calculated costs or percentages of other costs.

$$\begin{aligned}\text{Net smelter return [currency]} = \text{revenues [currency]} - (\,&\text{smelting fees [currency]}\\ &+ \text{penalty elements [currency]}\\ &+ \text{refine costs [currency]}\\ &+ \text{freight charges [currency]}\\ &+ \text{insurance [currency]})\end{aligned} \tag{3.9}$$

3.6. Operating cash flow

Now that the amount of ore and metal present in the ore is established, the operational expenditure is calculated. The method for the extraction will determine the energy that is required for the extraction of the ore from the orebody. The method will also determine the ore size and thus the method of the ore's vertical transport from the seafloor to the surface. The methods of Nautilus Minerals are chosen for both the extraction and vertical transport. The contribution to the economic feasibility is calculated by first calculating the energy requirements for both methods, see Equation 3.10 and Equation 3.11. The water depth could play a key role in these calculations. The energy requirements are not the same for every depth nor is getting the energy to these depths the same. This results a non-linear relation between water depth and energy consumption.

$$\text{energy for extraction [kw]} = \text{overall tonnage [tonnes]} \times \text{energy required per tonne [kW / tonne]} \tag{3.10}$$

$$\begin{aligned}\text{energy for vertical transport[kw]} = {} & \text{overall tonnage [tonnes]} \\ & \times \text{water depth [m]} \\ & \times \text{ energy required per tonne per metre [kW/tonne} \times \text{m]}\end{aligned} \tag{3.11}$$

$$\text{costs [currency]} = \text{energy [kW]} \times \text{ energy price per kW [currency/kW]} \tag{3.12}$$

$$\text{costs [currency]} = \text{energy [kW]} \times \text{energy price per kW [currency/kW]} \times \text{ offshore penalty [\%]} \tag{3.13}$$

After these calculations, the ore is virtually on board of the production vessel. The task is now to transport or ship the ore to a harbour, preferably nearby, and then transport it to processing plant. A simple calculation will fulfil for the transport over sea, see Equation 3.14. With equation Equation 3.13, the price for shipping the ore to the harbour can be calculated. The transport on land is similar to the transport over sea, see Equation 3.15. With equation Equation 3.12, the price for transporting the ore to the processing plant can be calculated.

$$\begin{aligned}\text{energy for shipping [kW]} = {} & \text{overall tonnage [tonnes]} \\ & \times \text{ distance to harbour [km]} \\ & \times \text{ energy required per tonne per km [kW / tonne km]}\end{aligned} \tag{3.14}$$

$$\begin{aligned}\text{energy for transport over land [kW]} = {} & \text{overall tonnage [tonnes]} \\ & \times \text{ distance to processing plant [km]} \\ & \times \text{energy required per tonne per km [kW/tonne} \times \text{km]}\end{aligned} \tag{3.15}$$

The ore has virtually arrived in the processing plant. Here it will be processed into concentrate and tailings. The concentrate will be sold to a smelter and the tailings will be disposed of in tailing pond. In this case it is assumed that the tailing pond is within the vicinity of the processing plant.

The total amount of ore will be processed in the processing plant. This means that all the energy per processing step per tonne can be summed and multiplied with the total tonnage in order to get the total energy cost for the mineral processing of the ore. Laboratory research should determine the efficiency and energy consumption of the equipment that is used for processing the sulphide ore, see Equation 3.16. The optimum for the equipment will need to be adjusted during the process of the ore, as no deposit is homogenously distributed, resulting in a variation of input for the mineral processing plant.

$$\begin{aligned}\text{energy mineral processing [kW]} = {} & \text{overall tonnage [tonne]} \\ & \times \sum \text{(energy required per tonne [kW/tonne])}\end{aligned} \tag{3.16}$$

Besides to the energy cost, there are costs for consumables, wear and labour. Consumables is dependant on the amount of ore that is processed, see Equation 3.17. This statement is, however, partly true. Not all of the ore is actually processed as many times as all of the other ore. However, this calculation is adequate for a first assessment on the economic feasibility of an seafloor massive sulphide ore deposit. The same statement holds for wear and labour costs. Therefore, this computation should be valued as a first estimate of price for consumable. Furthermore, the costs of the consumables per tonne is a summation of all the consumables that will be required for the mineral processing. The wear inflicted by the ore on the equipment is depending on the amount of ore that is processed over a certain time period. To calculate this wear, the time of processing is required and so is the total amount of ore processed needed as is the wear costs, see Equation 3.18. Labour in depending on the time period over which the ore is processed, see Equation 3.19.

$$\begin{aligned} \text{consumables costs [currency]} &= \text{overall tonnage [tonne]} \\ &\quad \times \text{ consumable costs per tonne [currency/tonne]} \end{aligned} \tag{3.17}$$

$$\begin{aligned} \text{wear costs [currency]} &= \frac{\text{overall tonnage [tonne]}}{\text{total time processing [days]}} \times \text{ wear grade [\% days / tonne]} \\ &\quad \times \text{ wear costs [currency / \%]} \end{aligned} \tag{3.18}$$

$$\text{labour costs} = \text{total time processing [days]} \times \text{ labour costs [currency / day]} \tag{3.19}$$

The contingency is a percentage, determined by the contingency rate, of the OPEX and can be calculated using Equation 33.22.

$$\text{contingency [currency]} = \text{CAPEX [currency]} \times \text{ contingency rate [\%]} \tag{3.20}$$

Now that we have processed the ore to a concentrate and tailings, we need to dispose the tailings and transport the concentrate to the smelter. The smelter could either be a smelter owned or from another company under a smelter contract. The smelter costs are already included in the net smelter return.

3.7. Cash flow after capital

The capital expenditure, or CAPEX, is a summation of all equipment that is used in order to extract the ore from the seafloor, ship it to land and process it to metal. The CAPEX can be calculated using Equation 3.21. This is the CAPEX without the contingency and depreciation costs.

$$\text{CAPEX [currency]} = \sum \text{(all CAPEX of equipment)} \tag{3.21}$$

All equipment that should be considered can be grouped into the processing steps as they are followed along the timeline:

- Extraction tools
- Vertical lift equipment
- Support vessel
- Shipping or horizontal transport
- Processing plant
- Tailing pond

Some of the equipment might already be in place like the processing plant. However, the additional cost that is generated by hiring or contracting should be accounted for under the cash flow after capital although this is not in line with economic accounting. The contingency is a percentage, determined by the contingency rate, of the CAPEX and can be calculated using Equation 3.22.

$$\text{contingency [currency]} = \text{CAPEX [currency]} \times \text{contingency rate [\%]} \tag{3.22}$$

There are multiple way to determine the depreciation costs. The following depreciation methods are possible:

- Straight line
- Double declining balance
- Annuity
- Sum-of-years-digits
- Unit-of-production
- Units of time
- Group
- Composite

Three methods are interesting for the deep-sea mining concept: straight line and double declining balance depreciation method. Straight line depreciation method uses the salvage value of the asset at the end of life. The same amount depreciation is charged each year over the life time, until the value has the same value as at the end of life. The annual depreciation can be calculated using Equation 3.25.

$$\text{annual depreciation costs [currency]} = \text{cost of fixed asset [currency]} - \frac{\text{salvage value [currency]}}{\text{life time [years]}} \tag{3.23}$$

The double declining balance depreciation method does not consider the salvage value in determining the annual deprecation. The book value of the asset that is being depreciated is never brought below the salvage value. The depreciation stops when the useful life of salvage value is reached. The depreciation costs is calculated using the book value of the asset at the end of the year, and the depreciation rate, see Equation 33.24 and Equation 3.25.

$$\text{depreciation rate [\%]} = 100 \times \left(1 - \left(\frac{\text{salvage value [currency]}}{\text{costs of fixed asset [currency]}}\right)^{\frac{1}{\text{life time [years]}}}\right) \tag{3.24}$$

$$\begin{aligned}\text{annual depreciation costs [currency]} = {} & \text{depreciation rate [currency]} \\ & \times \text{ book value at end of year [currency]}\end{aligned} \tag{3.25}$$

3.8. Net cash flow

The income tax is payed as a fixed percentage over the gross revenue, see Equation 3.26. The income tax is payed annually.

$$\text{income tax assessment [currency]} = \text{gross revenue [currency]} \times \text{ income tax [\%]} \tag{3.26}$$

The way royalties are calculated can differ depending on the contract with the land owner, see Equation 3.27. In order to calculate the royalty tax, a choice can be made between the following types of royalty taxes [40]:

- Gross revenue, a fixed percentage of the gross revenue or total income is payed.
- Net revenue, a fixed percentage of the net revenues is payed.
- Price per unit, a fixed percentage of the ore sold is payed.
- The calculation is then straight forward, a percentage is payed. The royalty is payed annually.

$$\begin{aligned}\text{royalty assessment [currency]} = {} & \text{amount over which royalty has to be payed [currency]} \\ & \times \text{ royalty [\%]}\end{aligned} \tag{3.27}$$

3.9. Net present value

The net cash flow R_t is needed to calculate the net present value (NPV). The net cash flow can estimated is steps. The CAPEX is most likely to be spend in the first year. It is than assumed that the revenue and OPEX is the same for each year. The amount of years t is known from the calculation on the economic exploitability of the deposit. An important factor to determine now is the discount rate i. The NPV can be calculated using Equation 3.28.

$$NPV(i, N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \tag{3.28}$$

For a certain discount rate, the NPV is null. This discount rate can be calculated using the internal rate of return (IRR). With this calculation it is possible draw a conclusion on the discount rate. A project is not feasible when the discount rate is higher than the IRR. A project is feasible when the discount rate is lower than the IRR. Calculating the IRR is useful when comparing multiple parameters on their sensitivity.

3.10. Sensitivity analysis

A sensitivity analysis is a technique used to determine how different values of an independent variable will impact a particular dependent variable under a given set of assumptions. Some of the quantified parameters will be used to calculate their sensitivity towards the economic feasibility of an SMS deposit. These quantified parameters are tax, copper price, CAPEX and OPEX. These parameters are the independent variables. The dependent variable is the IRR. The dependent variable IRR can be compared to other calculations where the outcome is the IRR. To make the input comparable, a range will be determined where there is a standard with a certain deviation of this standard. The deviations of the standard are comparable.

In order to illustrate the sensitivity of these parameters, an example deposit is created. This deposit contains 2.56 million tonnes of ore with a copper grade of 5.0%. The life of mine, using Taylor's rule of thumb, is four years or 48 months. This example deposit doesn't contain any other base or valuable metals. The NSR is assumed 95%. All properties of the example deposit are summarized in Table 3.1.

Table 3.1: Properties of the example deposit used for the sensitivity analysis.

Parameter	Standard
Tonnage	2.56 million tonnes
Copper grade	5%
NSR	95%
Tax	5.00%
Copper price	6,000 USD/tonne
CAPEX	500,000,000 USD
OPEX	10,000,000 USD

To illustrate the sensitivity, a range of values for the quantified parameters is considered. The standard, as indicated in Table 3.1, will function as the start point for the range of values. From this point, a range of -25% up to +25% of the parameter will be used to calculate the IRR. The rest of the parameters will stay the same. The calculated IRR can later be compared with the other IRRs of the other quantified parameters. To determine if there deviation from the standard has a higher deviation, or influence, on the IRR.

Tax is used as an example of this sensitivity analysis calculation. The range of tax starts at 3.8%, which is -25% of the 5% tax, and ends at 6.3%, which is +25% of the 5% tax. For every point in this range, the IRR is calculated and plotted. The same calculations are done for the copper price, CAPEX and OPEX. The IRR of the same weighted range differences, of -25% up to +25%, can now be compared in a plot, see Figure 3.2.

The plot of the outcomes of the sensitivity analysis indicates that the tax and OPEX have limited effect on the assessment of the economic feasibility. The price of copper and the CAPEX have major impact on the assessment of the economic feasibility. With this outcome, it can be concluded that

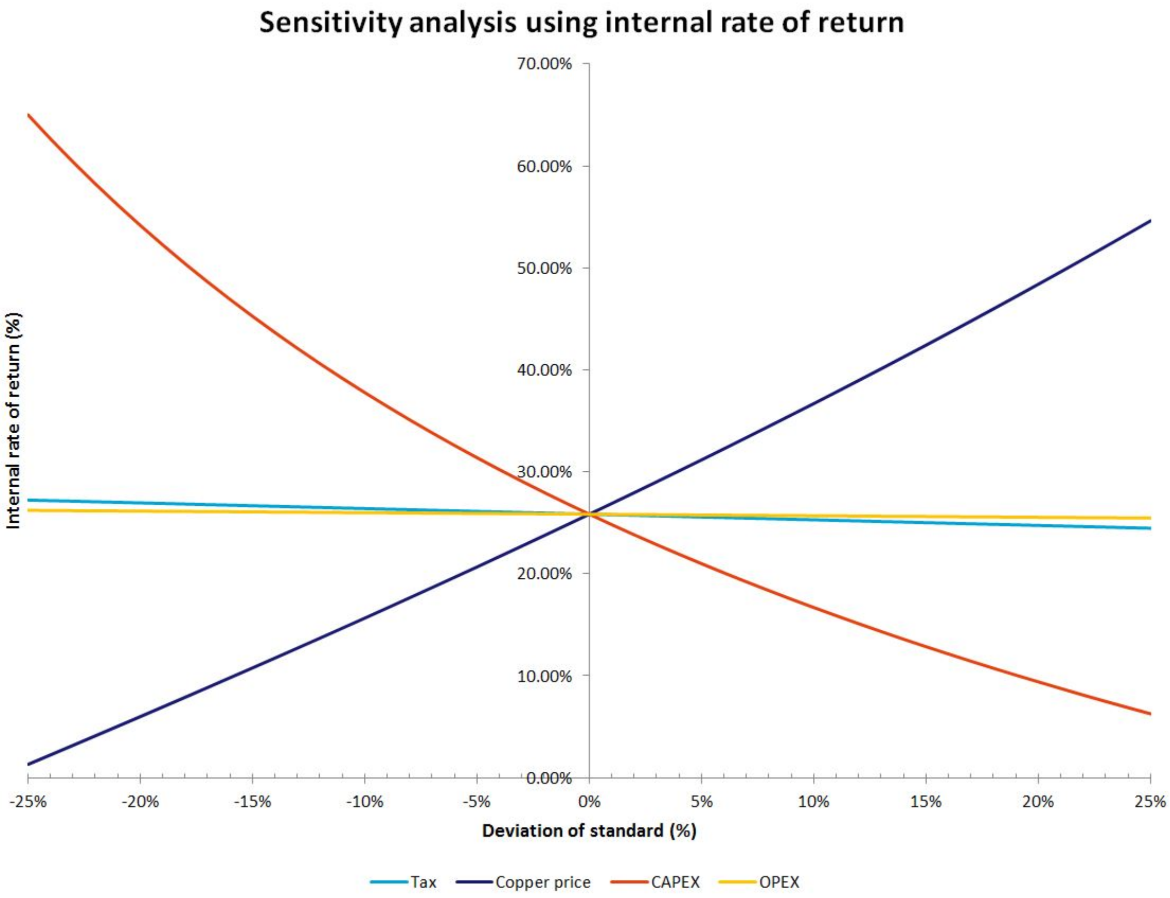

Figure 3.2: Sensitivity analysis using internal rate of return

extra efforts should be made in order to obtain the correct information on the copper price and the CAPEX. Both parameter pose an extreme level of uncertainty towards the assessment of the economic feasibility because of their sensitivity in the feasibility calculations. These observations on the sensitivity correspond with the earlier determination of the uncertainty levels done in the economic feasibility assessment.

4

Economic feasibility case study

4.1. Introduction

Nautilus Minerals Inc. has discovered a number of seafloor massive sulphide deposits in the Bismarck Sea, within the territorial waters of Papua New Guinea (PNG) [38]. Although Nautilus has discoverd multiple SMS deposits, they only have a development plan of their Solwara 1 site. The project will involve the extraction and recovery of SMS deposits in the expected water depths of between 1,500 and 2,500 m [14].

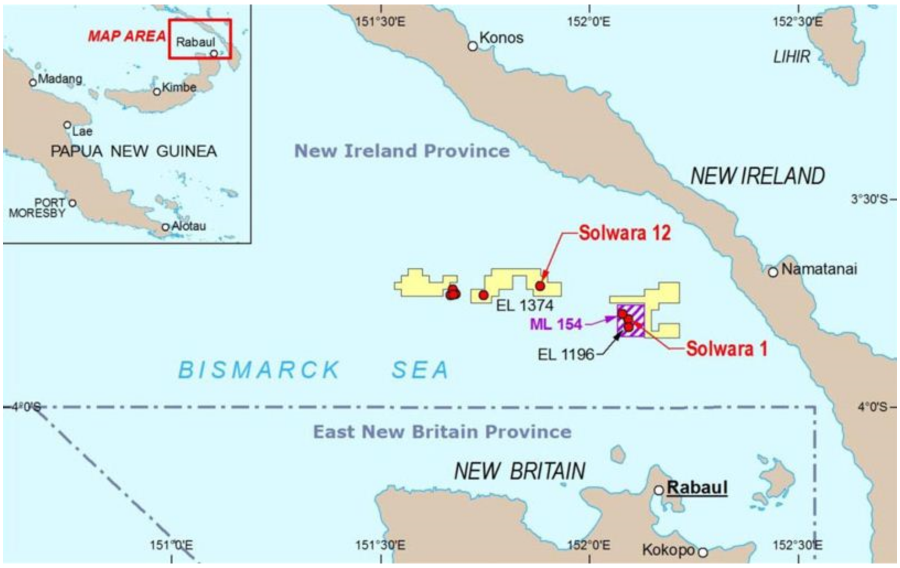

Figure 4.1: Map showing Solwara 1 and Solwara 12 project from Nautilus Minerals Inc. [38].

4.2. Geological resource

Golder Associates carried out a mineral resource estimate for the Solwara 1 deposit in 2007 [38]. The results of mineral resource estimate are summed up in Table 4.1. The indicated resource is composed of seafloor massive sulphides while the inferred resource includes lithified sediments and chimney material in addition to the seafloor massive sulphide. The indicated resource requires a geological confidence level to be classified at least medium, or yellow. For the inferred resource, the level of certainty can be high, or orange. In this thesis, only the resource with the highest level of confidence, indicated resource, is considered.

The Solwara 1 project is one main orebody. Therefore the overall tonnage is equal to the tonnage of the indicated resource. The overall grades are equal to the grades of the indicated resource. By

Table 4.1: Mineral resource estimates of Solwara 1 deposit [38].

Parameter	Indicated resource	Inferred resource
Tonnage [tonne]	870,00	1,300,00
Copper [%]	6.8	7.5
Zinc [%]	0.4	0.8
Silver [ppm]	23	37
Gold [ppm]	4.8	7.2

using the overall tonnage and grade information, it is possible to calculate the amount met metals that is present in the indicated resource, as presented in Table 4.2.

Table 4.2: Overall tonnages of tonnage, copper, zinc, gold and silver.

Parameter	Property
Overall tonnage [tonne]	870,00
Overall copper [%]	59,160
Overall zinc [%]	3,480
Overall silver [ppm]	200.1
Overall gold [ppm]	41.76

According to the study conducted by Nautilus the deposit is covered by sediments[14]. The thickness of this coverage goes up to 5.4 metre in thickness. Under this sediment, massive and semi massive sulphides are present. This is the main mineralised domain, varying in thickness from 0 to at least 18 metres. The level of uncertainty for the coverage is considered *'A3'*, as drillings confirmed the thickness on multiple locations, but not throughout the extent of the deposit. As for the thickness of the massive sulphide, the level of uncertainty is considered *'B3'*, a severe impact and unlikely. The levels of uncertainty comply with the classification, medium, of an indicated resource.

The gradual transition sideways is, due to drillings, classified as a low level of uncertainty. In vertical extent, drillings have been performed up to 18 metres. Meaning that everything under 18 metres has an extreme uncertainty. Here only assumption are made up to 18 metres, making the level of uncertainty low, or *'A3'* with a severe impact and remote likelihood.

The density of the deposit was determined by assessing the samples of the drill cores and chimneys [38]. The measured density ranges from 1.2 tonnes per cubic metre up to 3.0 tonnes per cubic metre, depending on the zone within the deposit. Both the deposit density and homogeneity of the density within the deposit are considered to have a low level of uncertainty. The impact remains severe, but the likelihood will be remote, or *'A3'*.

The location of the harbour and deposit are known and poses the lowest level of uncertainty.

The water depth is known for the location, posing the lowest level of uncertainty. The level of uncertainty for downtime will be considered for the equipment selection.

There is no grain size estimation or grain geometry estimation, resulting in a medium level of uncertainty with a moderate impact and likely likelihood, or *'C2'*.

For the geological resource it can be concluded that the highest classification a medium level of uncertainty is. The classification of indicated resource that Nautilus Minerals indicates for the resource

Geological resource	Level of uncertainty
Sediment coverage	A3
Gradual transitione	Low
Vertical extent	B3
Distance between deposits	A3
SMS deposit density assumption	A3
Homogeneity of density within deposit	A1
SMS deposit location	A1
Harbour selection with accessible processing plant	A1
Dipping orebody	A1
Longer downtime with increased water depth	A1
Increased energy consumption with increased water depth	A1
Dipping orebody	A1
Reactiveness of wet ore	A1
Effect of porosity	A1
Porosity estimation	A1
Grain size estimation	C2
Grain geometry estimation	C2

4.3. Economical exploitable

The estimated life time of mine is three years and one month, using the adjusted Taylor's Rule. With three years and one month, the production rate will need to be 780 tonnes per day. The level of uncertainty, using Taylor's Rule predicting the life of mine and thus the production rate per day, is set to an extreme level, as the impact is extensive and the likelihood is unlikely, or *'B4'*. All design of equipment is based on these figures. For both the seafloor tools and the vertical transport equipment are, according to Ecorys [25], the technology readiness levels at the level of experimental proof of concept. They score 3 out of 9 on the level of readiness scale. This means that they haven't been tested off-shore and pose an extreme uncertainty to the deep-sea mining project. The same goes for the hyperbaric conditions that the extraction tools is confronted with. Nautilus hasn't published any data or report to mitigate these issues.

Nautilus Minerals submitted an environmental impact report which was approved by the Department of Environment and Conservation of PNG. In this report Nautilus proposes to discharge the water by dewatering close to its point of origin at depths between 25 to 50 metres above the seafloor. This avoids any exposure or impacts on surface ecosystems. Potential impacts to surface pelagic animals result only from the presence of the surface vessels and their normal operations, including lighting, underwater noise and routine discharges. These impacts are similar to shipping generally. The main objectives of the environmental impact study were to understand the existing environment, potential impacts due to mining and how to mitigate significant impacts. As the report was excepted by the PNG government, it is considered to be a low uncertainty of unlikely and moderate impact, or *'B2'*. In this report, there is no discussion on the sedimentation that occurs during the mining operations, hence the highest uncertainty classification is awarded to this uncertainty.

In the report by Nautilus [14], they claim that the tailings from the flotation process are pumped to a tailings storage facility or alternatively to a deep-sea tailings placement facility. However, there is no extra information available on their tailing disposal plan. It is therefore awarded an extreme level of uncertainty with frequent likelihood and extensive impact.

For the economic exploitability of the resource, it can be concluded that an extreme level of uncertainty is present. This assessment of the seafloor massive sulphide resource would mean that the resource is not feasible for this feasibility phase. Mitigation measures are required to achieve a lower level of uncertainty before continuation in the project can take place.

Economical exploitable	**Level of uncertainty**
Predicting production rate	**B3**
Predicting life of mine	**B3**
Concept of extraction tools	**D4**
Extraction tools: production rate	**D4**
Extraction tools: equipment operability	**D4**
Extraction tools: erosion rates	**D4**
Extraction tools: downtime	**D4**
Extraction tools: interface with rise and lift system	**D4**
Extraction tools: hyperbaric effect	**D4**
Extraction tools: sufficient energy on the seafloor	**D4**
Concept of vertical transport	**D4**
Vertical transport: production rates	**D4**
Vertical transport: equipment operability	**D4**
Vertical transport: erosion rates	**D4**
Vertical transport: downtime	**D4**
Vertical transport: interface with seafloor tools and production vessel	**D4**
Vertical transport: sufficient energy on the seafloor	**D4**
Reactivity of the ore	**C3**
Deep-sea mining in the EEZ	**B3**
Deep-sea mining in The Area	**n/a**
Stakeholders	**D4**
Mining impact	**B2**
Plume dispersion	**B2**
Sedimentation	**D4**
Tailing pond design	**D4**
Location selection tailing pond	**D4**

4.4. Recoverable metal

Nautilus has done laboratory test on the recovery of copper. The recovery for copper is 85-90% of the total copper amount that is present in the resource. For this thesis the most pessimistic result of 85% copper recovery is used for further assessment, to minimize the extra uncertainty. The same test was done for gold where 75% was the most pessimistic result. No results of zinc and silver recovery were obtained in the research performed by Nautilus. In this thesis, the same zinc recovery is assumed as copper recovery. For silver the same recovery as for gold is assumed. The assumption poses an increased uncertainty for the overall metal grade. As no research is conducted for silver and zinc recovery, weighing the fact that both can influence the feasibility of the resource, the impact is classified as severe with a likelihood that is likely, or *'C3'*. Additional research on the samples for silver and zinc recovery can mitigate the impact and likelihood. The amount recoverable metal can be found in Table 4.9.

Table 4.3: Recoverable metal grade after the recovery grade.

Parameter	**Property**
Recoverable copper [tonne]	50,286
Recoverable zinc [tonne]	2,958
Recoverable silver [tonne]	150.1
Recoverable gold [tonne]	31.52

Recoverable metal	**Level of uncertainty**
Metal grade	**C3**

4.5. Payable metal

As the commodity price for copper, zinc, gold and silver is hard to predict, a bandwidth has been chosen with an lower and upper limit, for which the project would be feasible. The percentage that the project would be within the bandwidth history gives a first indication of what could be expected over the next years. The overall maximum metal price in history was chosen as the upper limit. The lower limits are shown in Table 4.4 for copper, in Table 4.5 for zinc, in Table 4.6 for silver and in Table 4.7 for gold. The tables show the historical price range from 5 up to 30 years before February 2016. For calculations of the bandwidth see Appendix A.1.

Table 4.4: Feasibility assessment for copper where the percentage indicates the period for which the historical price data is within the limit. The lower limit is set in the table. The upper limit is the maximum value of the dataset. The data set is from January 1980 up to February 2016.

copper	Historical data before February 2016 (years included)					
Lower limit (USD/tonne)	5	10	15	20	25	30
2,000	100.0	100.0	81.8	68.9	70.8	69.8
4,000	100.0	95.9	66.3	49.8	39.9	33.2
6,000	80.3	78.5	52.5	39.4	31.6	26.3
6,349	77.0	74.4	49.7	37.3	29.9	24.9
8,000	26.2	22.3	14.9	11.2	9.0	7.5

Table 4.5: Feasibility assessment for zinc where the percentage indicates the period for which the historical price data is within the limit. The lower limit is set in the table. The upper limit is the maximum value of the dataset. The data set is from January 1980 up to February 2016.

zinc	Historical data before February 2016 (years included)					
Lower limit (USD/tonne)	5	10	15	20	25	30
900	100.0	100.0	84.5	88.4	90.0	84.8
1,200	100.0	97.5	71.8	57.7	48.8	49.6
1,500	100.0	93.4	64.1	49.4	39.5	38.5
1,800	90.2	84.3	57.5	43.2	34.6	29.4
2,100	29.5	47.1	31.5	23.7	18.9	15.8

Table 4.6: Feasibility assessment for silver where the percentage indicates the period for which the historical price data is within the limit. The lower limit is set in the table. The upper limit is the maximum value of the dataset. The data set is from January 1980 up to February 2016.

silver	Historical data before February 2016 (years included)					
Lower limit (USD/tonne)	5	10	15	20	25	30
200	100.0	100.0	79.0	60.2	48.2	45.2
400	100.0	91.7	61.3	46.1	36.9	30.7
600	70.5	42.1	28.2	21.2	16.9	14.1
800	42.6	24.0	16.0	12.0	9.6	8.0
1,000	27.9	14.0	9.4	7.1	5.6	4.7

Nautilus Minerals gives an assumed price for two metals. The copper is assumed at 6,349 US dollar per tonne and for gold the assumed gold price is 41,310 US dollar per kilogram. For zinc and silver there are no assumed price values available. Over the past fifteen years, copper was almost for half of the time within the limits for a feasible extraction. Gold was only last five years for more than half of the time within the limits. The lifetime of mine of six years and months, according to earlier calculations, so the historical data of past five and ten years are used for the first estimate.

There are two ways to deal with this information. The first is to make an assessment on the level of uncertainty on the price with historical data in mind. The second is to assume that the metal will only be sold in the period when the metal price is high enough to make the project feasible and come up with an assessment on the level of uncertainty for that. The second would involve to many assumptions that are out of the scope in this thesis, therefore an assessment on the level of uncertainty on the price is done.

Table 4.7: Feasibility assessment for gold where the percentage indicates the period for which the historical price data is within the limit. The lower limit is set in the table. The upper limit is the maximum value of the dataset. The data set is from January 1980 up to February 2016.

gold	Historical data before February 2016 (years included)					
Lower limit (USD/tonne)	5	10	15	20	25	30
15,000	100.0	100.0	69.6	52.3	41.9	35.7
22,500	100.0	84.3	56.4	42.3	33.9	28.3
30,000	100.0	70.2	47.0	35.3	28.2	23.5
37,500	86.9	52.9	35.4	26.6	21.3	17.7
41,310	62.3	35.5	23.8	17.8	14.3	11.9
45,000	44.3	23.1	15.5	11.6	9.3	7.8

The level of uncertainty for the future of the metal price will have a unlikely extensive impact, or *'B4'*. The historical data helps to give a first indication for the future, as it also does for the volatility of the prices, resulting in the same level of uncertainty rating of *'B4'*. With this level of uncertainty, an assumption is made where the for 50% of the time in history, up to 15 years ago, the project would be feasible. With this assumption, a price for all metals can be obtained, see Table 4.8.

Table 4.8: Metal prices assumptions using historical data up to 15 years ago, with a feasibility range percentage of 50%.

Parameter	**Property**
Price for copper [USD/tonne]	6,305
Price for zinc [USD/tonne]	1,865
Price for silver [USD/kg]	448
Price for gold [USD/kg]	29,000

Payable metal	**Level of uncertainty**
Future commodity prices	**B4**
Volatility of commodity prices	**B4**

4.6. Net smelter return

Nautilus Minerals has signed an agreement with Chinese smelting company Tongling Nonferrous Metals Group for ores extracted from the Solwara 1 deposit in Papua New Guinea. According to the agreement, Tongling will pay for 95% of the recoverable copper, while the gold payment is fixed at 50% of the contained gold in the mineralized material, and payment for silver is fixed at 30% [45]. With this agreement, the unit deduction lapses. Because of this agreement, there are no values known for the smelting fees, penalties, refining charges, freight charges and insurance costs. From the agreement, it can be obtained that the gold and silver is treated as a by-product and not as a co-product. If it would be a co-product, the payment would have compensation comparable to the copper. There is no mentioning of the zinc payments. Because of the missing information on the fees and charges, it is not possible to calculate the net smelter return for the Solwara 1 project. As Nautilus does not do the smelting and treating itself, the level of uncertainty is non-existing for them.

With this agreement the amount of metal that will be used to calculate the revenue can be determined, see Table 4.9. For zinc is the same payment agreement of 95% of recoverable zinc chosen.

Table 4.9: Recoverable metal grade after the recovery grade.

Parameter	**Property**
Recoverable copper [tonne]	47,772
Recoverable zinc [tonne]	2,810
Recoverable silver [tonne]	45.0
Recoverable gold [tonne]	15.66

Net smelter return	Level of uncertainty
Smelting fees	-
Penalties	-
Refining charges	-
Freight charges	-
Insurance costs	-
Valuable metal co- or by-product	-

4.7. Operating cash flow

The operating expenditure for Nautilus Minerals is limited to the extraction and transport operations of the sulphide ore. The OPEX for mineral processing is for the Tongling Nonferrous Metals Group. This thesis will only consider the OPEX from Nautilus, as no information is available on these mineral processing expenditures.

Although the costs are for a production rate of 3,700 tonne per day, the OPEX given by Nautilus will be taken into consideration for the operating expenditure. The total OPEX of the operation would be 61.3 million US dollar for the indicated resource. The uncertainty level is increased by the uncertainty that the production rate is for a higher production rate calculated as the production rate that is used here, 780 tonnes per day. The impact will be severe and unlikely, or *'B3'*. Although, Nautilus backups its expenditures, it is still vague where they get their numbers from. The contingency was already calculated by Nautilus as 10% of the sub-total OPEX, see Table 4.10.

Table 4.10: OPEX from Nautilus Minerals with a production rate of 3,700 tonne per day [14]

Description	**Total daily costs [US dollar]**	**United mined costs [US dollar / tonne]**
Production support vessel	144,796	39.15
Seafloor mining equipment	20,130	5.44
Workclass ROV's	20,910	6.65
RALS	23,184	6.27
Support services	15,235	4.12
Barging	12,694	3.43
Sub-total OPEX run of mine to shore	236,949	64.06
Contingency (10%)	23,695	6.41
Total OPEX run of mine to shore	**260,644**	**70.47**

The study Nautilus conducted, indicates that as a result of the Solwara 1 location, well protected to the arrival of significant sea states from especially the north through east trough south to southwest directions, the waves will be mostly locally generated wind waves. A rough sea state is expected less than 1% of the time. A moderate sea state is expected to be less than 10% of the time. As moderate is assumed to be the highest sea state in which operations can be conducted, only less than 4 days of the year, operations can't take place due to weather conditions. The level of uncertainty is estimated as remote with minor impact, or *'A1'*.

Operating cash flow	Level of uncertainty
Estimating OPEX	B3
Plant design	-
Plant optimization	-
Lose/drifting icebergs	n/a
Unpredictable sea state conditions	A1

4.8. Cash flow after capital

The capital expenditure for Nautilus Minerals is limited to the extraction and transport operations of the sulphide ore. The total CAPEX is estimated at 382.8 million US dollar, see Table 4.11. All the CAPEX will be spend in the first year of the operation. The contingency was already calculated by Nautilus as

17.5% of the sub total CAPEX [14]. The information of Nautilus on justification of the CAPEX is limited. There is no justification on project services and owners costs. Nautilus doesn't develop the equipment that it will use itself, but buys it from other companies. Although they don't develop the equipment themselves, there will be development costs involved. It might be that they put this under project services. The same could be done for engineering and management costs. The start-up and closure costs and exploration and license costs are not included in the information on Nautilus Minerals. These costs will be estimated on 100 million US dollar based on the annual report from Nautilus Minerals [5]. This brings the total CAPEX to 482.8 million US dollar.

Table 4.11: CAPEX from Nautilus Minerals [14].

Description	Amount [millions US dollar]
Subsea mining equipment	84.1
Riser and lift system	101.1
Dewatering plant	24.0
Production support vessel mobilisation	6.5
Integration and testing	59.7
Barges	10.8
Project services	32.2
Owners costs	7.4
CAPEX sub-total	325.8
Contingency (17.5%)	57.0
Total initial CAPEX estimate (to shore)	382.8

Since there is limited and probably not complete information available information on the CAPEX, the impact of the uncertainty on predicting the CAPEX is estimated to be severe and likely, or *'C3'*. Nautilus accounted for the contingency allowances and depreciation costs, making these uncertainties unlikely and moderate in impact, or *'B2'*.

Cash flow after capital	Level of uncertainty
Predicting CAPEX	C3
Contingency allowances	B2
Depreciation costs	B2

4.9. Net cash flow

The royalty payable to the State of Papua New Guinea under the PNG Mining (Royalties) Act 1992 is 2% the net smelter return on all minerals produced, and 0.25% for the Mining Resource Authority. The total royalty to be payed is 2.25% [14]. The is no information that Nautilus will pay other forms of taxes to the PNG government. The uncertainty level is remote and will have a minor impact, or *A1'*.

Nautilus has been in a dispute with the PNGgovernment that was resolved in 2014 [54]. The government of Papua New Guinea has taken in interest of 30% in the Solwara 1 project [43]. Although there has been a dispute, the government has a conflict of interest to the Project. It is therefore expected that the impact will be severe but the likelihood will be remote, or *'A3'*.

The net revenue can now be calculated, see Table 4.12, using the royalty tax, the metal price Table 4.8 and the amount of metal from Table 4.9. This is the revenue over a period of six years and two months.

Table 4.12: Net revenue in millions of US dollars.

Parameter	Property
Copper	301.2
Zinc	5.5
Silver	454.1
Gold	20.2

Net cash flow	Level of uncertainty
Royalties and taxes	A1
Changes over time	A3

4.10. Net present value

All information is now available to calculate the present value for the Solwara 1 project, see Table 4.13. Year four only has two months. All capital expenses will be paid in the first year, while the operational expenses are paid every year.

Table 4.13: Present value calculations on the Solwara 1 project of Nautilus Minerals.

year	1	2	3	4
CAPEX	482,800,000	-	-	-
OPEX	19,881,081	19,881,081	19,881,081	1,656,757
subtotal	502,681,081	19,881,081	19,881,081	1,656,757
revenue	253,307,247	253,307,247	253,307,247	21,108,937
revenue after tax	247,607,834	247,607,834	247,607,834	20,633,986
total	- 255,073,247	227,726,753	227,726,753	18,977,229

Now the present value is calculated, it possible to determine the net present value. In order to do so, the discount rate is needed. The discount rate for the Solwara 1 project needs to be estimated, as it is not provided in the information published by Nautilus Minerals. An overview of the net present value versus the discount rate can be given, see Figure 4.2. From this overview it can be obtained that in order to be economic feasible, the maximum discount rate should be lower than 51.47%. It is expected that, even though the discount rate for deep-sea mining is higher than for mining on land, that the discount rate will be lower than 51.47%. Therefore, the level of uncertainty for the cost of capital is expected to have a unlikely and severe impact, or *'B3'*.

The technical risk has the highest level of uncertainty as it is related to the extraction and transportation techniques used for deep-sea mining.

Net present value	Level of uncertainty
Cost of capital	B3
Security of tenure within The Area	n/a
Technical risk	D4

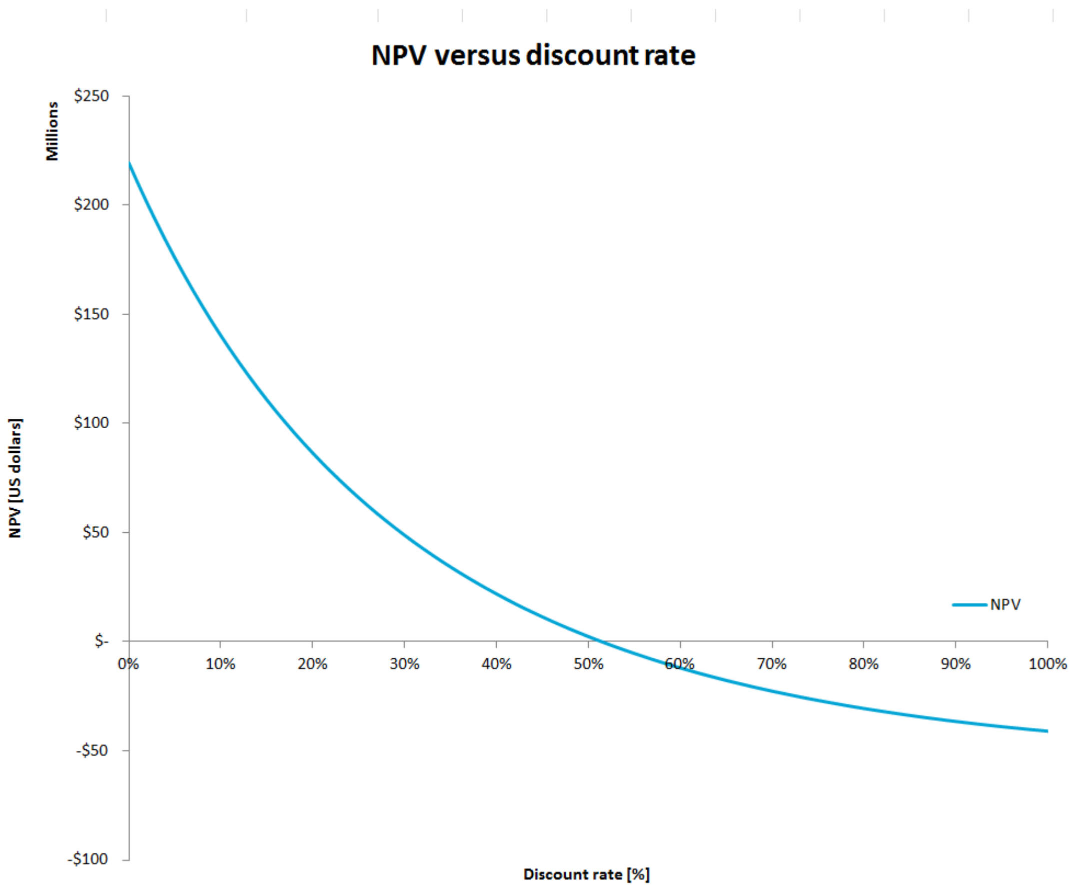

Figure 4.2: Net present value versus discount rate.

4.11. Sensitivity analysis

The same sensitivity analysis is done on the Nautilus Solwara 1 deposit as was done on the example deposit in Chapter 3.10. The difference is that for the Solwara 1 project all the metal prices are analysed on their sensitivity. The analysis indicates that gold, because of its high value, is more sensitive than silver on the economic assessment. Furthermore, the same conclusions can be drawn from the analysis. In the economic assessment of the feasibility of Solwara 1, Nautilus should pay extra attention to the more sensitive parameters: copper price, gold price and CAPEX.

Another conclusion can be drawn from Figure 4.3. If the deviation is 10% from the expected input, for both negative and positive, then the Solwara 1 project is still feasible up to a discount rate of 34%. For a discount rate higher than this 34%, the project would not be economic feasible anymore. If the deviation is 20% from the expected input, for both negative and positive, then the Solwara 1 project is feasible up to a discount rate of 20%.

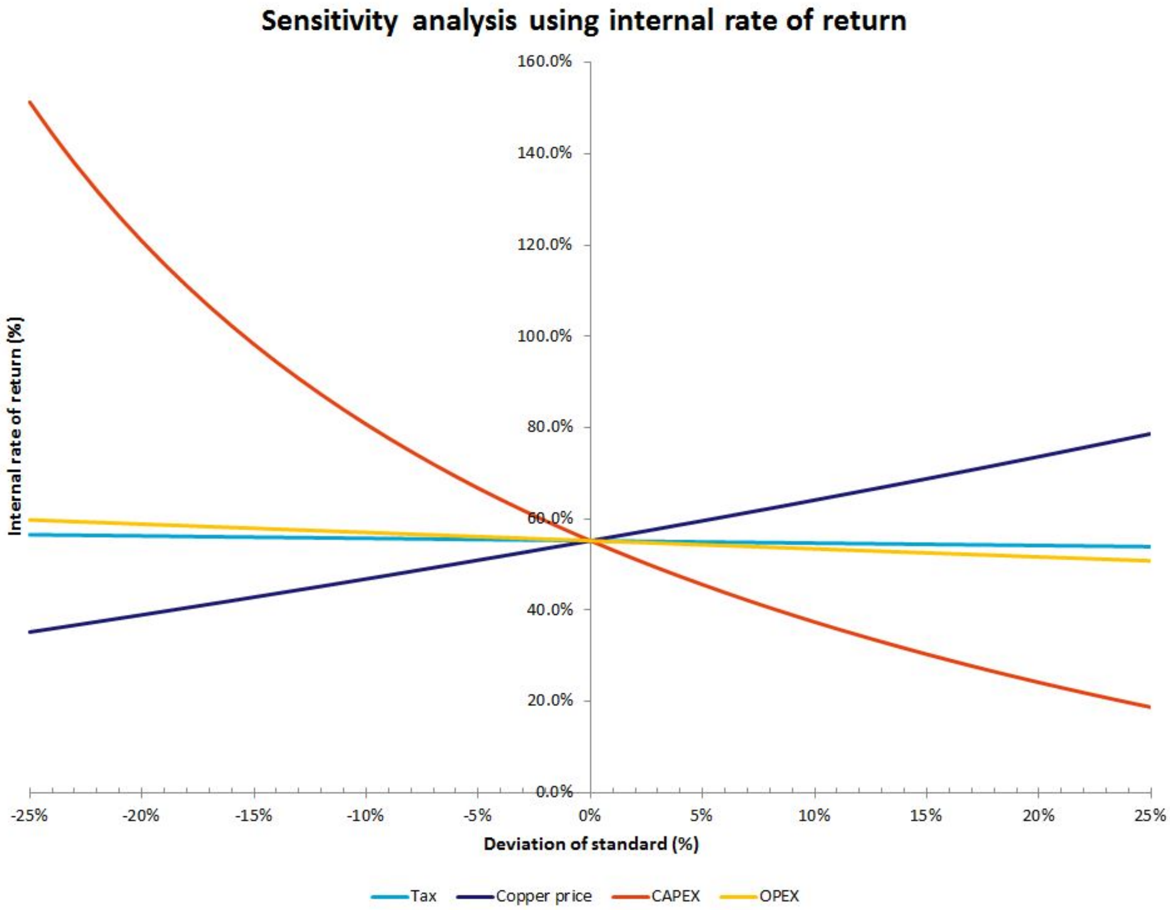

Figure 4.3: Sensitivity analysis using internal rate of return

5

Discussion, conclusion and recommendation

5.1. Discussion

When mining seafloor massive sulphide deposits a concept of three seafloor mining tools and a continuous vertical transport system is considered. According to Nautilus Minerals Inc. this concept is the best approach to mine a deep-sea massive seafloor deposit. However with a different selection of seafloor mining tools and a different approach for the vertical transport, other concepts of deep-sea mining could be more likely to be economically feasible. The concept of Nautilus has not been proven yet, as commissioning of the Solwara 1 project never took place. New approaches for deep-sea mining would require years of research and experiments, making the development of a new concept for deep-sea mining an uncertain endeavour. Because there are no genuine other concepts to mine deep-sea massive seafloor sulphide deposits, it is justified to use this unproven concept of Nautilus Minerals Inc.

The equipment selected in this thesis is designed for, or will be used by, Nautilus Minerals Inc. The level of technology of this equipment is however too uncertain to conclude that the equipment will function properly under these deep-sea circumstances. The approach of the mining, using a bulk cutter, is conventional and not very innovative on itself. Innovative approaches in the future could probably result in more effective and efficient seafloor mining. The method used for vertical transport also has to prove itself to be capable of transporting the ore up from the seafloor to the surface. Severe testing of all equipment, seafloor mining tools and vertical transport system, is required before any estimate on the production will hold. As for the deep-sea mining concept, it is justified to use these unproven tools of Nautilus Minerals Inc. as there are no genuine other deep-sea mining tool alternatives for the extraction or vertical transport of sulphide ores from the deep-sea.

The parameters that are involved with the assessment on the economic feasibility have uncertainties that are classified into different categories. Quantifying the uncertainties would be ideal, but due to the amount of the uncertainties and the new terrain of deep-sea mining, an extensive amount of assumptions would be required. The classification, with impact an likelihood, give a good first estimate on both impact and likelihood and therefore make the recognition of potential obstructions and challenges in the assessment of the economic feasibility of seafloor massive sulphide deposits detectable in an early stage of the deep-sea mining project. When more information becomes available on both extraction or the geological resource, the uncertainties should be quantified.

In the calculation for the energy requirement of the vertical transport of the sulphide ore, it is assumed that the energy required is linear with the increasing water depth. In practice, this will probably not be the case. As the effect of this increase in depth is outside of the scope of this thesis, no additional comments are given on this effect. It is noted that this effect takes place and should be studied in more detail.

Many factors and parameters are involved with the stakeholder analysis. Stakeholders can pose threats and uncertainties to the deep-sea mining operation and to the deep-sea mining project. In this thesis limited attention was paid to the stakeholder analysis as it is thought that the stakeholder analysis is a study on its own, as there are many stakeholders involved in deep-sea mining projects. Stakeholders can vary from international governmental organization, as the International Seabed Authority, to a local environmental organization. It is noted that the effect and importance of a thorough stakeholder analysis is required before commencing a deep-sea mining project.

In the case study of Nautilus' Solwara 1 project, only the indicated resource was taken. The indicated resource has a higher level of confidence than the inferred resource which is also given in the reports from Nautilus Minerals. A higher level of confidence of the resource results in a higher level of confidence in the assessment of the economic feasibility of that resource. The aim of this study is to gain a deeper insight in all the aspects that are involved in the economic feasibility of exploiting seafloor massive sulphide deposits in order to qualify a deposit to be economic feasible. Therefore the highest level of confidence is required, resulting in using the indicated resource and its parameters for further analysis.

The estimated life time of mine for the Solwara project is three years and one month, using the adjusted Taylor's Rule. The average production per day is around the 780 tonne. The actual production will be higher, as there will not be production every hour and every day. This results in building equipment that can handle a higher production rate than the daily average of 780 tonne. If the availability of equipment would be that 50% of the time, then the equipment should be designed to have twice the production rate of the average production per year. The estimated life time is similar to what Nautilus is planning, as they are planning to produce the Solwara 1 project in 2 years and 9 months.

For the recovery of the metals, the most pessimistic results were used to calculate the recovered amount of metals. Only the results of the recovery tests performed on samples of the Solwara 1 deposits are published, not the tests themselves. Therefore it is not possible to verify any of the test results and the drawn conclusions of them. Because of that, the most pessimistic results have been used to prevent falsely favouring economic feasibility conclusions on values that are possibly too high.

The metal Nautilus is aiming for is copper. Zinc could be argued to be a co- or by-product. As the same recovery for zinc is assumed in this thesis, here it is considered to be a co-product. Realistically zinc will probably be a by-product. As Nautilus didn't state any recovery figures for zinc, it has been assumed that zinc is a co-product. This can be verified when more information becomes available on the recovery. For the silver recovery similar assumption has been used. In this case it has been assumed that silver has the same recovery grade as gold. Until further investigation has been conducted which state otherwise, they can hold.

For determining the bandwidth of the historical metal price a period of fifteen years was chosen in the case study. The lower limit would be the limit for which 50% of the time, the project would be within the bandwidths limits. The 50% limit is chosen so that at least half of the time of the project, the project would be economically feasible. However, the Solwara 1 project will take three years and one month and not fifteen years. Due to the volatility in the metal price, it was chosen to take the lower limit over a longer period of time of fifteen years and not three. It could however be the case that the three years plus one month that the project takes would be completely within the time that the project would not be economically feasible. The lower limit that is obtained from the period of fifteen years is lower as for the lower limit over three years and one month. This results that considering a period of fifteen years is less favourable, but more reliable.

5.2. Conclusion

The aim of this study is to gain a deeper insight in all the aspects that are involved in the economic feasibility of exploiting seafloor massive sulphide deposits and how this can be assessed. This thesis should be used as a tool to get a first estimate on how to get from a geological occurrence to an ore reserve. In order to get to an ore reserve, a description of all parameters involved in the economic assessment of a seafloor massive sulphide deposits are investigated. These parameters involve parameters that are related to the geological occurrence itself, but are also involved with the other topics that need to be assessed in order to assess the economic feasibility. These topics include extraction, transportation, production, shipping, legal, commodity prices, OPEX, CAPEX, environment and discount rate.

All of the parameters that are involved in the assessment of the economic feasibility are classified on their level of uncertainty that they inflict on the deep-sea mining project. The classification is based on a system that estimates the impact and likelihood of uncertainties of the parameters. The classification knows four levels of uncertainty which are low, medium, high or extreme uncertainty. In order to commence the deep-sea mining project, the uncertainties should preferably have a low level of uncertainty, as this is an acceptable level of uncertainty. With a medium level of uncertainty, mitigation measures are required, but uncertainties represent a manageable level of uncertainty. For high uncertainties, extensive uncertainty mitigations should be implemented, while for extreme uncertainties, activities should be stopped unless mitigations have been implemented and the uncertainty is reduced to a lower level.

Information on the geological resource on beforehand of the project is limited. There is some information available, but with high and extreme levels of uncertainty. The mitigation for most of these uncertainties is drilling. It can be concluded that the information will become available by drilling will be very valuable to the mining project.

From the study conducted, it follows that the production rate and mine life needs further in-depth investigation. Even with mitigation measures, the level of uncertainty is high for these parameters. As deep-sea mining hasn't been done yet, there is no example or data available which can help when estimating the production rate and thus the life of mine.

Extraction methods used for deep-sea mining are still in their infancy. The technology readiness level of the techniques used in this study are at the level of experimental proof of concept. For the cutter there is no record of any experiments to test the behaviour of such cutter-heads to cut seafloor massive sulphide deposits at significant ocean depth. For the vertical transport system the behaviour of the system should be investigated in a series of experiments and field tests. Many uncertainties are still involved with the methods used for the extraction and vertical transport.

The legal perspective of deep-sea mining remains a challenge. The two zones where deep-sea mining takes place are the Exclusive Economic Zone and The Area. The first is closer to shore and is governed by a national authority that should have a legal framework in place in order to operate in the deep-sea. The Area is governed by the International Seabed Authority that regulates the permissions issued. Benefits of The Area are supposed to contribute to the benefits of mankind. Both legal frameworks have their own uncertainties.

Stakeholders can pose threats and uncertainties to the mining operation. To what extent they pose threats and uncertainties is investigated in a stakeholder analysis. Depending on the stakeholder the level of uncertainty can be high or low.

When mining a deep-seafloor massive sulphide deposit the impact on the environment is unknown. There are no precedents that can be used as example. It should be concluded that without the proper mitigations to allow for low level of uncertainty, no deep-sea mining activities should take place.

The geochemical composition of the sulphide ore from seafloor massive sulphide deposits is highly variable. Many published grades of seafloor massive sulphide deposits are strongly biased due to sampling of chimneys, which are easier to recover than sub-seafloor stock work. From the comparisons made between volcanogenic massive sulphide deposits and seafloor massive sulphide deposits it can be stated that the seafloor deposits have a higher metal grade on average for both base and valuable metals.

Seafloor massive sulphide deposits contain both base and valuable metals. In this study the base metals studied are copper and zinc, the valuable metals are silver and gold. There are different ways to determine the metal price. In this study it is chosen to use the two biggest well-known metal exchanges to determine the price, the London Metal Exchange and the CME group. There are macro and micro effects on the price of copper that make predicting the copper price have an extreme level of uncertainty. Although not as influenced by the production market, the gold price is equally hard to predict. It can be concluded that when predicting the future prices for these metals this will have an extreme uncertainty. This uncertainty could be mitigated by using a bandwidth for the metal price for which the project would be economic feasible. However, even after mitigation, the uncertainty for the future metal price is still highly uncertain. This is also the case for the volatility of the metal price.

The net smelter return serves two main purposes. The first is to provide a common denominator for the comparison of assays from polymetallic deposits. The second is to create a healthy awareness of the economic factors which determine the value of the ore. The valuable metals will most likely have an effect on the type of smelter contract as they might be seen as co-products instead of by-products.

The operating expenditure is the sum of mining, beneficiation and administration expenses and can be expressed in two ways, expenses per day or expenses per tonne. Most of the operating expenses for deep-sea mining have to be estimated as there is no example of deep-sea mining operations and many of the operations are new. Mitigation is possible with the use of simulations. The same goes for the mineral processing of the ore. This is done on land, due to the environmental regulations that prohibit seafloor tailing disposal.

The capital expenditure needs to predicted for many expenses as the deep-sea mining equipment needs to be designed and build. The estimation poses a medium to extreme level of uncertainty to the project.

The discount rate is used to determine the present value of future cash flows. The cost of capital depends on the mode of financing that is used. The level of uncertainty in costs of capital are extreme, as there are no precedents for discount rates in deep-sea mining. The political risk discount factor involved with the discount rate are subjective due to the uniqueness of every company. The security of tenure within The Area poses an uncertainty, as it could be close to the exclusive economic zone of another country. This uncertainty occurs when for instance the European Union want to start mining in the Pacific Ocean. Strong mitigation measures will be required in order to establish a discount rate for which the deep-sea mining project is still economically feasible.

The analysis of the parameters from the Nautilus Solwara 1 project indicate that there are still high and extreme levels of uncertainty present in the project. Evaluating the economic exploitability of the deposits shows that the equipment used for extraction and for vertical transport is not ready to be used, as it hasn't been tested. There are also concerns about the recoverable metal, where it is unknown how Nautilus determined the metal grade for the whole deposit. The price that Nautilus uses for the copper is somewhat similar to the price that has been used in this study. The assumed gold price from Nautilus is however much higher, due to the high gold price of the last couple of years. The high gold price can be too optimistic and should rather be chosen for a more restrained gold price, as has been calculated in this study. According to the assessed parameters in this thesis the Solwara 1 project is not feasible for commissioning. There are too many unknowns and the level of confidence is not high enough to conclude otherwise. From an economic perspective, leaving out the uncertainties, the Solwara 1 project is feasible when the discount rate is lower than 51.47%.

From the sensitivity analysis it can be concluded that some parameters have more impact on the economic assessment than others. These parameters with a higher sensitivity are the price of copper, the price of gold and the CAPEX. Extra attention should be paid when these parameters are analysed, as their input will have a high influence on the outcome.

5.3. Recommendation

- The assessment on the economic feasibility in this thesis is tailored for seafloor massive sulphide deposits. It is expected that with limited adjustments, the same assessment can be made for manganese crust and polymetallic nodules. The uncertainties discussed in this study could have a greater impact and additional uncertainties will be involved as the type of deposit is different from the seafloor massive sulphide deposit. It is advised to make this assessment on the different deposits in order to conclude if seafloor massive sulphide deposits are economically more feasible and attractive to exploit.

- Calculations that are done in this thesis are very straight forward. The impact of the uncertainties is however, not illustrated by these calculations. Extending and deepening of these calculations could make sensitivity analysis possible for more parameters than only the ones studied in this thesis.

- Many of the geological resource mitigations involved drilling, as drilling is the most accurate and highest confidence manner of determining many of the geological parameters. However, drilling on the seafloor is expensive and takes a long time. There is a limited selection of drills available in the world that can handle these kinds of drilling operations. It is recommended to investigate if designing and building a drill is economically more beneficial than renting the limited available drills that are present today.

- Keeping the information on parameters up-to-date is crucial for the economic assessment, as new insights and techniques could mean the difference between economically feasible or not feasible. It is recommended that when new information becomes available, it is implemented in order to have the most accurate assessment on the economic feasibility.

- In the calculations on energy consumption of the equipment used for extraction and vertical transport, it is assumed that the water depth is linear with the energy consumption. This is probably not the case. A study should be conducted on the effects of water depth on the influence on the equipment and the increased energy used by this equipment.

- A stakeholder analysis is required for every mining operation and it is recommended that this is also done for every deep-sea mining project.

A

Calculations

A.1. Bandwidth metal price history

```
function [ PERCENTAGE ] = PRICE_BANDWIDTH( price_history , lower_limit , upper_limit , months_ago)
% PRICE_BANDWIDTH can be used to calculate the PERCENTAGE of the bandwidth
% that is within the history price limits.
%    price_history    = vector with price history (in months)
%    upper_limit      = upper boundary of bandwidth
%    lower_limit      = lower boundary of bandwidth
%    months_ago       = determines the age
if upper_limit <= lower_limit
    error('Upper limit should be greater than your lower limit!')
end
n = length(price_history) ;
k = 0 ; % amount that is within boundaries
for i = (n-months_ago):n
    if price_history( i ) >= lower_limit
        if price_history( i ) <= upper_limit
            k = k + 1;
        end
    end
end
PERCENTAGE = ( k / (months_ago + 1) ) * 100;
end
```

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