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A viability study into shallow water offshore mining, with a focus on mineral processing techniques

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Van Oord
Marine ingenuity

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A viability study into shallow water offshore mining, with a focus on mineral processing techniques

by

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Preface

This report presents the findings of the research I performed to obtain the title of *Ingenieur* or *Master of Science* in Offshore Engineering from Delft University of Technology. In my thesis, I consider the opportunities and technical challenges in the shallow water offshore mining business. The research was performed between September 2016 and June 2017 in collaboration with Van Oord Dredging and Marine Contractors.

During these months, I learned a lot about offshore mining in the broadest view possible, from resource estimating to selling end-products. I tried to look at it from a technical as well as a business perspective, to assess the potential of this new discipline.

Luckily, I had help from others, without whom this project would not have been (most of the time) so enjoyable. First, I want to thank all my family and friends, for supporting me throughout all my years of studying in Delft. Special thanks to Steven, Bas, Sergio, Pieter and all others who helped me structure my thoughts and gave me feedback during this project. Finally, thanks to Nina for supporting and helping me when I needed it the most.

The project could not have been a success without my supervisors at the university and Van Oord. Thanks, Sape, Mike, Austin, Dirk and Roel, for many hours of listening to me and reading my findings and problems and guiding me to hopefully a good result. Furthermore, I want to thank Van Oord for trusting me with this project and giving me the freedom to explore all ins and outs. Special thanks to Robert Dijkema and Willem van Driel for assisting me in my technical and financial challenges.

Kees Arets
Rotterdam, June 2017

Summary

Rationale for this research

The increasing world population and consumption, and the rising dependency on certain countries for the supply of raw materials lead to the demand for new raw material resources. At the same time the complexity of new land-based mining operations increases. Both trends contribute to an increase in the chances for a viable offshore mining business case.

Goal and scope

The aim of this research is twofold. The first aim is to fill knowledge gaps in the offshore mining value chain, with a focus on the processing of the mined material. The second goal is to assess if shallow water offshore mining is a viable business option for Van Oord. These goals are subdivided into three research questions:

- What is the current state of technology and the market for shallow water offshore mining?
- How should a shallow water offshore mining project be structured?
- Is shallow water offshore mining a viable option, based on a case study?

Explicitly left out of the scope is the exploration of mineral deposits and the detailed or new design of an extraction method for subsea minerals. Furthermore, resources beyond the continental plate are not part of this research.

Current state of technology and market

An extensive literature study was performed, comprising of an assessment of potential offshore mineable minerals and their respective markets, and an analysis of current land-based mineral processing techniques and its limitations in an offshore environment. Furthermore, environmental, legislative and tax aspects were described (i.e. “modifying factors”, according to the JORC code). An overview of current and prospective offshore or marine mining projects, and current dredge mining projects is included as well.

Conclusions

Offshore mining still has a long way to go before it is standard practice. The main minerals of interest are bulk commodities. Offshore mining project need economies of scale to justify the use of the large dredging equipment. Forecasting mineral prices or demands is not a straightforward process, if possible at all. Mineral processing is an opaque discipline as it is dominated by several large manufacturers who keep their knowledge and experiences to themselves. Designing a processing plant is mainly done by testing, optimizing, and upscaling of a pilot plant. From a legislative perspective, a lot of work must be done since there is almost no legislation in place, creating uncertainty for prospective projects. The unfavorable public opinion towards offshore mining seems to play a role in the environmental permitting processes, this is mainly due to a lack of knowledge with respect to: environmental effects and new working methods. Plume forming is considered the main environmental impact. Although there are no significant offshore mining projects realized to date, current projects (in the design phase) show that environmental aspects, permits, and large financial up-front investments are important delaying factors.

Framework for offshore mining

A framework for executing an offshore mining case study is developed. The framework is based on the offshore mining value chain, and aims to preserve overview when assessing a complex project. A list of key parameters to assess a project's feasibility and viability was derived from this framework.

Conclusions

The design of the mining method and mineral processing plant is an iterative process.

Case study: viability of a shallow water offshore mining project

Based on the developed framework, the viability of the Classified case study is assessed. A mining operation is highly location specific. Therefore, an assessment of local climate, legislation, taxation, Classified market, and local environmental aspects is essential. For the case study, the mineral deposit has been studied and based on its mineral characteristics a location specific processing flow sheet is developed. From the flow sheet, a mining vessel was selected. This resulted in a set of execution alternatives, from which a preferred alternative was selected. For the selected alternative, the viability of the project is assessed with the use of a discounted cash flow model (DCF-model).

Conclusions

The case study concluded that shallow water offshore mining is feasible, and can be viable. However, the results should be interpreted carefully. With respect to applicability of the used model and case study, the framework and model can be used for other minerals and locations, given some minor adjustments are made. Sensitivity analysis are performed on some of the projects parameters, including WACC, OPEX, CAPEX, export price, distance to shore, and inflation.

Conclusions of the research

The first goal was to identify knowledge gaps. The main gaps are the impact on the environment, and the lack of legislation regarding offshore mining. Furthermore, it should be noted, that the public opinion regarding offshore mining is an important factor to take into account. On a technical level, the main challenge is to match throughputs of large dredging equipment with a processing plant and the local demand for the mined mineral. Furthermore, designing a mineral processing plant is an opaque and highly specialized task, which should be dealt with in collaboration with a mineral processing equipment manufacturer.

The second goal was to assess the viability of a shallow water offshore mining project. From the case study, a positive net present value was found from the DCF-model, indicating a viable project which could be attractive. The developed case study assessment tool was found to be useful and provided insights in the value chain of offshore mining. The assessment tool can be used in other projects as well.

Abbreviations and nomenclature

Abbreviation	*Definition*	*Explanation*
BPL	Bone Phosphate of Lime	The weight percentage of the phosphor containing compounds in the rock/deposit. See section 2.2.
CAGR	Compounded Annual Growth Rate	Percentage with which on average a certain variable has grown, each year, over the indicated period.
CAPEX	Capital Expenditure	The initial purchasing costs of a capital certain item. A capital item will last longer than one production cycle, so it is not *used* during production.
EEZ	Exclusive Economic Zone	A sea zone prescribed by the UNCLOS over which a country has special rights regarding the exploration and use of marine resources. See section 04.2.
F.A.S.	Free Alongside Ship	Delivered at the port, transport costs for the buyer.
F.O.B.	Free On Board	Determines at what location the responsibility for insurance and transportation changes from seller to buyer.
GDP	Gross Domestic Product	The total value of goods produced and services provided in a country during one year.
NPV	Net Present Value	The balance of future costs and revenues made present by discounting.
OPEX	Operational Expenditure	The amount of money spent on a certain item during the operations phase, so without initial purchasing costs or depreciation costs.
ROV	Remotely operated vehicle	The vehicle, mostly a subsurface device, which can be remotely operated from a "mother" vessel. It can be hardwired to the mother vessel or be completely free (unmanned submarine)
UNCLOS	United Nations Convention on the Law of the Sea	The international agreement from the Third UN Conference on the Law of the Sea. The law regulates the worldwide distribution and use of marine resources (to whom they belong), as well as environmental aspects. See section 4.1.
WACC	Weighted average cost of capital	The weighted average expected return on the capital employed by the company. Capital employed is made up of equity (from shareholders) and loans (from lenders) See section **Error! Reference source not found.**.

Symbol	*Definition*	*Explanation*

t	Metric tonne	1000 kilograms
kt	Kiloton	1000 metric ton
Mt	Megaton	1.000.000 metric ton
Mtpa	Megaton per annum	Megaton per year
mm	Million	10^6 – used for expression involving money
bn	Billion	10^9 – used for expression involving money
T	Tesla	Unit of measurement of the strength of a magnetic field
NM	Nautical Mile	1852 meters
m	meter	1 meter
km	Kilometer	1000 meter

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1 Introduction

1.1. Offshore mining will become relevant in due time

There are three main reasons why offshore mining will become reality in the near future:

- World population keeps rising at an increasing pace and with it the consumption rises even faster, leading to an increase in demand.
- As a result of increasing international tensions, countries feel the growing need to be more self-sufficient in their raw material supply.

Offshore mining could fulfill the increasing demand for an alternative supply of certain minerals. The following sections explain the arguments above more in-depth.

Supply challenges: Increasing difficulty of new mines

Onshore mines cope with increasing complexity. Difficult mining methods, increased need of processing and remoteness of the mine locations are all examples of challenges the mining industry faces. As the sum of these challenges reaches a certain threshold, it will compete with the difficulties encountered in offshore mining.

Demand increases: Rising population and consumption

As the world's population just passed 7.500.000.000 people and is still growing at a rate of 1.2% (90.000.000) each year, the demand for new products is ever increasing (Worldometers.info 2016). This in combination with the increasing wealth of a large part of the population, increases the demand for raw materials even further. The increase in demand for raw materials will, at constant supply, lead to an increase in price.

International tensions: desire for independence in supply of key raw materials

With the current renewed tensions between Russia and the West and the wars and revolutions in the Middle East, countries increasingly feel the need for self-reliance. This also holds for their needs in food and raw materials. As this need increases, the need for new and more diversified sources of raw materials increases as well.

Is offshore mining the solution?

The challenges involved in mining increase and the demand for raw materials does as well, leading to higher prices. As prices of raw materials increase, it is justified to explore and exploit deposits which require more efforts (in terms of money and challenges). The main part of the world's surface is covered by oceans, it is thus assumed and proven that vast amounts of raw materials can be found there. However, the hostility (depth, no land, etc. etc.) of these remote areas makes it more expensive and challenging to extract these materials. Due to the aforementioned increase in prices, the extraction of these offshore deposits becomes viable.

Countries are not only looking for extra mineral deposits, they are also looking for mineral deposits in different locations, as described in the third statement above. By being less dependent on a certain country or regime for critical raw materials, a country can become less vulnerable in case of political instability. Furthermore, it reduces the problems which could arise if one of the supplying countries for any reason is no longer able to deliver the minerals.

Problem statement

Offshore mining could lead to the availability of new deposits of raw materials. Currently, it is not yet applied, leaving it uncharted territory. In this thesis, offshore mining will be addressed by looking at the complete value chain. The value chain is shown in Figure 1-1.

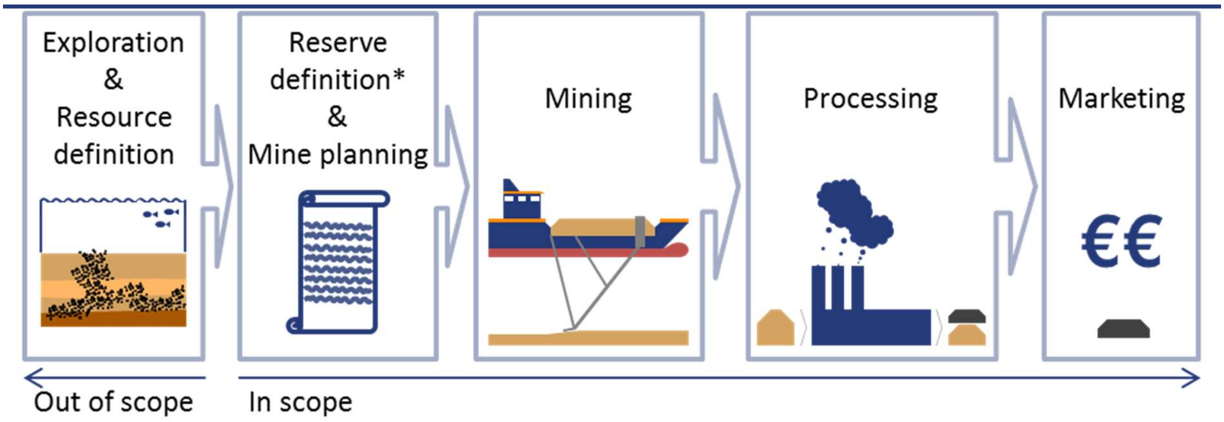


Figure 1-1: Offshore mining value chain as used for this thesis.
*By means of the "Modifying factors" a resource evolves into a reserve, according to the JORC (JORC 2012). The modifying factors include: environmental, legal, economical, marketing social, and governmental factors. See Figure 2-1.

Some areas of the value chain are better known than others. The methods for exploration have already been developed for research and commercial purposes. The marketing is comparable to the marketing for onshore mining since the end-product is the same. The mining aspects fall within the Van Oord expertise and are therefore assumed known. The areas contracts, legal and environment, and processing, still need further investigation for shallow water offshore mining projects.

Goal of the research

The first aim of this study is to fill knowledge gaps in the offshore mining value chain, with a focus on the processing of the mined material. The ultimate goal is to assess if offshore mining is a viable business option for Van Oord.

Sub-research questions and layout of the report

The goals of the research is divided into three sub-questions, which each have their own part in the report. After each part, a conclusion is drawn covering the sub-questions.

Part A: What is the current state of technology and the market for shallow water offshore mining?

- Which minerals are of interest for shallow water offshore mining projects?
- How should mined minerals be processed and what are limitations due to an offshore environment?
- What is the current state of legislation for shallow water offshore mining?
- Which main environmental impacts should be considered for offshore mining?
- What is the current state of the offshore and dredge mining industry?

Part B: How should a shallow water offshore mining project be structured?

- What steps should be taken to design a shallow water offshore mining project?
- What are the main design variables?

Part C: Is shallow water offshore mining a viable option, based on a case study?

1.2. Scope

The scope of the research is defined following some preliminary assumptions, listed below:

- The currently available dredging equipment should be used for the mining process. Realistic adaptations can be done. However, possibilities are monitored over the complete continental shelf, as this can become accessible in the near future.
- Using the current dredging techniques also means that the mining process itself and, pumping the mined material to the surface, will not be included in this research, as it is presumed known and already broadly applied.
- Exploration is seen as a mature discipline, as there is already a lot of experience with offshore mineral exploration. Exploration will thus not be part of this research. This also includes prospecting or actively looking for new locations for offshore mining.

Figure 1-2, shows a global representation of the scope of this research. Figure 1-3, has a more in-depth scope of the research, focusing on some specific items.

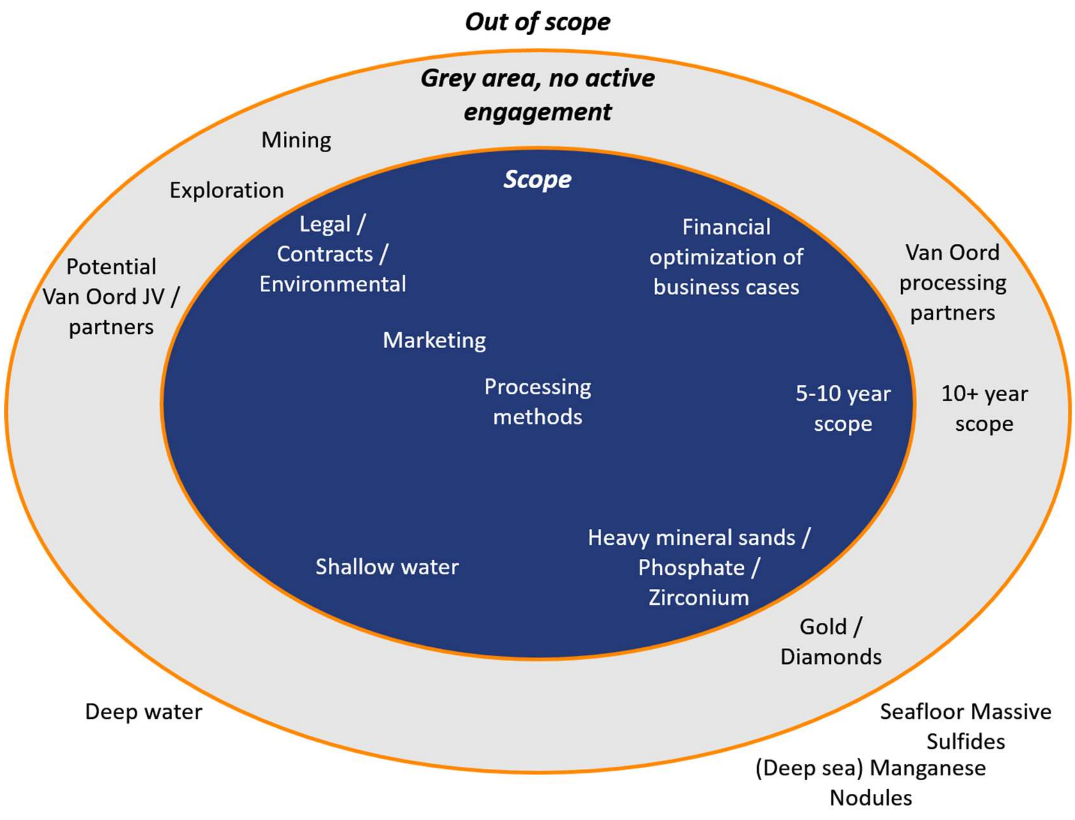


Figure 1-2: Scope of this thesis.
Blue is in scope, gray is not actively engaged, outside the orange border is definitely out of scope

	In scope	Out of scope
Processing	• Global and detailed processing calculations • Equipment sizing estimate • Production schedule estimates • Mining integration	• Detailed (manufacturer) level equipment sizing
Legislation	• General description of legislation • ISA	• Country specific legislation descriptions
Environment	• General assessment of environmental considerations of offshore mining • Comparison with normal dredging	• Description of all specific environmental impacts due to offshore mining • Plume mitigation strategies
Finances	• Inflation based on 5yr US average • Export prices of minerals are spot (31-04-2017) prices corrected for inflation	• Inflation forecasting • Exchange rate fluctuations
Model	• Justified and verified • Phosphate • Basic set-up for an offshore mining project	• Validation • Mineral indifferent • Detailed application for offshore mining projects • Vendor specific items or characteristics

Figure 1-3: Detailed scope with respect to certain aspects of the research.

Part A What is the current sate of technology and the market for shallow water offshore mining?

Introduction and reading guide

Part A will go into the assessment of the current state of technology and the market for shallow water offshore mining. Offshore mining is a combination of different lines of business: dredging, terrestrial mining and commodity economics. Understanding each of these branches on a business as well as technology level is important for understanding offshore mining. Assessing the bigger picture leads to the identification of knowledge gaps and forms a starting point to create a roadmap for shallow water offshore mining.

Part A aims to answer the following sub-questions.

- Chapter 2 – Which minerals are of interest for shallow water offshore mining projects?
- Chapter 3 – How should mined minerals be processed and what are limitations due to an offshore environment?
- Chapter 4 – What is the current state of legislation for shallow water offshore mining?
- Chapter 5 – Which main environmental impacts should be considered resulting from offshore mining?
- Chapter 5 – What is the current state of the offshore and dredge mining industry?

2 Minerals for shallow water offshore mining

At the basis of each mining operation lies the mineral which is sought. The mineral determines the mining operation, processing operation, and the economics of the project. As this section gives general information about a mineral, it is important to keep in mind that the same mineral found in different locations should be processed in a completely different way because of the environment it is in.

Reading guide

- Paragraph 2.1 – Basic knowledge and definitions regarding mineral mining
- Paragraph 2.2 – Minerals of interest for shallow water offshore mining
- Paragraph 2.3 – Assessment of minerals of interest for shallow water offshore mining

In Appendix B a more detailed overview of the discussed minerals from the third paragraph can be found.

2.1. Basic knowledge and definitions regarding mineral mining

Classification system for resources (Van Kauwenbergh 2010)

Mineral deposits can be classified based on two pillars:

- Geological, physical and chemical properties, such as grade, quality, tonnage, depth, and, thickness, determine the resource classification.
- Profitability, based on the costs of extracting and marketing in a given economy (legislation) at a given time (called: "modifying factors" in the JORC code), determine the reserves classification.

In this report, we will make use of the JORC (Joint Ore Reserves Committee) code. The JORC code is "the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves" which stipulates in what category a deposit should be classified. Other countries have similar classification systems. Classification using the JORC-code is shown schematically in Figure 2-1.

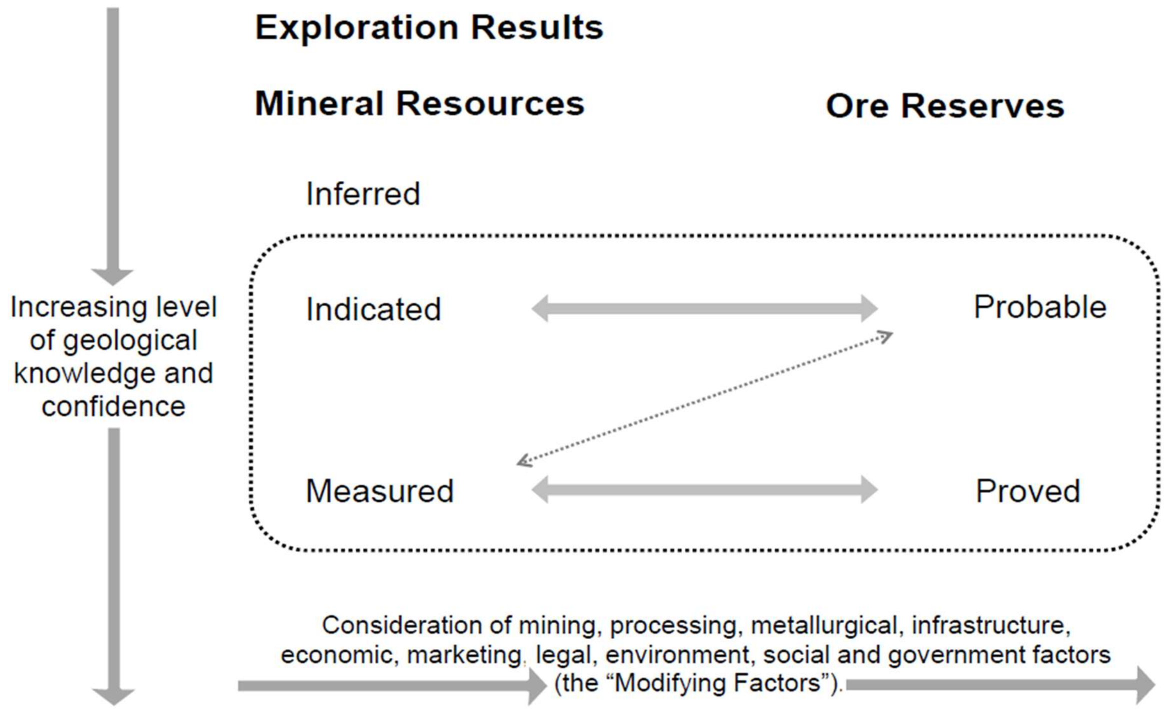


Figure 2-1: JORC code classification of resources and reserves (JORC 2012)

As shown in Figure 2-1 the JORC code determines five different classifications of a deposit: mineral resources can be inferred, indicated and measured, whereas ore reserves can be probable and proved. A deposit slides along these scales depending on the knowledge of geology and the "modifying factors".

The classification of a resource is a process performed by a specialist. Mineral resources are classified based on the level of geological information available. The geological information is combined with the modifying factors to evaluate whether a mining project is feasible. Achieving the proved class indicates that a project is viable based on detailed information of both the geology and the modifying factors.

However, a reclassification of a measured mineral resource to a probable ore reserve does not mean a sudden lack of geological information. In this case, fairly complete, geological information is combined with incomplete information about the modifying factors. When there becomes more information available about these modifying factors, the ore reserve moves from probable to proved, if it turns out to be economically feasible, since the geological information was already complete.

Gangue material

Gangue material is a general term for the main material which is excavated or dredged from a deposit, excluding the target mineral. The gangue material is partly or entirely invaluable but contains the valuable or target mineral of the deposit in its mixture or structure. In the processing of the excavated material, the gangue is separated from the target mineral and deposited in the tailings.

Cutoff grade

The cutoff grade is a certain level below which an ore body does not contain sufficient valuable material or minerals to economically justify processing it. The initial mine cutoff grade is estimated during a feasibility study; however, it can change during the exploitation phase of the mine as more detailed information comes available or market conditions change.

2.2. Minerals of interest for shallow water offshore mining

It is not clear which minerals are suited for shallow water offshore mining. To create an overview of possibly suitable minerals, a classification of 96 minerals present in the earth's crust was made, based on a quick scan of the properties and applications of the mineral.

The complete list of 96 minerals can be found in Appendix A. These 96 minerals were evaluated based on a variety of parameters like occurrence, appearance, industrial applicability, worldwide production and use, a rough estimate of extraction method (need for toxic chemicals), and toxicity of the mineral itself. Not all of these parameters were available for each mineral. However, for every mineral, there was enough information available to give a reliable estimate of its potential for shallow water offshore mining.

The first round was a rough separation (i.e. Yes, Maybe and No) based on common knowledge. Minerals which scored a "no" were not interesting for an offshore mining operation. Minerals which scored a "maybe", had to be evaluated more in depth. All minerals which scored a "Maybe" were, in the second round, classified as either "Yes (maybe)" or "No (maybe)", after more extensive research. In the table below an overview of all minerals with potential for offshore mining are given. In the rest of this chapter from section 2.3 and onwards, some of these minerals will be looked at in more detail.

Table 2-1: Selected minerals for further review. See Appendix A for a complete list of reviewed minerals. [classified]

2.3. Assessment of minerals of interest for shallow water offshore mining

The seven minerals that scored an immediate "Yes" on the rough classification in paragraph 2.2, were investigated in more detail.

The assessment is done to see which of them have the most potential to result in a viable offshore mining project. Due to time constraints, only Classified have been investigated so far.

The assessment of a minerals attractiveness is based on the following parameters:

- Marketing
  - Size – indicates the size of the market (demand in Megaton) and subsequently how likely is it a large new player will disrupt the current market dynamics.
  - Price – indicates the price pressure on the market (supply-demand situation).
  - Forecast – indicates the consensus of different sources about the price and demand in the market.
- Processing – indicates the difficulties which can generally be expected in the processing of the mineral.
- Occurrence – indicates the abundance of the mineral in a shallow water offshore environment.

The three minerals' attractiveness for shallow water offshore mining is assessed in a qualitative manner, based on a five-step scale (i.e. '++', '+', '0', '-' or '--'). The values are based on the extensive mineral descriptions in Appendix B.

The results of the assessment are shown in Figure 2-2, on the next page. The assigned scores for each mineral are motivated in the subsequent paragraphs. For an in-depth analysis of the minerals discussed, and all relevant sources, see Appendix B.

[Classified]

Figure 2-2: Assessment of attractiveness for prospective shallow water offshore mining minerals.

Classified: assessment of minerals

3 Overview of mineral processing methods

Chapter 2 indicated which minerals are suited for a shallow water offshore mining operation. This chapter moves further down the value chain and explores the different steps and processes which can be used in a mineral processing plant.

Introduction to the mineral separation process

In order to produce a saleable product, the mined substance will need treatment. Although the process is different for each mined substance, it generally comprises of a selection of the following eight steps.

1. Size reduction (comminution)
2. Size separation
3. Gravity concentration
4. Dense medium separation
5. Froth flotation
6. Magnetic and electrostatic concentration
7. Leaching (chemical separation)
8. Dewatering

After the preprocessing, the ore satisfies the specifications to be sold on the (world) market. It depends on a variety of factors if all the steps above are necessary or if upgrading is necessary at all. These factors are all related to the difference between the target specifications and the mined specifications, and the environment the minerals come from (gangue material). Relevant parameters include grade of minerals, grain size, moisture, gangue material and, impurities. (Fuerstenau & Han, 2003)

Besides the upgrading steps, some peripheral processes should be considered. They form an integral part of the processing of minerals and, include:

- Slurry and materials handling
- Wear and tear
- Process operations: processing systems and dust, noise and vibrations control

This report does not elaborate on these processes.

Basis of separation

Most pre-processing or upgrading procedures depend on separating mined substances from gangue, impurities and the actual valuable mineral. Separating minerals can be done on the basis of some key characteristics. These characteristics are defined as the basis of separation (e.g. specific gravity, magnetic susceptibility, electrical conductivity, size, solubility, reactivity and optical characteristics). All separation methods are based on one or sometimes more than one of the above-mentioned characteristics (Fuerstenau & Han, 2003).

Designing a processing plant

Processing minerals is a highly specific task and is for the majority based on the local ore characteristics. As stated by (Lisiansky et al. 2015) each deposit needs detailed testing to ensure an optimal separations plant can be designed.

Every location has its own soil composition and requires a suitable processing plant for that specific location. Designing the plant involves detailed studies of the involved materials and extensive testing. These tests involve building a pilot plant: a copy of the plant with a smaller throughput.

Reading guide

In the first paragraph, a general overview is given of all steps which can be taken in a mineral separation process. In the following paragraphs, these mineral processing steps are elaborated on. For each step, important equipment and, the separation principles are discussed. Basics of mineral processing.

In this chapter, the terms mineral processing, mineral separation and, mineral upgrading are used interchangeably.

- Paragraph 3.1 – Size reduction
- Paragraph 3.2 – Size separation
- Paragraph 3.3 – Gravity concentration
- Paragraph 3.4 – Dense medium separation
- Paragraph 3.5 – Froth flotation
- Paragraph 3.6 – Magnetic and electrostatic separation
- Paragraph 3.7 – Leaching or chemical separation
- Paragraph 3.8 – Dewatering
- Paragraph 3.9 – Overview of important mineral processing equipment manufacturers.

3.1. Size reduction (Comminution)

In the process of comminution, the mined ore is mechanically processed, reduced in size, in order to separate the valuable product from the gangue material. The gangue material is the more or less worthless material which (most of the time) forms the majority of the mined ore, like sand or rocks. Separating the ore from the gangue results in an early upgrade of the mined material and a large tailings stream which can directly be diverted to a discharge site. In general, comminution demands a very large energy input. On average, this process consumes up to 50% of all energy used for mining and processing combined. (CEEC 2013)

Comminution steps are main cost drivers in a mineral processing facility. Both CAPEX and OPEX tend to have a significant contribution to the costs of the facility. This is mainly due to the very high forces and impacts which are inherent to the intended result; size reduction. As a result of these high forces, the equipment's wear and tear costs are high. Furthermore, most size reduction equipment makes use of consumables like liners, balls, and rods, these need to be changed regularly, increasing OPEX costs. Another OPEX driver is the large amount of energy needed for the processes to take place, due to the energy needed to reduce the size of rock. (InfoMine USA 2010)

The comminution process is most likely to be avoided in an offshore environment. Main reasons, therefore, are the high energy consumption (and thus need of fuel) and the high stresses and loads on the deck of the processing vessel. Furthermore, as dredged are regarded the mining vessel in this report, hard material or rock will be mined using a Cutter Suction Dredge. The dredge head in this case already functions as a first comminutions step. However, after mining large pieces of rock, these most likely have to undergo further size reduction before they can move further in the upgrading process.

Possible methods for comminution are: crushing, grinding, and milling. Which will be explained next.

Crushing

The mined materials' size is reduced by crushing due to compression or an impact against rigid surfaces. Crushing in predominantly a dry process and is performed in several, relatively small, steps. The reduction ratio of a crushing stage is defined as the maximum particle size going in, compared with the maximum particle going size out. Different kinds of crushers exist, including: jaw crushers, gyratory crushers , cone crushers, and impact crushers. Each crusher has its own advantages and applications within a mineral processing facility. This is mainly based on the ability to produce more or less fine material and a more or less uniform product size. An example of a cone crusher used in terrestrial mining, see Figure 3-1. (Fuerstenau & Han 2003) (Wills 1997)

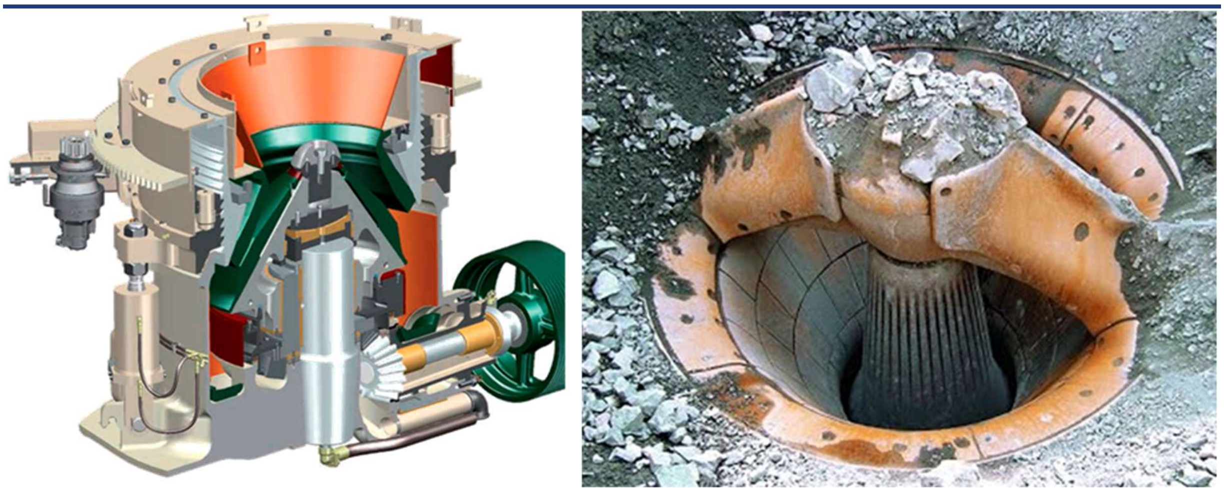
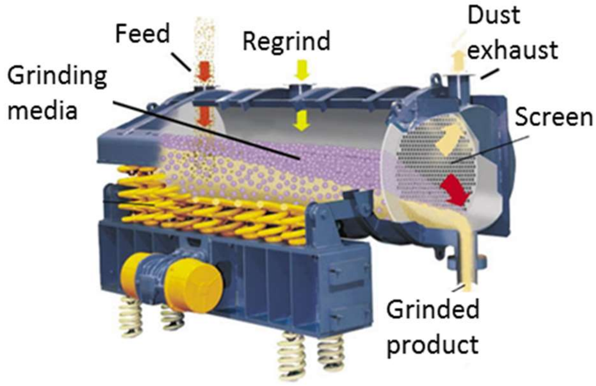


Figure 3-1: Stationary cone crusher. (Metso 2017)

Grinding

The mined substance is reduced in size via an abrasive process combined with impacts due to the free motion of unconnected media as balls and rods. Grinding is usually performed in a wet environment, although dry grinding is possible as well. The grinding step is usually the last in a comminution sequence, as it is able to produce an fairly uniform and fine product. Grinding uses more energy and is more costly than crushing. Grinding is done in tumbling mills, of which three basic types can be distinguished: rod, ball, and autogenous. During the recent history, a shift from conventional mills (balls and rods) to autogenous mills has taken place. Figure 3-2, schematically shows a grinding mill. The grinding media can either be steel rods or balls. (Fuerstenau & Han, 2003) (Wills 1997)



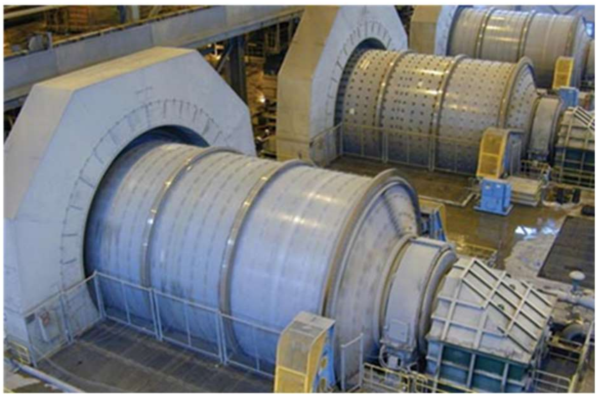


Figure 3-2: Grinding mill. (Skala Australasia 2017) (FLSmidth 2017)

3.2. Size separation

Size separation is dividing the material based on one or more of its particle properties. For the purposes of mineral processing, this can be done to prepare for the follow-up processing step or if only a specific grain size is sought. This way you can prohibit very fine material going into a crusher or large material clogging or damaging equipment meant for smaller particles. (Fuerstenau & Han 2003)

For separating the material based on size, roughly two methods can be used: Screens and classifiers. They differ on their basis of separation. Screens allow particles to pass through a raster and, separates based on geometrical form, irrespective of weight. Whereas classifiers are based on the suspension of particles in a medium and separates them based on particle size and specific gravity. Screens are a more exact way to determine particle size fractions. However, classifiers are able to separate more exactly based on specific gravity and are more suitable for very small particle sizes. (Metso 2015)

For classifiers generally, the medium density is of great importance, as a higher density hinders the movement of particles, thus making exact separation harder.

For both screens and classifiers, different equipment classes exist, which are defined below. Which piece of equipment should be used for certain grain sizes, is shown in Figure 3-3.

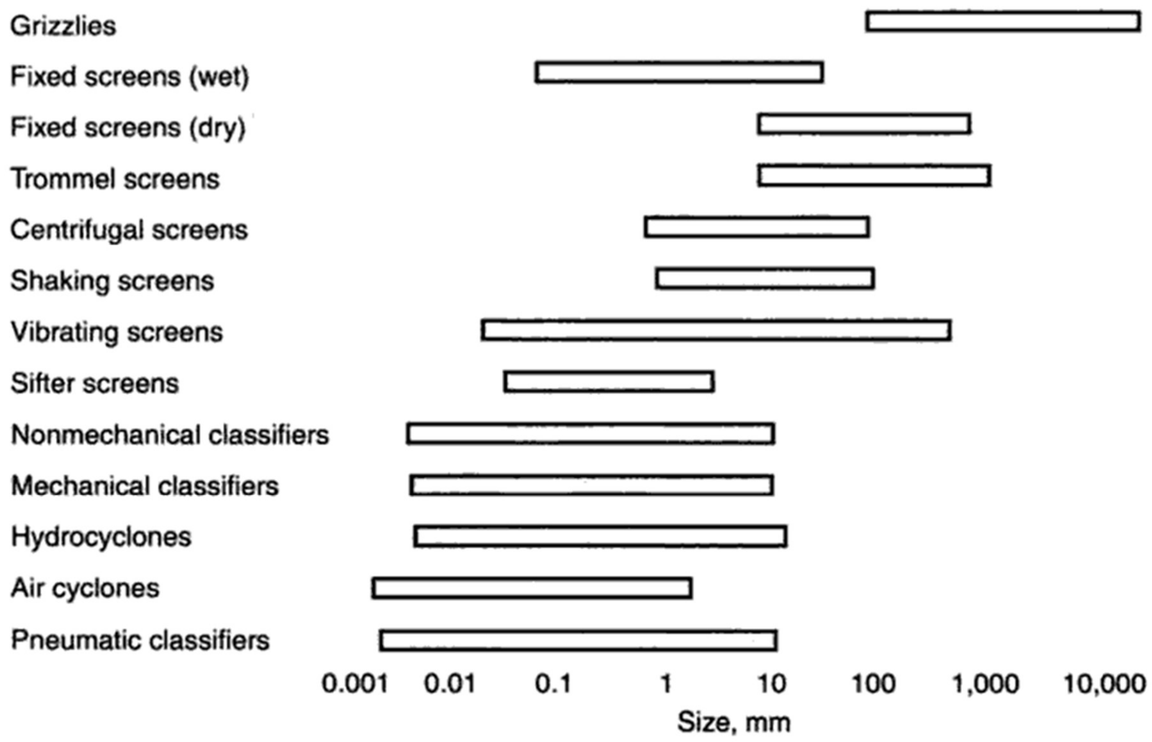


Figure 3-3: Application range for sizing devices. (Fuerstenau & Han 2003)

Partition curve

The partition curve is an important indicator of the effects of a separation process. An example of a partition curve for a hydrocyclone is shown in Figure 3-4. Partition curves can be used for all separation equipment.

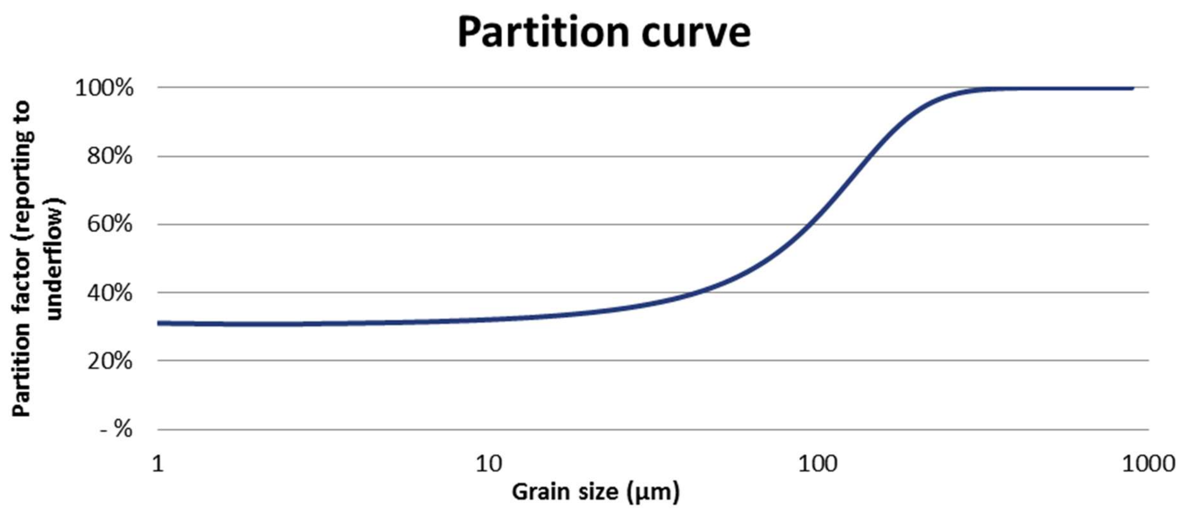


Figure 3-4: Partition curve for a hydrocyclone, D50=109µm.

The partition curve shows how much material, of a certain size, reports to the underflow or overflow. As can be seen in the figure above, for the hydrocyclone given here, approximately 30% of all material reports to the underflow anyway. This is explained by the drag force exerted on the smallest particles, by water. This value is called the Bypass Fraction (Rf) and is calculated by measuring the amount of water reporting to the underflow with respect to the total amount of water going into the hydrocyclone.

Furthermore, the partition curve always is an S-curve. The steepness of the S determined the sharpness of separation. The S is located “around” the D50 grain size. The D50 grain size is the size of the grains of which 50% reports to the underflow and 50% to the overflow.

By taking sampled of a separated material, before and after passing a separation step, the efficiency of the process can be monitored. Partition curves can also be used for designing a separation step for a processing plant. For estimating purposes, formula’s exist to determine the partition curve of a particular piece of equipment.

A schematic representation of the partition curve is shown in Figure 3-5.

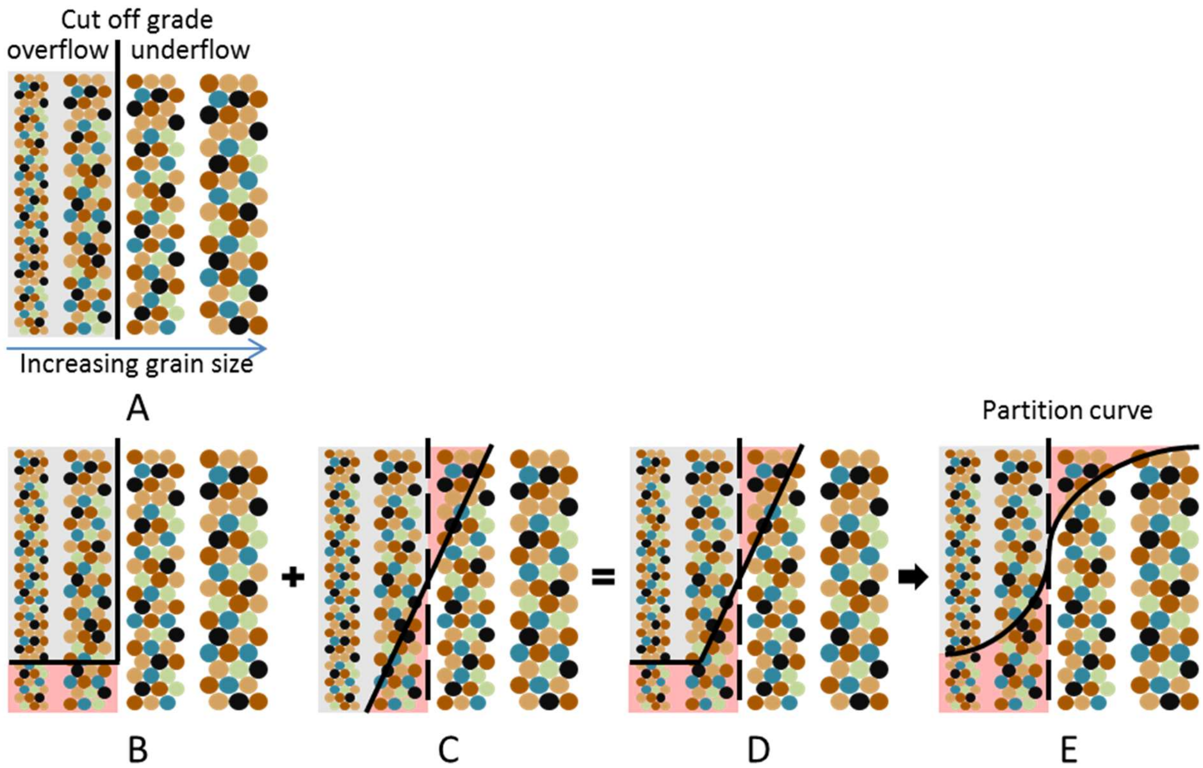


Figure 3-5: Schematic representation of the partition curve. A: separation around the D50, in and ideal situation. Left report to the overflow (fines particles, right to the underflow coarser particles). B: Rf value, these particles report to the underflow in all cases. C: Partition around the D50, in a non-ideal, but realistic scenario. D and E: Combination of B and C leads to the partition curve.

Screens

Screens separate the ore purely based on the size characteristics. The screens have certain openings which only allow passage to grain sizes under a certain size. There is a wide variety of screens on the market. The most common ones are:

- Grizzlies
  Grizzlies are a first rough separation step, in the order of 10.000 to 100mm particles. Figure 3-6 shows a grizzly separator.
- Fixed, revolving, shaking, vibrating, centrifugal and, trommel screens
  These screens are more like large sieves and perform well in separating smaller particle size than the grizzlies. However, extremely small particles cannot efficiently be separated by screens, as the openings of the screen will clog. The separation domain of screens lies between 1.000 and 0.1mm. Figure 3-6 shows an example of a grizzly and a vibrating screen separator.
  - Centrifugal and trommel screens are mechanically driven cylindrical screen. They are often used as a first or intermediate dewatering step.

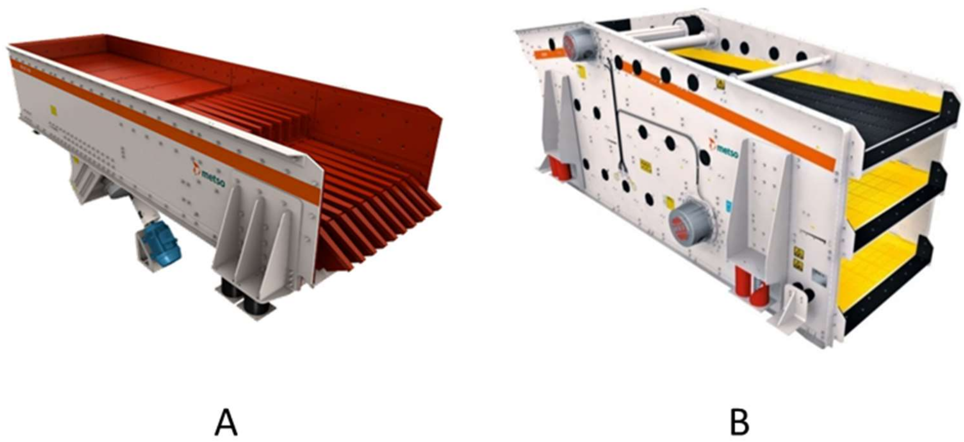


Figure 3-6: A: Grizzly separator. B: Vibrating screen separator. (Metso 2017)

The effectivity of screens is based on a couple of parameters (Metso 2015):

- The inclination of the screening plate.
  Inclination makes a difference as it influences the way the material is led past the holes in the screen. The material can be “shaken” through the screen as a result of stratification of the bed, or by freefall along with the plate. Most screening equipment only has one inclined plane, however, around 20% of screening devices uses multiple different inclinations.
- The motion of the screening plate, which is needed to progress the material over the screen.
  - Inclined plates can produce a circular and a linear motion.
  - Horizontal plates can produce an elliptical and a linear motion.
- Screening media characteristics.
  The thickness, material, kind of holes and kind of screening plate all influence the capacity of the screen.

Classifiers

Classifiers separate the ore based on the specific gravity characteristic. Classifiers use the weight of the grains to separate the particles in the ore using gravitational or centrifugal forces. As the method is not directly linked to the specific gravity, but to the weight of a particle, the size of the particles also plays an important role. Therefore all particles should have (almost exactly) the same size in order to separate on specific gravity. If only the absolute weight plays a role, size is not important. This can be the case when the material is uniform in specific gravity and separation on size is desired. Otherwise, a size separation step and/or a comminution step should precede the classifying step.

Classifiers mostly operate in the 12 to 635 mesh spectrum (Metso 2015), which is about 20-1400µm in the Tyler mesh system.

The main subdivision between classifiers can be made based on their medium: water or air. Further classification can be made per medium type. Below a summation of the different classifiers is given (Fuerstenau & Han 2003):

Water based classifiers

- Non-mechanical (Fuerstenau & Han 2003)
  This kind of classifiers uses surface sorters or induced flows by adding water (called "hydraulic water") in order to classify particles based on (hindered-)settling velocity.
    - Surface sorting, cones are often used for desliming (very fine sizing). At very high feed rates, these kind classifiers can be used to filter out large coarse particles, to prevent damage to downstream equipment. Either way, this method is based on gravitational force and the settling velocities in a fluid.
    - Free- and hindered-settling hydraulic classifiers use hydraulic water to enlarge the difference in settling velocity between particles. Heavy particles settle faster (or, at all) in a higher countercurrent then lighter particles, assuming equal specific gravity. The heavy particles are separated at the bottom of the tank, whereas the lighter particles proceed to the next tank with a slower countercurrent.
      In general, it can be concluded that hydraulic classifiers have a small capacity-to-size ratio, this makes them less economical for application in a floating plant and large tonnage operations.
    - Hydrocyclones are a form of non-mechanical water based classifiers as well. Due to their broad application, a more in-depth description is given in the section below.
- Mechanical (rake, spiral, drag) (Fuerstenau & Han 2003)
  Mechanical classifiers have moving parts which move the sized particles from the separation zone to the overflow. These systems can have a horizontal of a vertical current, "hydraulic water" can also be added.

Air based classifiers

Air or gas classifiers use physical forces to classify within the 0.1-1000µm range. Separation takes place based on forces acting on particles due to gravity, centrifugal force, aerodynamic drag and collision forces. As the application of dry classification equipment is unlikely in a marine environment below only a summation of air classifiers is given. A lengthy description of their exact way of working is omitted.

- Cyclones (Fuerstenau & Han 2003)

Air based cyclones work similarly to hydrocyclones. However, they are applied less frequent.

- Sturtevant SD classifier (Fuerstenau & Han 2003)
  This device makes use of all the above-mentioned forces for its classification process. It can be used to separate fines from the coarse material without the use of water.
- Other air or gas based classifiers include expansion chambers, vane classifiers, tank through-flow, inertial classifiers and recirculating flow classifiers.

Hydrocyclones (Fuerstenau & Han 2003)

Hydrocyclones separate based on the centrifugal force between fine and coarser particles. The hydrocyclones are actually a kind of non-mechanical water based classifier, but as they are applied very broadly, they are considered separately. The fluid together with the particles enters the hydrocyclone almost perpendicular, resulting in a spiraling motion in the cyclone itself. As a result of gravity the spiraling motion is also oriented downward, however, the hull of the cyclone is conically designed under a wall angle of 12-20degree. This results in an increase in suspension speed when going down in the hydrocyclone. This results in a reverse vortex for finer particles, which is thus directed upwards. At the top of the cyclone, a vortex finder is situated which leads the suspension of finer particles and most of the water out of the cyclone. The coarser particles which were too heavy to be included in the vortex are drained from the bottom of the hydrocyclone, at atmospheric pressure. In Figure 3-7 a hydrocyclone skid is show as well as the working principle of a single hydrocyclone.

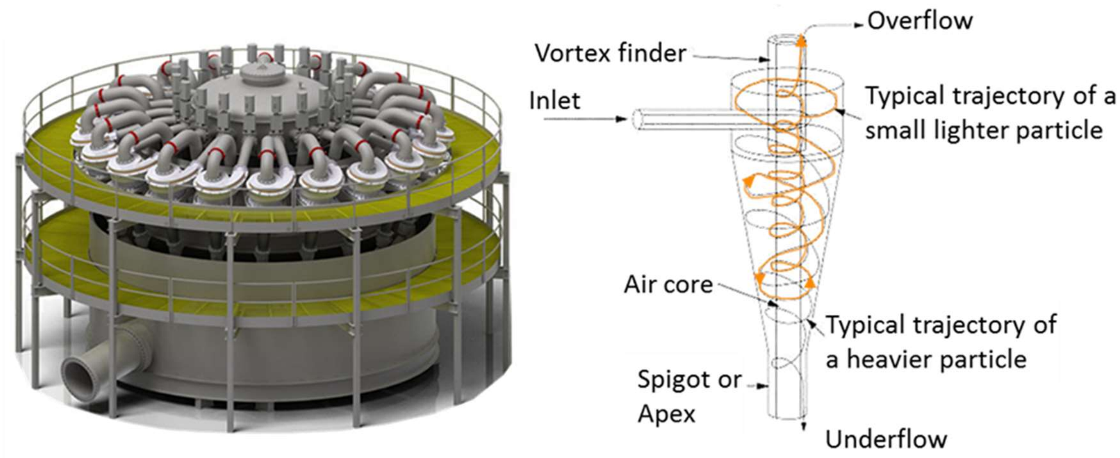


Figure 3-7: Hydrocyclone skid and working principle. (Metso 2017)

To determine the efficiency of a hydrocyclone or to design a hydrocyclone processing step, the partition curve can be used. See section 3.2, above.

3.3. Gravity concentration (Wills & Finch 2015)

Gravity concentrators separate the material based on their relative movement in response to the difference in specific gravity and one or more forces. These forces can be the result of the resistance of fluids like water.

The principle of gravity separation became less favorable with the invention of froth-flotation, see section 3.5, but became more popular again due to its low chemicals and energy consumption and its relatively low impact on the environment.

For gravity separation, it is important that there is a significant difference in specific gravity between the mineral and the gangue material. This can be expressed via the expression below. Generally, the efficiency of the process decreases as the absolute value of the quotient decreases, as shown in the equation below.

$$\frac{\rho_h - \rho_f}{\rho_l - \rho_f} > |2.5|$$

$$\rho_h = Highest\ specific\ gravity, \qquad \rho_l = Lowest\ specific\ gravity,$$
$$\rho_f = Specifi\ \ density\ of\ fluid\ medium$$

Besides the difference in specific gravity, the size of the particles is of great importance as well. As larger particles will be affected more by the fluid. The efficiency of the gravity concentration process increases when the particle size increases. In order to reduce the effect of size differences between particles, adequate size control (sieves and classifiers) is required, prior to a gravity separation process.

Special attention should be given to the removal of slimes ($D_{50} \leq 63\mu m$), as slimes will increase the viscosity of the fluid, which will result in a different selection process (less sharpness in the result). It is therefore common practice, in gravity separation processes, to divert the flow of particles with a size smaller than 10µm.

Also in gravity separation, the partition curve as explained in Paragraph 3.2 (Figure 3-4 and Figure 3-5), plays a large role.

Below a short explanation of the most commonly used gravity separation systems.

Gravitational concentrators

Jigs (Wills 1997)

Jigs operate in a similar way as the free- and hindered-settling hydraulic classifiers, see section 3.2. As stated, this separation method is based on settling velocity, which is based on the combination of specific gravity and particle size. As a heavy and large particle can have the same settling velocity as a light and small, size monitoring is very important for this method. Jigs are widely used on tin dredges. The largest have a capacity of 300m3/h with a maximum particle size of 25mm. For the principle of the jigs, see Figure 3-8.

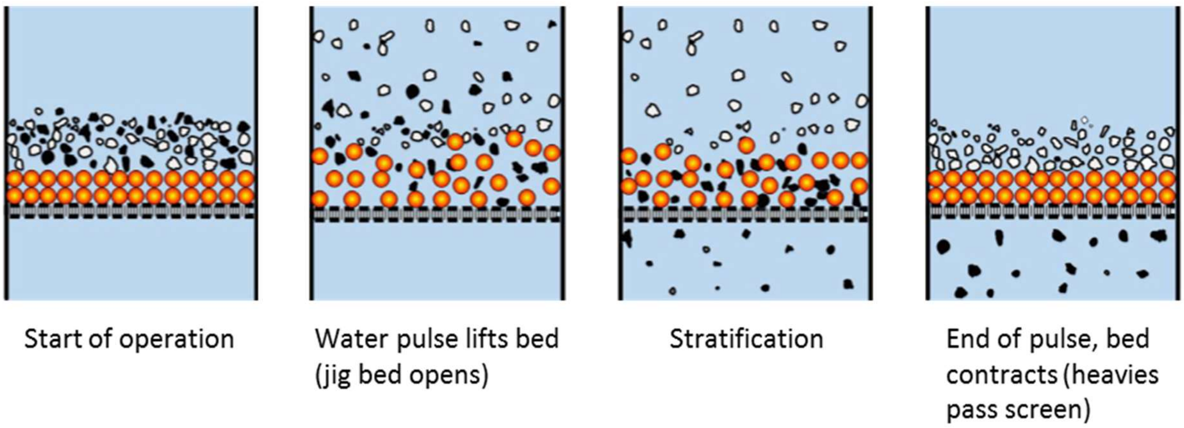


Figure 3-8: Working principle of a jig (Wills & Finch 2015)

Shaking tables (Wills & Finch 2015)

This form of concentrators also uses the settling difference due to specific gravity differences combined with particle size as a basis for separation. On a shaking table, the particles crawl forward as a result of a shaking motion the table makes. The particles are separated by a cross flow of water over the table which flushes the lighter particles out of the longitudinal grooves. See Figure 3-9 for the setup and concentration principle of a shaking table. Capacities of shaking tables lie in the order of 0.5t/h (100-150µm) to 15t/h (15mm) depending on particle size.

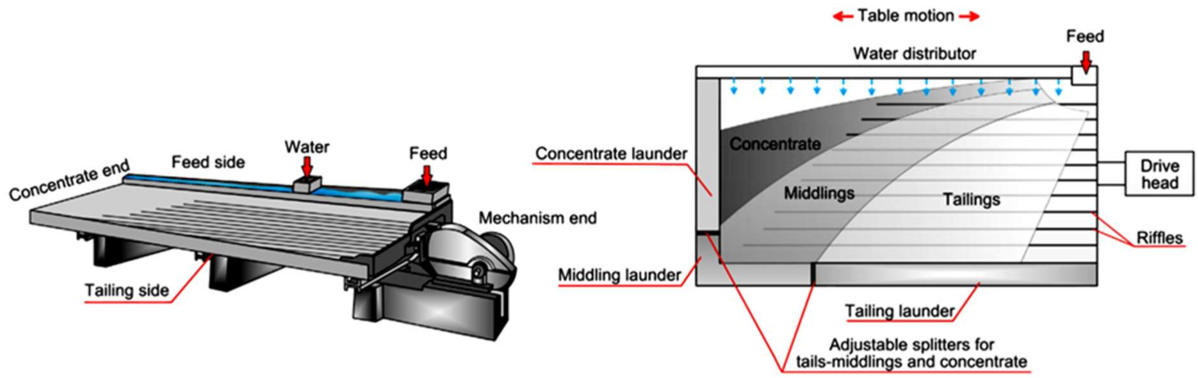


Figure 3-9: Shaking table setup and working principle (Wills & Finch 2015)

Spirals (Wills & Finch 2015)

Spirals have been applied broadly for the treatment of heavy mineral sand deposits. The feed of a spiral can vary between 15% and 45% solids per volume, with a size of 75-3000µm. As the mixture flows spirally downward, the centrifugal force and, different settling rates, stratify the flow. Heavier minerals end up on the inside of the spiral whereas lighter material gets flung to the outside. Spirals are a good concentration method however the quality of the separated material should be monitored as a cross-flow in the radial direction of the spiral could deteriorate the results.

Centrifugal concentrators (Wills & Finch 2015)

Centrifugal concentrators depend on creating an apparent gravitational field. This way the gravitational concentration processes described in 3.3 execute much faster than under normal (1G) circumstances. However, the equipment as described has to be modified. An example is a centrifugal jig. This equipment combines the jig as described above but rapidly rotated. Throughput can be very high for centrifugal concentrators, however, they work best with a very low heavy mineral per volume content.

Fluidized bed separators (Wills & Finch 2015)

FBS' (fluidized bed separators) concentrate the induced slurry by means of providing a counter current from the bottom of a settling tank. The method is similar to the one used in hindered-settling hydraulic classifiers, see 3.2. FBS' are however able to obtain high throughput rates, especially when looked at a per square meter basis.

Sluices and cones (Wills & Finch 2015)

Sluices are relatively simple concentration devices, being just an inclined plane over which the material flows, forming a stratified flow. At the end of the sluice, the flow goes over the brim of the sluice and due to differences in flow speed, within the stratified flow, is separated in different partitions based on weight.

Cones are used in combination with sluices and are used to contain the material in the equipment.

Cones combined with sluices can handle significant throughputs. An example of a cone and sluice structure is a Reichert cone, a schematic of the Reichert cone can be seen in Figure 3-10, on the next page. The combination of different sluices and cones results in a good grading of partitions.

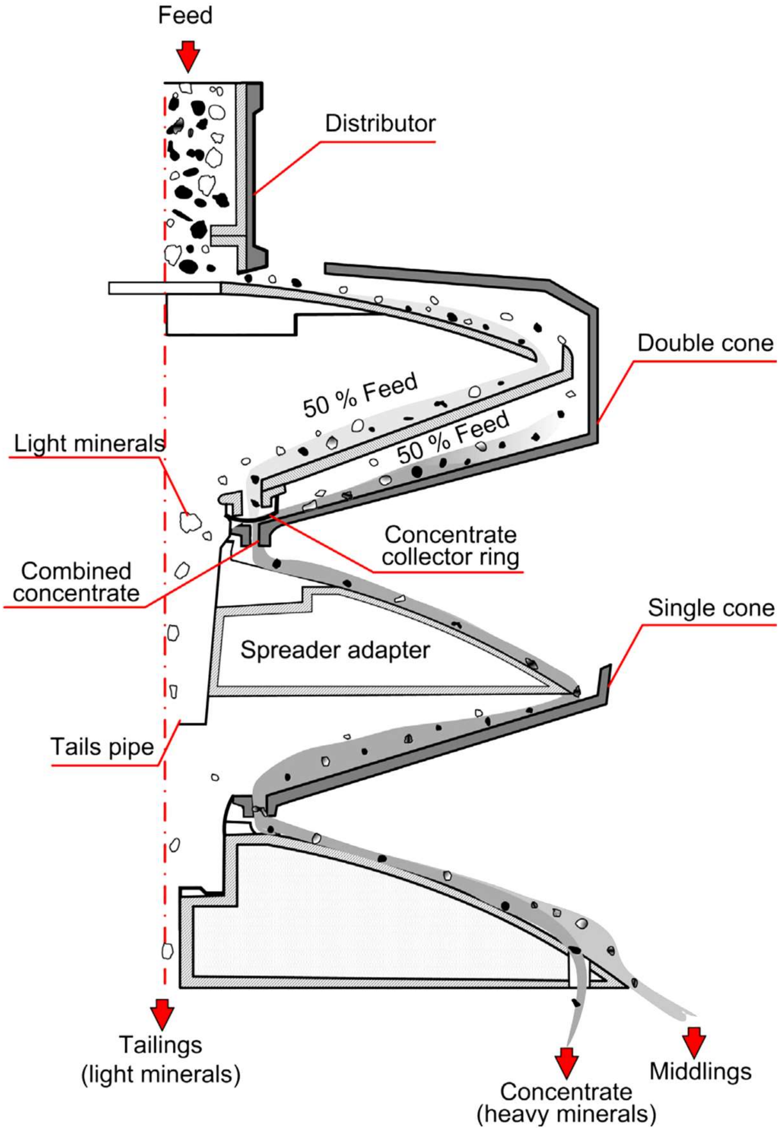


Figure 3-10: Principle of the Reichert cone concentrator (Wills & Finch 2015)

Dry processing (Wills & Finch 2015)

Pneumatic tables and air jigs

A pneumatic table and an air jig work the same as their hydraulic counterparts, with the distinction that here air is used instead of water. For an elaboration of the working principles, see above. The pneumatic table is for instance used when clearing quartz from zircon.

3.4. Dense medium separation (DMS) (Wills & Finch 2015)

This separation method is also known as heavy medium separation (HMS) or the sink-and-float process. The main applications of DMS are pre-concentration of minerals and are a common step in the coal purifying process. Especially the first application could be interesting for offshore mining as it is a first step in separating the main gangue material from the useful minerals, even before a comminution steps.

In essence, the DMS process is a gravity based separation step. It uses a heavy fluid, which makes the lighter particles (mostly the gangue) float in the liquid. These can then be disposed of and the useful minerals sink and can be obtained. Most natural heavy liquids are toxic, therefore in industrial processes, a suspension of particles in water is used as "heavy liquid". Generally, a concentration below 15% of finely ground suspensions in water behave as simple Newtonian fluids and can thus be used as a medium in DMS. When higher levels are used the fluid becomes non-Newtonian and a minimum stress should be exerted to move within the fluids, making flotation of a material harder. This is often overcome by stirring the mixture making it less viscous.

Dense medium separation has some clear advantages. First, it is able to make a very clear separation as the specific gravity of the fluid can be exactly set and measured. The density can also be changed easily and fast allowing for a change in influx material. However, the DMS process is rather expensive due to the ancillary equipment needed as well as the need for the heavy liquid medium, its recycling and, constant monitoring of the process.

For metalliferous minerals like tin or iron, the DMS process can be very beneficial. Mostly when the sought mineral is present in lobes or is easily separated from the gangue and/or is present in relatively large particles, DMS is applicable.

The process of DMS can be combined with the in 3.3 described centrifugal separators and the in 3.2 described hydrocyclones.

For more in-depth information about DMS, chapter 11 of (Wills & Finch 2015) forms a good starting point.

3.5. Froth flotation (Wills & Finch 2015)

The flotation process uses the minerals' proneness to water as a basis for separation. If a mineral is hydrophobic, it repels water, it can attach to air bubbles and be floated. This makes the flotation process also relatively complex as it thus comprises three phases (water, air, solids), as well as some chemicals.

In a froth flotation cell, the mixture of fluids and solids is agitated causing enough turbulence for the hydrophobic particles to attach to the bubbles and float to the surface. Here the bubbles with the attached solids form a froth. This froth is then recovered. Usually, the froth contains the sought mineral (direct flotation). The opposite is reverse flotation than, the froth contains the gangue. See Figure 3-11 for a schematic of the principle of froth flotation.

For flotation to be successful, particle size should be carefully monitored and kept small. Otherwise, the solids cannot adhere to the bubbles and the process fails.

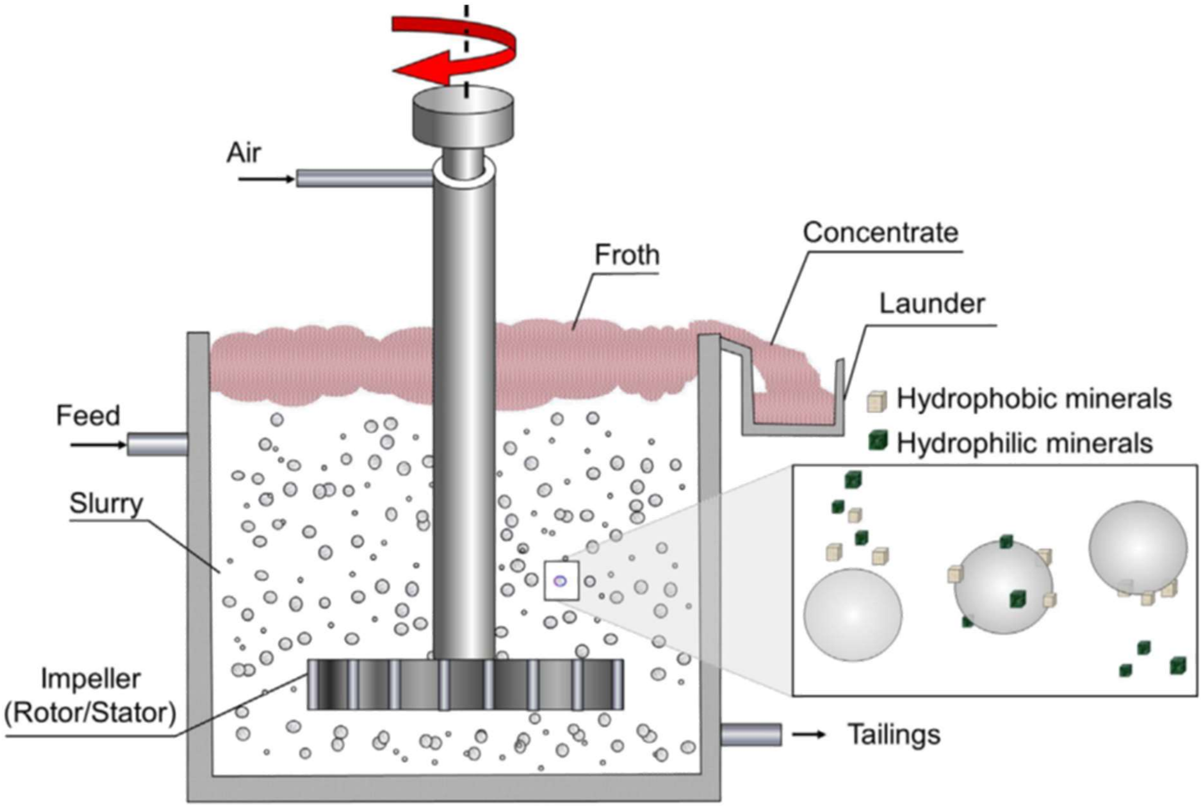


Figure 3-11: Principle of froth flotation (Wills & Finch 2015)

Chemicals in the flotation process

As stated before the froth flotation process almost never happens without the extensive use of chemicals. The chemicals used in the flotation process can be classified as surfactants (collectors and frothers) and regulators (activators, depressants, dispersants and pH modifiers)

it is important to sustain a stable froth because when the bubbles burst, they also dump their solids, which start to sink again. This is done by using flotation reagents called frothers. They have three goals:

- Aid formation and preservation of small bubbles in the fluid
- Reduce bubble rise velocity
- Aid formation of the froth

Most frothers are heteropolar, meaning that they have a hydrophobic and a hydrophilic side. This enables them to attach to hydrophobic solids and the water on the other side. A common example of heteropolar substance is soap.

For the minerals to be hydrophobic, it is needed for them to be nonpolar. These minerals inherently are hydrophobic and thus do not attach to water and are able to be floated. Examples of these minerals are coal, graphite, and diamond. However, most minerals are polar and so are hydrophilic. There are five groups of hydrophilic minerals. The first being only a little hydrophilic, the last being very hydrophilic. See Table 3-1 for the classification of some minerals, which are indicated as interesting for offshore mining, according to their hydrophobicity. These minerals need collector chemicals in order to enable them to float. An example of a much applied collector is kerosene.

Table 3-1: Hydrophobicity of selected minerals (Wills & Finch 2015)

Mineral	Group (1 to 5 increasing hydorphil)
Magnesite	Group 3
Apatite	Group 3
Monazite	Group 3
Ilmenite	Group 4
Rutile	Group 4
Magnetite	Group 4
Hematite	Group 4
Cassiterite	Group 4
Zircon	Group 5

The regulators are used to alter the surfactants and mineral properties in order to optimize the flotation process.

- Activators alter the minerals which need to be floated so that they can interact and attach to the collector chemicals.
- Depressants make sure some (gangue) minerals are hydrophilic in order for them to not form a froth. This is vital for the economic viability of the process.
- Dispersants form a hydrophilic layer around a particle making sure it will not float and making it unable to form aggregates.
- pH modifier, as the process contains many different chemicals as well as minerals, water, and air, it is important to make sure the mixture has an optimal pH for its reactions to take place.

As many chemicals are used in the flotation process, and these account for a considerable part of the OPEX of the plant, there is a need for regenerating these chemicals. This makes the plant quite extensive as well as complex. The use of chemicals itself, also makes froth flotation less attractive in an offshore environment. Moreover, for the efficient operation of a froth flotation plant, a stable (not moving) subsoil is needed, making it not usable offshore due to vessel motions.

For more in-depth information about froth flotation, chapter 12 of (Wills & Finch 2015) forms a good starting point.

3.6. Magnetic and electrostatic separation (Wills & Finch 2015)

These two methods are important for separating minerals. Often they are used in sequence. A striking example of this is the separation of heavy mineral sands in which both electrostatic as magnetic minerals are found.

Magnetic separation

As the name suggests magnetic separation uses the magnetic properties of a mineral as a basis for separation. It is used to separate different valuable minerals as well as valuable minerals from gangue. In general, all minerals are in some way affected by a magnetic field, although for some minerals this effect is too small to be detected. As all minerals are affected, they can also be classified into two categories:

- Diamagnetic materials, these are minerals which are repelled by a magnetic field and they tend to move to a location where the field is less intense or absent. The forces resulting from this tendency, however, are very small and this group of materials is often regarded as non-magnetic. Examples are: quartz
- Paramagnetic materials are attracted to magnets and tend to move towards locations with higher magnetic intensity, subsequently, these materials are considered magnetic. Examples are: ilmenite, rutile, and monazite

A mineral becomes paramagnetic if there are unpaired electrons in its molecular structure, which create magnetic dipoles. When such a material is affected by a magnetic field, the dipoles are aligned and a magnetic force directed along the lines of the magnetic field arises. The strength of the magnetic force is dependent on the number of unpaired electrons as well as the molecular shape to the mineral.

A magnetic separator has to have a non-homogenous magnetic field. Otherwise, particles will only orient, and they will not be tempted to move to a more or less magnetic place. This can be done by placing two opposite magnetic poles of the same strength but different area opposite of each other. The strength of a magnetic separator does not automatically improve the separation. On the contrary, a stronger magnet can also “capture” weakly magnetic gangue instead of the sought mineral, thus reducing the separation effectivity. A stronger magnetic field can also reduce the magnetic susceptibility of certain iron minerals. Figure 3-12 shows the working principle of a magnetic separator.

Magnetic separators can be classified in four different machines:

- Low-intensity magnetic separators (<0.3T), are mainly used for ferromagnetic materials and other highly paramagnetic minerals.
- High-intensity magnetic separators (>2T), are used for the recovery of weakly paramagnetic minerals, like beach sands, tin ores, and rock phosphate. In low-grade iron ores, high-intensity magnetic separators can be used instead of flotation or gravity-based methods.
- High-gradient magnetic separators are used to separate paramagnetic minerals of low magnetic susceptibility. These machines need a high volume of iron to cope with the high magnetic fields, making them very expensive.
- Superconductive magnetic separators are the future for economically sustaining very high magnetic fields. These magnets use super cooled alloys as magnets to produce a strong magnetic field.

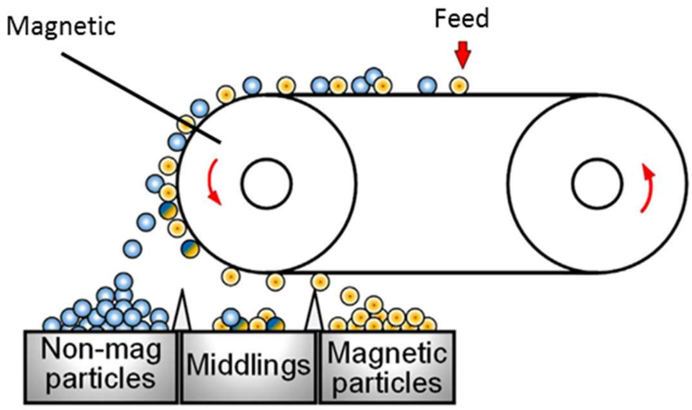


Figure 3-12: Working principle of a magnetic separator

Electrical separation

Electrical separation uses the differences in electrical conductivity between different minerals. As every mineral has a different electrical conductivity, separation should be easy, but electrical separation only has limited applicability as the feed should be completely dry. However, especially heavy mineral sands can be very well separated using electrical separation. There are some limitations on that application as well, the throughput is fairly low as the feed is preferably one particle deep and, the particles have to be very small (<75µm).

For electrical separation to work, there is always the need for a preprocessing step in which the mineral particles are selectively charged. As most electrical conductivity occurs on the surface of a particle, electrical separation can be seen as a method, similar to flotation, based on the surface characteristics of particles, which can be changed (slightly). This is the opposite of for instance gravity and magnetic separation as they rely on properties of a mineral, which cannot be changed.

There are three ways of preprocessing which each also need their specific electrical separation equipment. These are:

- Ion bombardment, the particles are subjected to a very high current, bombarding it with gaseous ions, which charge them. A typical separator associated with this method is the high-tension roll, see Figure 3-13, on the next page.
- Conductive induction, the particles are subjected to an electric field, which polarizes them. Conducting particles are able to pass or redistribute the ions, losing their polarization. Nonconductive ions remain polarized and thus attached to the earth source on the roll which looks similar to the high-tension roll. This method is mainly used to separate strong conducting particles from weak ones.
- Frictional charging uses the difference in electrical charge between two (semi-conducting) minerals as result of their collision to separate the two. The process is dependent on the Fermi[1] levels of the particles. However as this process needs to take place in a highly controlled

[1] The Fermi level is the thermodynamic work required to add one electron to the body, excluding the work needed to free the electron form wherever it came from.

environment, as for instance also the material of a conveyor belt is interacting in these small charge difference reactions, the applications in industry are very limited.

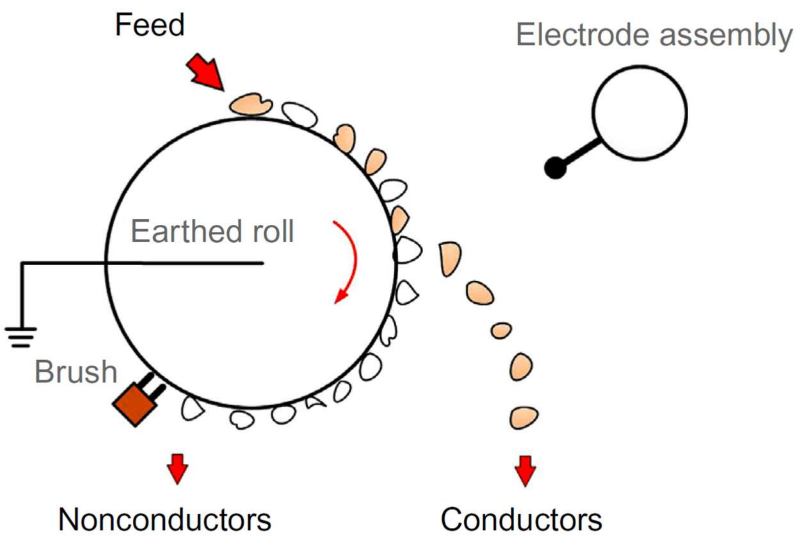


Figure 3-13: Working principle of an electrical separator. Shown: High-tension roll (Wills & Finch 2015)

Table 3-2: Conductivity of selected minerals (Wills & Finch 2015)

Nonconductivity	Conductivity
Apatite	Cassiterite
Monazite	Diamond
Quartz	Gold
Zircon	Hematite
	Ilmenite
	Magnetite
	Rutile

3.7. Leaching or chemical separation

Leaching is the process in which minerals are extracted from a solid by dissolving them in a liquid. Aqueous dissolution is a special form of leaching as it uses water as a solvent. An example of aqueous dissolution is the separation of chloride and, or sodium ions from normal salt (NaCl).

As leaching involves large quantities of hazardous solvents (acids) it is not further considered as a potential separation method in offshore mineral processing. Therefore, no further elaboration is included in this report.

3.8. Dewatering (Wills & Finch 2015)

Almost all mineral separation processes involve the use of significant quantities of water. However, most of the end products have stringent requirements regarding the accepted percentage of contained liquids. In order to comply with these requirements, a processing plant needs a liquid-solid separation step, in which water or any other liquid is separated from the minerals. This process does not only apply to the saleable minerals but sometimes also to tailings.

Dewatering methods can be broadly divided into three groups:

- Sedimentation (gravity and centrifugal)
- Filtration
- Thermal drying

The liquid-solid separation step usually consists of a combination of the abovementioned methods.

Sedimentation (gravity and centrifugal)

Sedimentation is an efficient and low-tech method of separating solids from liquids based on their specific gravity. The larger the differences in specific gravity the faster the sedimentation goes. Settling rates in a sedimentation process are furthermore dependent on particle size and shape, weight volume content of the particles and, fluid viscosity. When water is used as a carrier liquid, minerals can always be separated based on sedimentation.

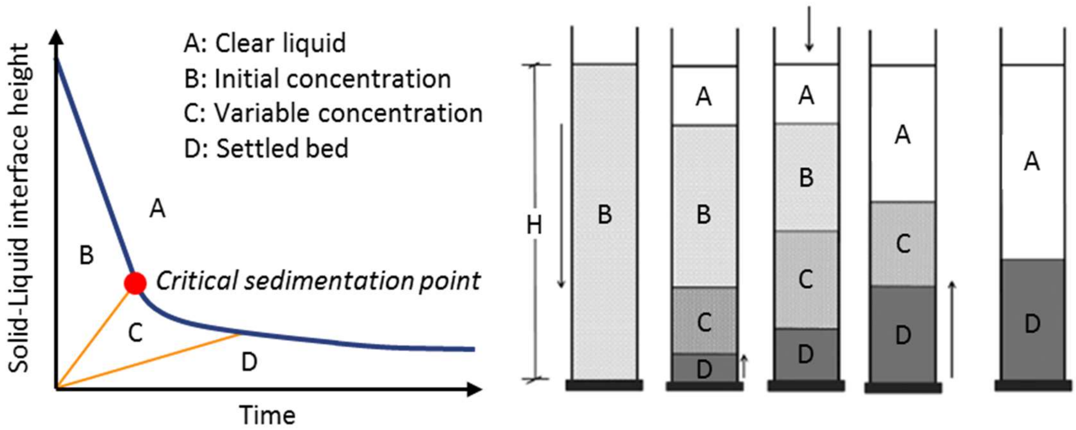


Figure 3-14: Sedimentation process schematic. Tangent of graph corresponds to the velocity of sedimentation (Wills & Finch 2015)

Flocculation

To increase the suspension speed, particle size and weight could be increased either by coagulation or the use of flocculants. These processes cause aggregation or agglomeration of mineral particles, creating flocs. Flocculants are long-chain polymers which bind the minerals, creating larger flocs. Coagulation is the process of changing the surface charge of particles forcing the particles to attract each other (instead of repel) and form flocs. Using seawater in the processing plant can act as a coagulant as it contains large amounts of the positive ion sodium.

Thickeners

Thickeners are the most widely used dewatering techniques, as it is a relatively cheap and high capacity process. Thickeners are used to increase the concentration of the suspension by sedimentation, as well as producing a clear liquid (supernatant) on top. The thickened suspension is drained on the bottom (underflow) of the tank, the supernatant is drained by overflowing the tank.

The thickener consists of a large diameter tank (2-200m) with a depth between 1m and 7m. The suspension of minerals and liquid is fed through a feed well in the center of the tank under fluid the surface. In the tank, at the bottom, there are one or more rotating radial arms, each with a couple of blades. These blades are shaped in such a way, they rake the sediments towards the center of the conical bottom of the tank. In the center of the tank, there is an outlet for the underflow (the sediment). See Figure 3-15 for a schematic of a thickener.

As the required movement of the rake arms is very low, energy consumption of thickeners is very low, compared to other steps in the processing plant. Wear and maintenance costs are also low as the thickeners are fairly simple pieces of equipment.

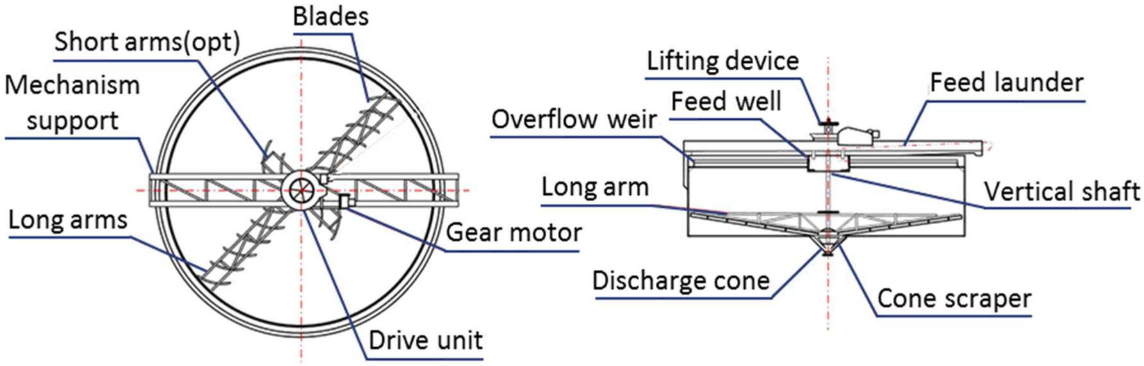


Figure 3-15: Schematic of a thickener (Wills & Finch 2015)

Underflow lines in a thickener need to be as short and straight as possible, in order to reduce the risk of clogging. For pumping the underflow, which is a thick viscous fluid, diaphragm pumps are needed. These pumps are positive action pumps for mediums heads. Stopping the underflow pumps can result in serious damage to the system as the risk of choking is present.

Other gravity sedimentation devices

Tray thickeners are used to obtain a size reduction, with respect to the conventional thickeners. Tray thickeners are in essence multiple normal thickeners which are stacked upon each other.

A lamella thickener, or inclined plate settler, consist of two parts: The upper tank containing lamella plates under a 55˚ angle and a lower tank with a rake. The plates increase the sedimentation velocity of particles as they can slide down under relatively low friction. Thickening is achieved in the bottom tank.

Centrifugal sedimentation

Centrifugal separation can be seen as enhanced gravity liquid-solid separation, as sedimentation velocities are increased due to centrifugal force. Centrifugal sedimentation can be performed in centrifuges or hydrocyclones.

Hydrocyclones are relatively cheap and in essence, a good way to dewater a suspension. However small or light particles will disappear in the overflow. Flocculation is not an option as the forces in the hydrocyclone will break up the long chains.

Centrifuges are a more expensive choice, however, they are better suited for dewatering than the hydrocyclones. The solid bowl centrifuge (or decanter) has the widest application, as it is able to continuously discharge solids. For a schematic of the continuous bowl centrifuge, see Figure 3-16.

The feed for centrifugal liquid-solid separation can be in the range of 0.5-70% solids, with particle sizes varying between 2µm and 12mm. The produced product has a moisture content between 5-20%. Centrifugal separators vary in size between 15-150cm length and have throughputs of 0.5-50M^3/h of liquid and 0.25-100t/h of solids. The main driver for final moisture level is the length of the beach (conical) part of the centrifuge. A long shallow beach will result in the lowest moisture levels.

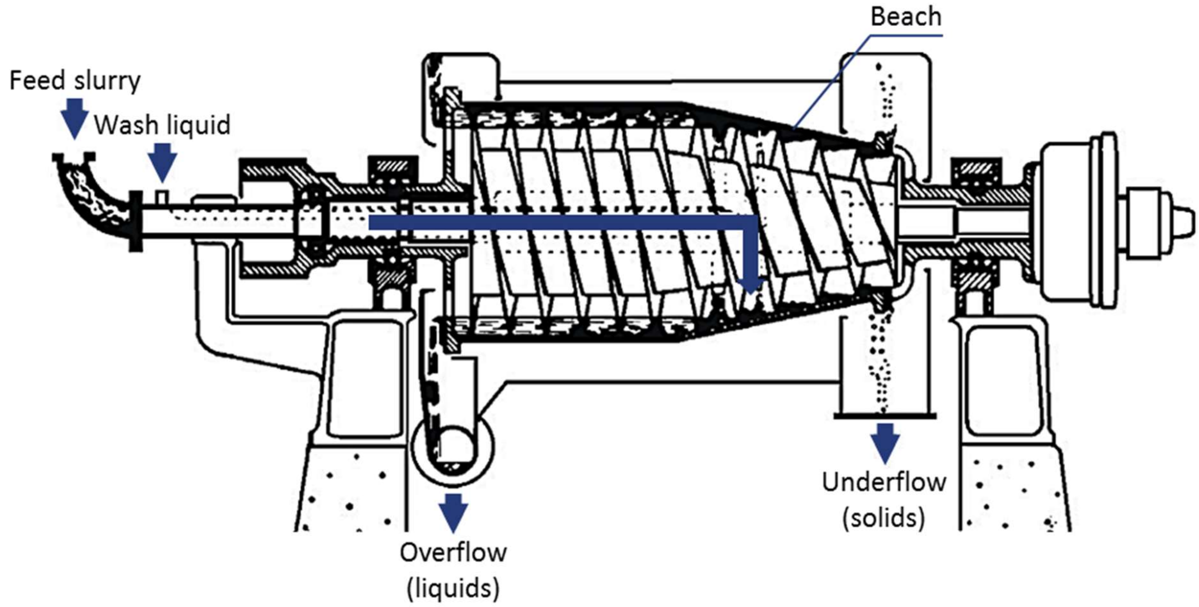


Figure 3-16: Continuous bowl centrifuge schematic (Wills & Finch 2015)

Filtration

Filtration is a process in which a liquid-solid separation takes place by means of a porous medium which will retain the passage of the solids (filter cake) but lets the fluids pass. Slimes can have a negative effect on the filtration rate as it can clog the filter. Flocculation is used to aid filtration and can reduce the impact of slimes.

The filter medium is the most important parameter in designing the filtration equipment. The medium should be able to retain solids without blinding. Furthermore, it should be strong and corrosion resistant. Often the first layer of the substrate is used as part of the filter medium. Common materials of which filter media are fabricated are cotton, glass fiber, ceramics, and metals.

Basically, there are two types of filtration mechanisms, pressure, and vacuum filtration. With pressure filtration, positive pressure is applied to the slurry to “push” it through the filter, this is the most common technique. With vacuum filtration, a vacuum is created behind the filter to “suck” the water through. Filters are suitable to separate fairly fine (<100µm) solids (with flocculation) from the dense slurry feed (50-60% solids per volume).

Filters exist in many different configurations and setups, including Horizontal and vertical pressure filter, tube press, batch and continuous vacuum filters, rotary drum filter, (ceramic) disc filter, horizontal belt filter, pan filter and, hyperbaric filter

Thermal drying

The drying of mineral concentrates is the last step in the processing sequence prior to shipment. Its aim is to lower to moisture content to *above* 5% weight. If the moisture content is below this level, dust losses become relevant. The main dryer types are hearth, grate, shaft, fluidized bed and, flash dryers. However, the most common dryer used is the rotary dryer.

Rotary thermal drying

Rotary thermal drying equipment uses hot air or gases to dry the mineral concentrate. The tube in which the mineral is fed is placed at an angle, so the material moves under gravity. The tube also rotates to mix the mineral concentrate and dry it evenly. Parallel flow thermal dryers insert the hot gas at the feed end, counter-current flow thermal dryers insert the hot gas at the product end of the rotating tube. Parallel flow dryers are the most common as they have higher capacity, however, only counter-current flow dryers can dry a product to 0% moisture. A schematic of a rotary dryer is shown in Figure 3-17.

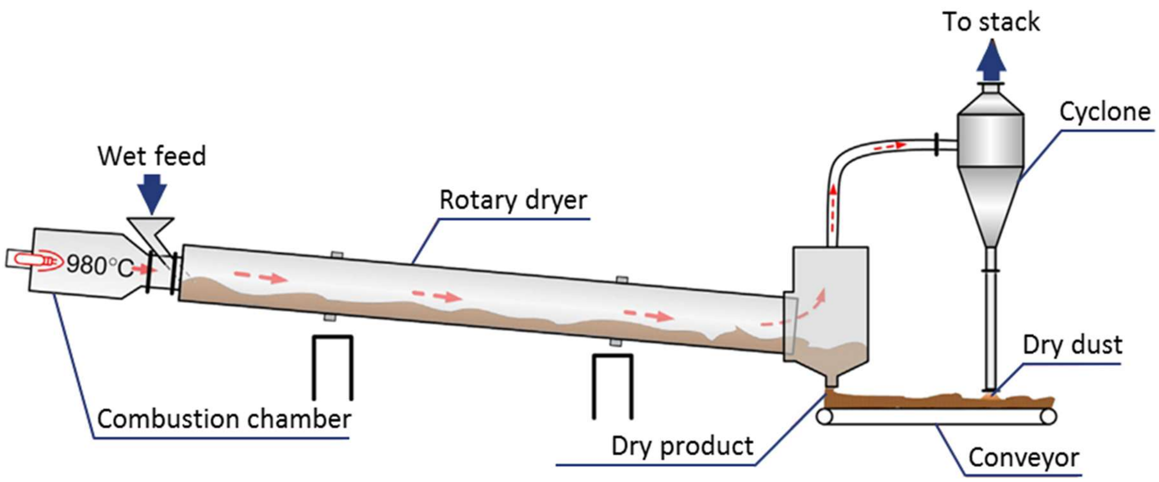


Figure 3-17: Direct fired, parallel flow rotary dryer (Wills & Finch 2015)

3.9. Processing equipment manufacturers

Worldwide there are numerous suppliers of mineral processing equipment. The list below, therefore, is not complete.

- Metso (Sweden) – All-round mineral processing and handling equipment manufacturers and consultants
- FLSmidth (Denmark) – All-round mineral processing and handling equipment manufacturers and consultants
- ThyssenKrupp (Germany) – All-round mineral processing and handling equipment manufacturers and consultants
- Outotec (Finland) – All-round mineral processing equipment manufacturers and consultants
- Terex (United States) – Mobile crushing, screening and washing plants
- IHC Merwede (The Netherlands) – Consultants for (offshore mineral processing) as well as a minor processing equipment manufacturer

4 Legislation and taxation

As in any large-scale project, legal aspects can have a large impact on the project operations or even on its feasibility, subsea mining is no exception.

Reading guide

- Paragraph 4.1 – United Nations Convention on the Law of the Sea (UNCLOS)
- Paragraph 4.2 – Maritime zones as defined by the UNCLOS
- Paragraph 4.3 – Current regulatory frameworks
- Paragraph 4.4 – Taxation and royalties schemes

4.1. United Nations Convention on the Law of the Sea (UNCLOS)

The UNCLOS is the most important piece of legislation when it comes to the oceans and seas. It regulates which countries laws apply in which areas and itself governs the rest of the high seas. The area of the seafloor and subsoil governed specifically by the UNCLOS, so outside the limits of national jurisdiction, is named the Area. (United Nations 2001)

UNCLOS was first established in 1982 and came into effect after the 60 countries had ratified the convention. This did not happen until 1994. As of June 2016, 167 countries have ratified the UNCLOS treaty. It should be noted, the Unites States of America have not ratified the treaty as they object provisions of Part XI of the treaty. Part XI of the UNCLOS treaty regulates the minerals present on the seabed of the Area and, establishes the International Seabed Authority (ISA). As the US believes Part XI of UNCLOS in unfavorable for American business, they are in agreement with the rest of the treaty. Figure 4-1 gives an overview of countries which ratified the UNCLOS treaty and which did not.

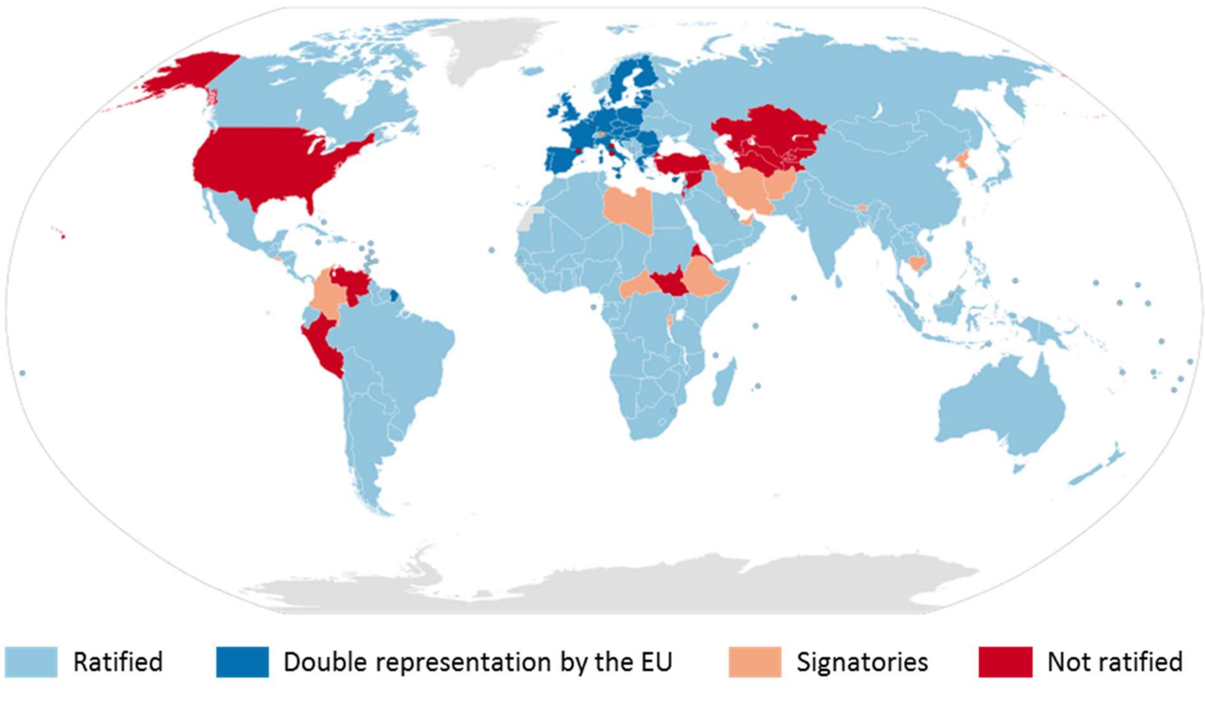


Figure 4-1: World map of countries ratifying the United Nations Convention on the Law of the Sea. (Wikipedia 2015)

4.2. Maritime zones as defined by the UNCLOS

The UNCLOS regulates the seas and oceans of the world. A first step in doing so is defining which areas belong to which country. In Figure 4-2 the classification system as agreed in the UNCLOS is shown.

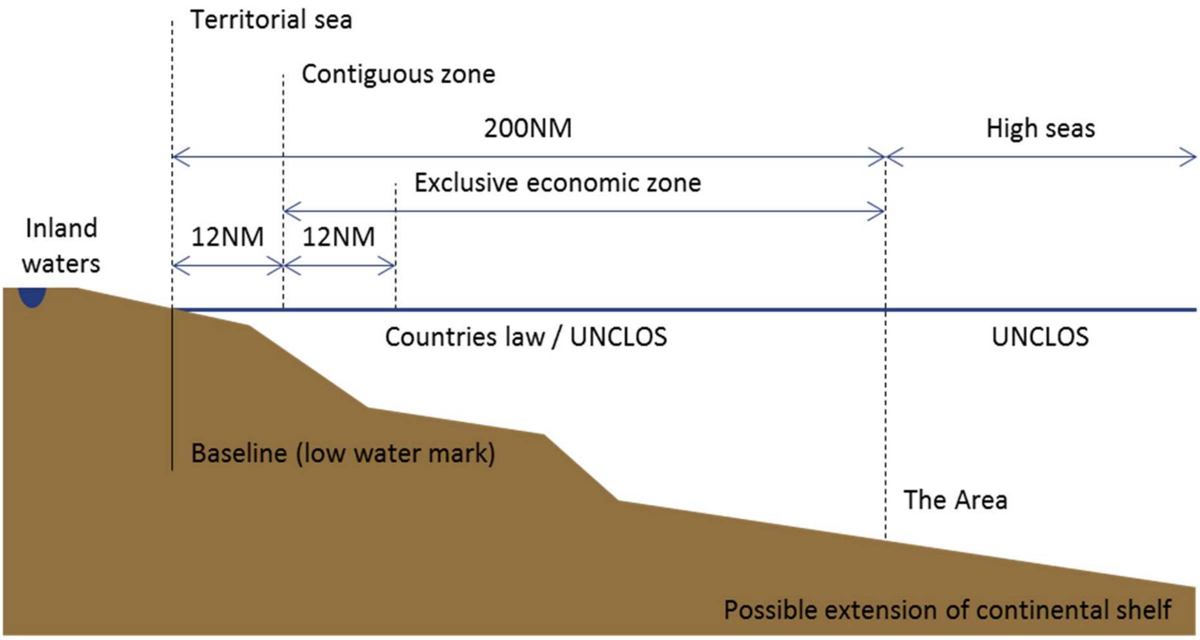


Figure 4-2: Marine zones as classified by the United Nations Convention on the Law of the Sea. (United Nations 2001)

In Figure 4-2 it can be seen that the first 12 nautical miles are characterized as the Territorial Sea, in which the adjoining country has complete sovereignty and owns all resources, as well in the water column as in the seafloor. When measuring distances from shore, UNCLOS uses the “baseline”. The baseline is mostly the low-water line along the coast.

The contiguous zone is not relevant for mining as it only applies to rules regarding shipping. The country can only regulate the following: customs, taxation, immigration and pollution in this area. However, the contiguous zone also belongs to the exclusive economic zone of a country (EEZ). The EEZ is maximum 200 nautical miles wide, measured from the baseline. In the EEZ the coastal state does not have sovereignty but has some rights towards the resources present in the water column and under the seafloor.

Additionally, it should be noted that the minerals on and in the continental shelf up to 350nm from the baseline or 100nm from the 2500m depth isobath can be attributable to the coastal nation. The resources in the water column above this extra area is never attributable to the country.

Normally, the area outside the EEZ is known as the “High Seas”, which is governed by the UNCLOS and its acting authority the ISA. The seabed in the Area and the resources it contains, excluding the part of the continental shelf which belongs to coastal nations, are “the heritage of mankind”. This means any revenues are attributable to mankind as a whole. (United Nations 2001) & (ECORYS 2014)

4.3. Current regulatory frameworks

As stated above, the ISA is established by the UNCLOS treaty as an authority responsible for regulating the Area, especially with respect to deep-sea mining. However part of the responsibility for legislation in the Area still lies with the national governments. In the EU only the UK and Germany have such laws. France is currently drafting them. For most other countries terrestrial mining laws apply to deep-sea mining projects, when in the EEZ or on the continental shelf.

With regards to shallow water offshore mining, most projects will lie inside the exclusive economic zone of a coastal nation. As stated before, only a few countries have specific legislation in place for offshore mining, namely: UK, Germany, France, the US, Fiji, Japan and, (almost). Some other countries have slightly adjusted their legislation for terrestrial mining, making it applicable for offshore mining as well. These countries include, amongst others: The Netherlands, Italy, China, Greenland, Papua New Guinea and, Portugal. However many countries do not have any offshore mining legislation and have no intentions of drafting them in the near future.

What most legislations have in common is the fact that different permits are needed to start an offshore mining operation. These include (Mateparae 2014):

- Prospecting and or exploration permits, needed for determining the mineral quantities present, bathymetry, soil characteristics and, sampling. Prospecting permits are often used for low impact mineral search. When more intrusive or higher impact (on the environmental) work has to be done, an exploration permit is often needed.
- Mining permit needed to be able to start the actual mining. This permit evaluates amongst other aspects the procedures, quantities and if all legislation is followed.
- Marine consent (often part of the mining permit), this permit is given when an environmental impact analysis is done and the governing authority is satisfied with its results regarding the effects of the operation on the environment (flora and fauna), the mitigating measures and, emergency procedures.

The lack of regulations results in many uncertainties for prospective mining companies and governments alike. These uncertainties relate to, amongst other issues: Environmental requirements, royalty and tax regimes, remediation requirements, safety regulations, community compensation due to adverse effects of offshore mining and, responsibilities in case of emergencies. All these uncertainties lead to fewer investments in offshore mining projects. (ECORYS 2014)

4.4. Taxation and royalties schemes

As most shallow water offshore mining projects will lie in the EEZ of a nation, they will have to pay royalties over the mined minerals and tax over the gained revenues. The tax and royalty scheme is solely based on the tax authorities of the local government. As stated in paragraph 4.3 above, most countries do not yet have dedicated offshore mining legislation. This usually means they do also not have dedicated tax and royalty schemes in place for offshore mining. Therefore usually the applicable tax and royalty schemes for terrestrial mining are applied as a first estimate for project viability.

Including the tax and royalty scheme in projects, first viability estimation is of great importance as it usually embodies a (relatively) large sum of money. Common corporate tax rates are in the range of 35% and have to be paid over the profit a company makes. What a country understands under profit depends on the tax code as well.

With respect to the royalties, countries have different regimes. Royalties can be paid as a percentage of the complete revenue, as a percentage of the sold goods or, as a percentage of profits. The royalty scheme can also depend on the phase in which the project is. When the project is not yet profitable, the royalty rate can be significantly lower. Furthermore, depending on the schemes described above, the royalty rate can vary with commodity prices. Schemes in which royalty rates depend on commodity prices or the profitability of a project make the government more involved with the projects wellbeing, due to the shared risks involved. This in opposition to a mere collecting attitude of a government. For instance, when the royalty rate is just a percentage of the revenues of the company, which takes no profitability, business cycle effects or other external effects into account. (Mateparae 2014) Most royalties have to be paid, ad valorem, meaning as a value added tax.

Besides royalties and taxes companies have to pay the local government for obtaining and maintaining the necessary permits and consents. The value of these contracts is relatively low, compared to their value to the project, for which holding these permits is of vital importance.

5 Environmental implications

This chapter outlines possible environmental effects due to shallow water offshore mining. As each location has its own specific flora, fauna and legislation only an overview of the most important effects is given.

Measuring effect on the environment

The impact of a mining operation on its environment can vary. To determine magnitude of the impact, four points should be assessed (ECORYS 2014):

- Nature of the impact – What is the threat?
- Duration of the impact – Should be as short as possible
- Size of the impacted area – Should be as small as possible
- Potential for recovery after the impact – Should be as high as possible

Assessing these criteria is highly dependent on the specific location and its flora, fauna, wave and current climate, and bathymetry.

Reading guide

- Paragraph 5.1 – Possible impacts of offshore mining on the environment
- Paragraph 5.2 – Tailings related impacts
- Paragraph 5.3 – Public awareness with respect to offshore mining and its implications
- Paragraph 5.3 – Directions for further research

5.1. Possible impacts of offshore mining on the environment

Plumes

Plumes are caused by disturbing the seabed or by discharging dredged slurry into the water column. In offshore mining this can be the case by dragging a draghead over the seabed, discharging tails or overflowing the hopper. These plumes are considered to have an important environmental impact on their surrounding as they function as large underwater dust clouds. When the “dust” settles, it can bury organisms under a layer of sediment, closing it off of their surroundings. Plumes are known to affect predominantly the smallest organisms, like plankton. As plankton is at the bottom of the food chain, reduced growth of the population can indirectly impact larger species as well (ECORYS 2014).

Table 5-1: Impact analysis of sediment plumes.

Nature of impact	Plume in the water column. Risk of covering organisms.
Duration of impact	Whole project, however the focus area changes with mining location, spreading the impact over a larger area.
Size of impacted area	Possibly large, depending on local climatological characteristics and discharge depth.
Potential for recovery	Hard to indicate. Depends on which habitats are affected and the thickness of the sediment layer.

As can be seen in Table 5-1, sediment plumes can have a large effect on the environment. However generating plumes is inherent to a dredging operation, therefore mitigating it is advisable. Measures to mitigate a plume are:

- Disposing of tailings and overflowing material at an as deep as possible depth. Doing so shortens the horizontal distance the material can travel before sedimentation takes place, thus reducing the influenced area, see Figure 5-1. Discharge near the bottom also reduces the effect the plume has on phytoplankton, which predominantly live in higher levels of the water column (Odyssey Marine Exploration 2014) & (Narvaez McAllister et al. 2016). Mitigating options are:
    - A practical way of doing so is by employing the second suction pipe of a trailing suction hopper dredge (TSHD) as a tailings disposal pipe, pumping the material almost to the seafloor. With this option, care must be taken for the discharge speed, otherwise this could result in turbulent flow at the seabed, inducing a plume on its own.
    - Another option would be using a discharge pipe attached to the bottom of the vessel and hoovering, with the use of an ROV, above the seabed where it gradually discharges sediment. Using this method leaves the second suction pipe of the TSHD available for mining.
- Adjust the draghead to reduce turbulence of the subsea floor. By adjusting the draghead in order to induce less turbulence or, encapsulate it to pump up all loose sediments, reduces one of the sources of sediment plumes.

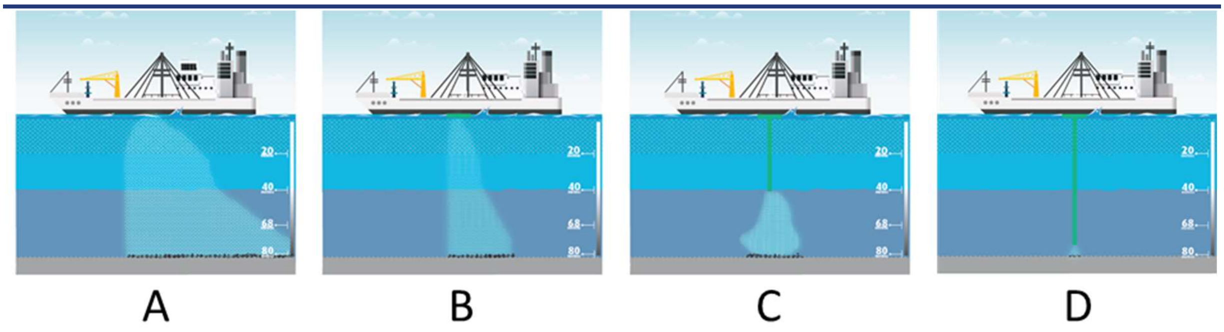


Figure 5-1: Schematization of the impact the depth of discharge of tailings or other material has on the affected area on the seabed. A: Discharge at the surface. B: discharge at the bottom of the vessel (approximately 10m water depth). C: Discharge somewhere along the water column. D: Discharge just above the bottom. (Narvaez McAllister et al. 2016)

Noise

Underwater noise can impact certain animals, especially marine mammals like whales and dolphins tend to be affected by underwater noise. Sources of underwater noise in a marine mining operation are: thrusters and propellers, (underwater) pumps, draghead, and vessel engines sounds (ECORYS 2014).

Table 5-2: Impact analysis of subsea noise.

Nature of impact	Underwater noise, inducing stress on marine mammals
Duration of impact	Whole project, however the focus area changes with mining location.
Size of impacted area	Medium, depends on pitch, intensity of the noise, and sound carrying capacity of the water. As well as animal specific hearing capacities.
Potential for recovery	Animals will be scared away and can experience stress. However large incidental noise loads can result in hearing damage to animals

There is already extensive experience with reducing marine noise or guarding the safety of animals for subsea noise. This experience is mainly found in the offshore and offshore pile driving industries.

A mitigating measures could be deploying a network of sound producing buoys, holding off marine mammals of the dredge site. This can mitigate damage to the hearing organs of the animals due to large noise loads near the mining vessel. Van Oord developed such a system under the FaunaGuard brand. It is currently used in several dredging projects and yields satisfactory results (Van Oord 2017).

Habitat intrusion

As part of the mining operation the seabed is excavated by a dredge, this leads to the loss of habitat for organisms living in this specific area. The presence of (mining) vessels in the area can also influence the living or breeding areas of certain species. An example of the influence a mining operation can have on the breeding and living areas of whales and turtles can be found in section **Error! Reference source not found.**.

Table 5-3: Impact analysis of habitat intrusion.

Nature of impact	Intrusion in the living area of certain species of flora and fauna in the seabed or the water column above it.
Duration of impact	Whole project, however the intrusion of the seabed only occurs when actively mined. The intrusion of the water column is variable and depends on vessel movements.
Size of impacted area	Small, area of the seabed affected is relatively small and flexible. Area of the water column affected is small as well as it only concerns the vicinity of the mining, processing and exporting vessels.
Potential for recovery	With respect to the intrusion on the seabed, it depends which species are affected and on the homogeneousness of the seabed. A more homogenous seabed will recover faster than an inhomogeneous seabed. With respect to intrusion in the water column, the potential for recovery is high.

With respect to habitat intrusion, the environmental effects are not very high. This is mainly due to the relatively small footprint as well as the good potential for a fast recovery. To minimize the impacts on the seabed, it is important to have good understanding of the local conditions. Mitigating actions which can be taken are:

- The mining plan can be adapted to avoid sensitive areas on the seabed.
- FaunaGuard as described in the previous paragraph, can be used to minimize the impact on animals in the water column.
- Rehabilitation of the bathymetry after the mining took place can be used to enhance the recovery potential.

Chemical spills

Some offshore processing steps need the addition of hazardous chemicals. An example of such a processing step is froth flotation, see section 3.5. Working with chemicals in an offshore environment introduces the risk of spills.

Table 5-4: Impact analysis of chemical spills.

Nature of impact	Spills of chemicals to the sea.
Duration of impact	Only if a spill occurs. When it occurs, the duration is hard to determine.
Size of impacted area	Depends on size of spill and duration of spill before it can be contained. However, there is a potential for a large affected area as wind and waves can spread the spill fast.
Potential for recovery	Depends on which chemicals are spilled, the affected area and

For chemical spills a zero-tolerance policy should be applied. Therefore, *if* spills are an option, extensive mitigating measures should be taken, which could include:

- An extra vessel should be at site at all times to help contain the spill to an as small as possible area.
- For all chemicals used on board an emergency plan should be made, including the best method for containing a spill for each chemical, as well as the best method to treat affected flora, fauna and humans.
- A special officer could be hired, monitoring all equipment in which chemicals are used as well as chemicals handling.

5.2. Tailings related impacts

As with all mining operations, offshore mining produces tailings. Tailings include all material which is not needed to produce the end product and are thus a product of the mineral processing facility. As an offshore mining operation is seen as a sizeable operation, the produced tailing streams are considerable as well. As the mineral processing facility can be placed either on- and offshore, these are also the locations where tailing streams need to be handled.

In all cases the composition of tailings depends on in which mineral processing step the tailings are produced. The origin of the tails therefore, influences the grain size distribution, as well as possible containments as a result of added chemicals during mineral processing steps. If the tailings are affected by added chemicals, they should be treated to neutralize or extract these chemicals, before disposing of the tailings. (Wills 1997)

Offshore produced tailings

Offshore produced tailings should ideally be disposed of right away, as storing them would require a significant investment. Therefore when mineral processing takes place offshore, a continuous re-depositing system is preferred.

However, depositing the tails back to the seabed, directly after the processing facility could lead to environmental problems. As described above, depositing should be done in an orderly manner in order to prevent plume forming. Furthermore, it depends on local legislation if it is possible to deposit the tails back on the seabed.

From a more practical view, depositing the tailings at the seabed can be challenging. Depositing the tailings at the same location as they were mined could help rehabilitation of the seabed, however this could also lead to dilution of the mine. This is due to the thickness of the mineable layer, which can be thicker than the maximum layer a dredging vessel can mine, leading to the necessity to dredge the same location multiple times before the whole deposit is mined. If the tailings are put back at the original location, the average grade at that location would dilute.

Options for direct tailings disposal include:

- Direct re-depositing via the second suction tube to the seabed.
  This would lead to a decline in productivity of the mining vessel. The mining vessel should then also be directly connected to the processing vessel at all times, or be the processing vessel itself. Dilution of the mine could be a threat in this scenario, although the tailings are not deposited in the exact same location, but a couple of meters to the side. The mine plan could be adapted to deposit the tailings in a previous dredging through, where the mineral rich layer is already completely mined.
- Direct re-depositing through a fall pipe under the processing vessel.
  The same considerations as above, for the use of the second suction pipe, are valid. However, if the mining vessel and the processing vessel are physically further separated, depositing the tailings can be done at a convenient location.

Other options for tailings disposal, from an offshore processing locations are limited. This is mainly due to the quantity of produced tailings and the distance to shore, making transport and storage of all produced tailings onshore Improbable.

Onshore produced tailings

When the processing facility is located onshore, the same holds as stated above. A continuous depositing of tailings should be facilitated. This could be done in the form of a tailings basin. However, due to the quantity of the tailings, a considerable amount of land will be needed.

On land tailings need to be desalinized as well. As the mined material is mined from the seabed, it is contaminated with salt, making it unfit for storage on bare land. The salt from the tailings will seep through to the subsoil, making it unfit for vegetation as the salt content will be too high.

Due to the very high quantity of tailings over the mines life, it is improbable to store all tailings onshore. Therefore a combination of temporary onshore storage and offshore disposal should be sought. Another option would be to separate the tailings in usable aggregates (sand and gravel) and an unusable part. The usable aggregates can be sold, whereas the unusable part can be deposited offshore or onshore (if permitted and available space allows).

5.3. Public awareness with respect to offshore mining and its implications

Globally there is a fair amount of resistance against deep-sea mining. Most of the resistance is fed from the lack of knowledge of the effects deep-sea mining can have on the environment. As can be seen in chapter 6, many projects experience delays due to problems with obtaining their environmental permits. These problems are more than once caused through lobbies of activist groups opposing deep-sea mining. An example of a project delayed by (amongst other things) public opinion and its influence on the permitting processes is the Solwara 1 project of Nautilus Minerals, which is ongoing since 2009 (Radio New Zealand 2016). Another project which is delayed due to extensive environmental permitting and public consultation procedures is the Taranaki Bight project of Trans-Tasman Resources, which is currently for the second time applying for marine consent. (Environmental protection Agency New Zealand 2017)

An example of negative public opinion is the article: “Ban on deep-sea mining”, by the Papua New Guinean Church (The National 2017). In this article the, leaders of the church of the PNG, oppose deep-sea mining in PNG waters. They claim it endangers their livelihoods and the technology isn’t proven. With this statement the church supports local communities, who have raised questions concerning the Solwara 1 project of Nautilus Minerals. (The National 2017)

Some positive articles are published as well. But, the majority of articles published have a negative tone towards deep-sea mining. The main concerns heard are:

- The unclear impact of deep-sea mining on the environment, in particular the effect of plumes.
- The effect of deep sea mining on fish populations and the communities depending on them.
- The lack of understanding of the deep-sea environment.
- The uncertainties associated with a new working methods for mining at great depth.

Relation to *shallow water* offshore mining

The resistance described above is predominantly focused on deep-sea mining. This is mainly due to the Solwara 1 project, which is the first (deep-sea) offshore mining project, and thus forms the center of public debate, and the lack of legislation and guidelines. See Chapter 4. [Classified]

However, for shallow water offshore mining, less public opposition can be expected as there are some significant differences with respect to the main concerns for deep-sea mining as described above. These differences include:

- The working method is extensively proven for shallow water mining, as it is conventional dredging.
- Environmental effects of dredging are known and studied, and mitigating actions are tested.
- The knowledge of the seabed, and its flora and fauna at shallow water depths is much greater.

5.4. Directions for future research

Suggestions for future research are:

- Plume forming and its effects on the shallow water environment due to different mining techniques. This is already partly being done by F. van Grunsven at the Tu Delft as a PhD study. The study is as part of the TREASURE program, which aims to identify environmental and ecosystem parameters that need to be monitored in the context of deep-sea mining, and test approaches to carry out monitoring. (de Stigter 2017)
  However, research into applying the (theoretical) findings of van Grunsven to practical mitigating measures or equipment with respect to plume forming would be interesting.
- Long term effects of seabed intrusions due to mining. This is a main point of concern, as this is still uncharted terrain.

6 Current projects, tenders, and other developments

Currently, no real offshore mining projects have actually commenced mining, with the exception of diamond mining offshore Namibia. However, there are some companies and countries developing offshore mining projects. Below a summary of some of these projects is given.

Reading guide

- Paragraph 6.1 – Chatham Rise, New Zealand – Phosphates
- Paragraph 6.2 – Classified
- Paragraph 6.3 – Kenmare Resources, South Africa – Ilmenite, rutile, and zircon (inland dredging)
- Paragraph 6.4 – Classified
- Paragraph 6.5 – Sierra Rutile, Sierra Leone – Rutile, ilmenite, and zircon (inland dredging)
- Paragraph 6.6 – Classified
- Paragraph 6.7 – Classified
- Paragraph 6.8 – Short description of other related projects:
    - CASS, New Zealand – Iron & Ilmenite, gold and silver
    - Debmarine, Namibia – Diamonds
    - PT Timah, Indonesia – Cassiterite
    - Solwara 1, Papua New Guinea – Copper and gold (deep sea mining)

6.1. Chatham Rise Project – New Zealand

General information (Yzeiraj 2016)

Location	New Zealand, 450km east of Christchurch, 350-450m depth, see Figure 6-1.
Companies	Chatham Rock Phosphate (CRP) owns the licenses. CRP is a publicly traded company of which 10% is owned by management and 3.7% is owned by Boskalis. Currently, the company is in a reverse takeover[2] by Antipodes Gold Limited. This construction is employed to obtain a listing on the Canadian Venture Market in order to get easier access to new capital.
Minerals	Phosphate nodules (21-22%)

In December 2013 a 20-year mining permit is issued for 380km2 at the Chatham Rise site. The estimated reserve in this area amounts to 23.4mt, with an expected grade of 21-22%. The project is estimated to start production in 2020, with an averaged mining speed of 30km2 per year, mine life will amount to approximately 15 years. This is however subject to obtaining Marine Consent from the New Zealand government and finding a vessel which is able (or will be modified to) harvest the phosphate

[2] A reverse takeover is a takeover in which the buying party is in fact being acquired by the 'sold' company. Mostly the acquiring company is smaller than the company being acquired. The transaction often has as a goal for the merged company to benefit from the acquiring (buying) companies legal structure. In this case the sought after benefit for CRP is Antipodes dual listing on the Canadian and New Zealand stock exchanges.

nodules. Currently, the vessel Queen of the Netherlands of Boskalis is named as a prospective mining vessel.

Environmental permit problems

Chatham Rock Phosphate already applied for marine consent with the Environmental Protection Authority of New Zealand (EPA), however, the permit was declined in February 2015. Main reasons for this rejection were (Castle 2016):

- Concerns regarding the mitigating measures with respect to the stony coral present at the site.
- Concerns regarding the stated size of the economic benefits due to the projects.
- No acknowledgment of the EPA of the project's environmental benefits: less CO_2 emission due to less transportation of phosphates, less phosphorus washed out from the land due to the use of another processing method (no use of superphosphates).
- Mining will take place in a benthic[3] protection area.

Further concerns raised by the EPA were:

- Impact on marine biota (corals) due to dredging of the upper layer of the seabed
- Effect and impact of the sediment plume generated by the dredging activity. Especially on fisheries and the local environment.
- Effects on marine mammals and seabirds

CRP is looking to reapply for marine consent in the near future.

Figure 6-1: Chatham Rise Phosphate prospected mining area. Approximately 821km^2, east of New Zealand (New Zealand Petroleum & Minerals Authority 2013)

6.2. Classified

6.3. Kenmare, Moma Mineral Sands Mine – Mozambique

[3] The benthic zone is the ecological region at the lowest level of a body of water including its sediment and (sub-)surface layers

General information

Location	Mozambique, 2km inshore and 50km north of Moma
Companies	Kenmare Resources is a publicly traded company, listed on the London and Dublin stock exchanges
Minerals	Ilmenite, rutile, and zircon

Project description

The Moma Heavy Minerals mine in the north-east of Mozambique is an inshore development making use of dredges for their mining activity. The dredges cut their way through the deposit transferring their cuttings subsequently to the wet concentration plant and the separation plant. The complete sequence from mining to exportable product is shown in Figure 6-2.

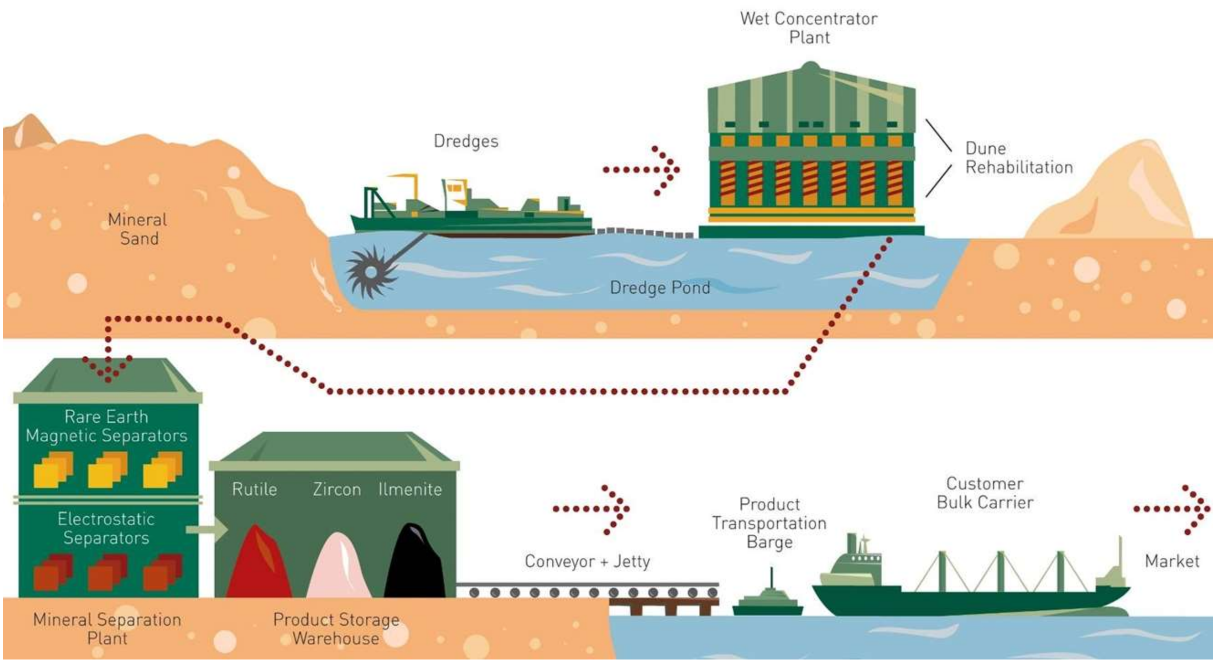


Figure 6-2: Moma Heavy Minerals mine in Mozambique, operations schematic. (Kenmare Resources 2017a)

As can be seen in Figure 6-2, the export products are transported via conveyor belts to jetty. At the jetty, a self-propelled transshipment barge is loaded which at its turn will load an offshore moored bulk carrier. This solution makes the construction of a deepwater port or jetty unnecessary. An overview of the Kenmare Moma Heavy Mineral mining project can be seen in Figure 6-3.

The current capacity of the Moma facilities is 1.2Mt ilmenite, 75kt zircon, and 18kt of rutile, the last two being co-products of the main mineral Ilmenite. The total operating costs of the mine amount to 130-144million US$, which results in 120-132US$ per ton of finished product. (Kenmare Resources 2017b)

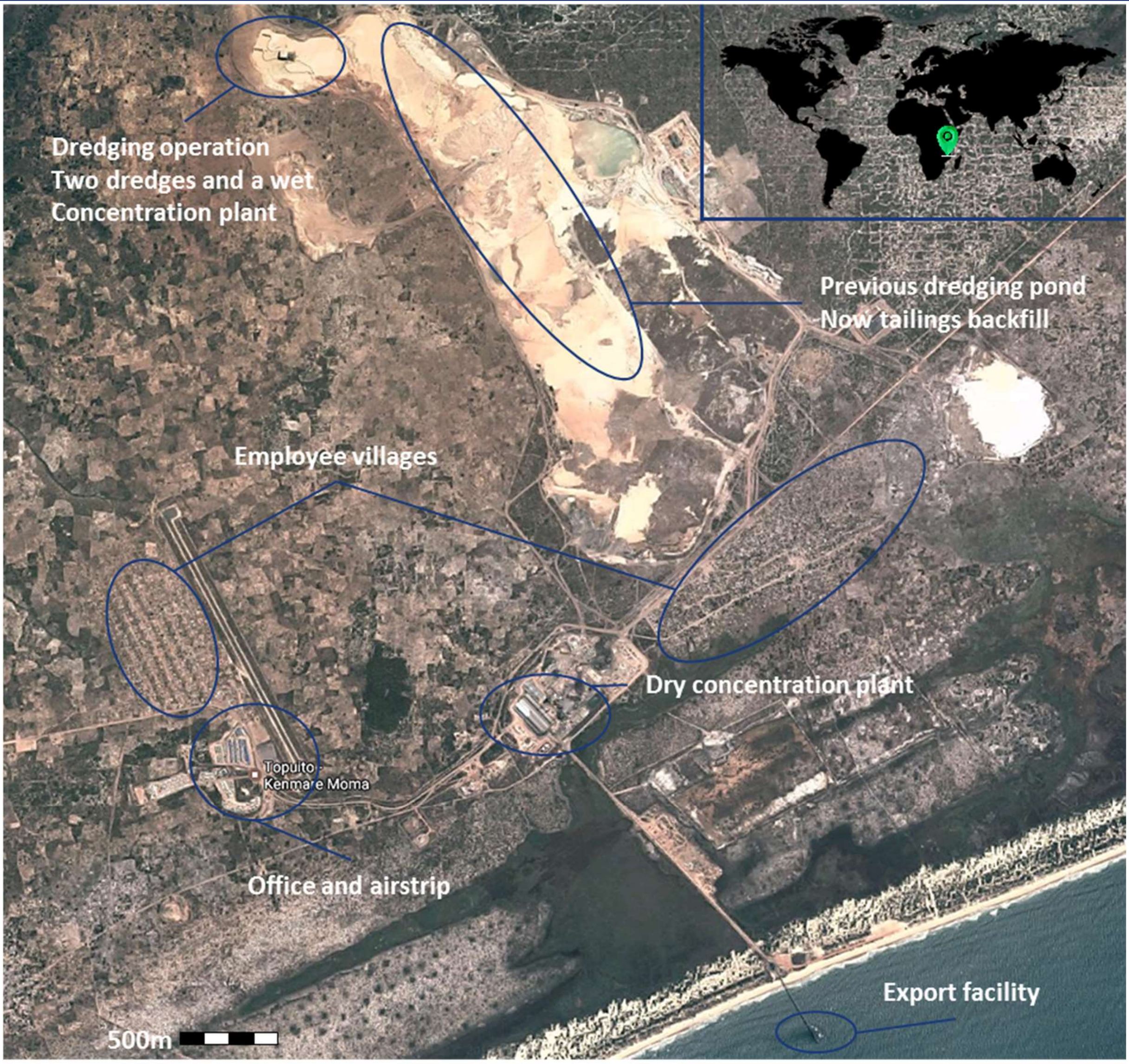


Figure 6-3: Kenmare Moma Heavy Minerals mining project, Mozambique. (Kenmare Resources 2017a)

Processing plant

Wet concentration plant

The first processing step after the dredges is the wet concentration plant. In this plant, the most of the gangue material (silica) will be separated from the heavy mineral content (HMC). This is done by starting with separating the oversize particles from the slurry by means of trommels or vibrating screens. The second step is to separate the HMC from the silica, this is done by making use of the differences in specific gravity between the HMC and the silica. The feed is passed over progressive stages of spiral gravity separators. This produces an HMC stream and a tailings stream. The latter is directly deposited behind the wet concentration plant in settling ponds. The HMC flow represents approximately 5% by weight of the total dredged material and is pumped to buffer ponds near the separation plant.

The deposited tailings are thickened and dried until they can be used to rehabilitate the environment to its pre-mining state.

Separation plant

The Mineral Separation Plant (MSP) employs screens, magnetic, electrostatic and gravity separation circuits in order to separate HMC into valuable minerals and tails. The plant is also able to tailor specific product grades of ilmenite, rutile, and zircon, to meet specific customer requirements.

The MSP is fed from the buffer in which the slurry has dried to an acceptable moisture level. The feed is first passed through a wet high-intensity magnetic separator (WHIMS), in which the ilmenite is separated from the rutile and zircon. The ilmenite is further separated by means of electrostatic separation is two categories and subsequently dried to make it ready for export.

The non-magnetic stream (non-ilmenite) is fed to a wet gravity separator (wet shaking tables) to remove any remaining silica and other contaminants. Afterwards, the stream is fed to an electrostatic separator, separating the rutile (conducting) from the zircon (non-conducting) minerals. Both mineral flows are dried and stockpiled for export.

6.4. Classified

6.5. Sierra Rutile (ILUKA) – Sierra Leone

General information

Location	Sierra Leone, 30km inshore and 140km southwest of Freetown
Companies	Iluka Resources acquired the Sierra Rutile development in December 2016 as a fully owned subsidiary.
Minerals	Rutile, ilmenite, and zircon

Project description

The Sierra Rutile development consists of a wet and a dry mine. The wet mine employs an inshore bucket ladder dredge and a floating first concentration plant. In the floating concentration plant, a heavy mineral concentrate is formed. This concentrate is transported to the dry concentration plant, approximately 10km to the north. Here the concentrate is separated in the different end products: Rutile, ilmenite, and zircon. The dredge has a capacity of around 750tph. In total, the operation produces around 175.000t per year. All end products are transported to a nearby (14km) inshore port facility. Figure 6-4 gives an overview of the wet mining operation of Sierra Rutile. The presented area here is about $14km^2$. (Sierra Rutile 2016)

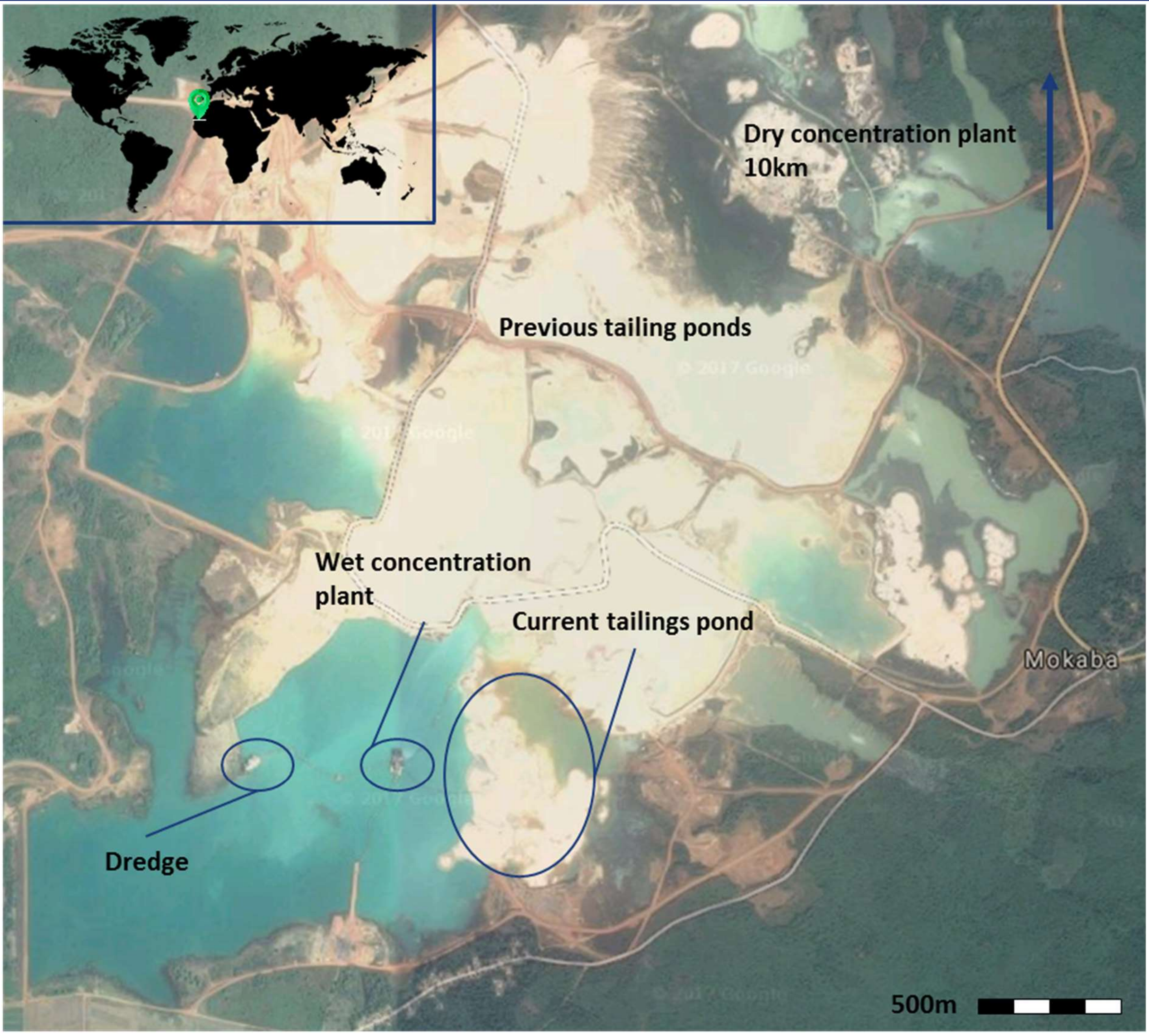


Figure 6-4: Sierra Rutile Lanti Dredge mining operation. Based on Google.maps.com, assessed 14-05-2017 and (Sierra Rutile 2017)

Sierra Rutile claims to be the world's largest natural rutile deposit. Mostly rutile is produced as a byproduct of an ilmenite deposit. However, at the Sierra Rutile development, rutile is the main product and ilmenite is the byproduct. The complete resource base of the Sierra Rutile developments is shown in Table 6-1. With Table 6-1, it should be noted that only 20% of the total area of the mining lease has been examined, which leaves a large potential upside for the resource.

Table 6-1: Sierra Rutile resource classification. (Sierra Rutile 2017)

Resource classification	Mt	Rutile	Ilmenite	Zircon
Measured	66	1,0%	0,2%	0,1%
Indicated	692	0,9%	0,2%	0,1%
Inferred	138	1,0%	0,0%	0,1%
Total	896			

6.6. Classified

6.7. Classified

6.8. Short description of other related projects

Cass Offshore Minerals – New Zealand

Location	New Zealand, two prospecting areas nearshore of the northern island of New Zealand. All within the territorial waters (12NM range from shore) of New Zealand.
Companies	Cass Offshore Minerals, which consists of two other companies: • Iron sands Offshore Mining Limited (IOM) • Pacific Offshore Mining Limited (POM)
Minerals	IOM: Iron sands POM: Ilmenite, gold, and silver

The CASS projects are still in the early exploration phases. Both projects still have to produce their first resource classification reports. (Cass Offshore Minerals Limited 2017)

Debmarine – Namibia

Location	Offshore Namibia, 90-140m depth
Companies	50/50 owned by the Namibian government and De Beers (world's largest diamonds producer). De Beers is owned by Anglo American (85%) and Botswana (15%).
Minerals	Diamonds

Debmarine is a joint venture company between De Beers and the government of Namibia. It focusses on diamond prospecting (exploration) and mining. The company currently operated six mining vessels, of which the latest was launched in early 2017.

Debmarine uses two methods to mine diamonds from the seabed:

- Horizontal mining: Making use of crawlers to transport diamond bearing gravel to the processing plant on the vessel at the surface.
- Vertical mining: Drilling holes in the seabed and transporting the drilled substance to the processing vessel at the surface

The processing plants onboard the mining vessels of Debmarine are complete automated to reduce the risk of human interference with the small but valuable diamonds. The processing plant produces sealed canisters filled with diamonds which are on a regular basis collected by helicopter. To optimize production, tailings are dumped directly overboard. Figure 6-5, gives an example of one of Debmarines vessels which employs horizontal mining. (De Beers Group 2017)

Figure 6-5: Debmarine mining vessel. The mining crawler can be launched from the stern of the vessel. (Laing 2016)

PT Timah – Indonesia

Location	Indonesia, Bangka Belitung Islands and part of Riau Islands, 15-70m depth
Companies	Completely owned by the state of Indonesia

Minerals	Cassiterite (tin)

PT Timah is a state-owned mining company, mining cassiterite in both on- and offshore environments. Offshore, PT Timah employs a fleet of bucket and cutter dredges to mine the cassiterite rich sediments. Total dredging capacity is about 3.5million m^3 per month. (PT TImah (Persero) 2017)

Solwara 1 – Papua New Guinea

Location	Papua New Guinea (PNG), between the New Ireland and New England Islands, 35km offshore, 1600m depth
Companies	85% Nautilus Minerals and 15% Papua New Guinea Government Nautilus Minerals, publicly traded, main shareholders: 27% owned by MB Holding Company (same owner as the Sandpiper project) 15% Metalloinvest Holding (Limited
Minerals	Copper and gold

The Solwara 1 project is the most advanced deep sea mining project. Most deep sea mining projects are miles away from mining, whereas Nautilus already has its subsea equipment built and, is steadily underway with its mining vessel and riser equipment. See Figure 6-6 and Figure 6-7 (next page) for impressions and pictures of the mining vessel and subsea mining equipment. (Nautilus Minerals 2017a)

Currently the Nautilus underwater equipment as shown in Figure 6-7, is in PNG waiting for its first full scale tests. The mining vessel is currently being built in south-eastern China, and is well under way. Them mining vessel, or Production Support Vessel (PSV, as it's called by Nautilus), will be over 225m long and 40m wide and will remain position by a dynamic positioning system. The PSV is designed to carry all subsea equipment, the riser system and accommodate approximately 180 persons. A power generation plant of 31MW will be installed on the vessel to facilitate all mining processes and vessel movements. (Nautilus Minerals 2017b)

The predicted production of the PSV is such that the vessel needs to offload the mined material each 5-7 days. The mined material is only dewatered at the PSV's deck. Further processing takes place at another location (onshore). The dewatered water, is pumped back to the seabed. (Nautilus Minerals 2017b)

The PSV is chartered to Nautilus by the yard who is building it, for a minimum period of five years, at a rate of approximately 200.000US$ per day. After the five year period, Nautilus has the option to buy the vessel or extend the charter period. (Nautilus Minerals 2017b)

Figure 6-6: Impression of Nautilus Minerals mining vessel. (Nautilus Minerals 2017a)

Figure 6-7: Nautilus Minerals seafloor production equipment. (Nautilus Minerals 2017a)

The environmental permit was already awarded in December 2009, followed by the mining permit in January 2011. The project is now scheduled to start testing in the first quarter of 2019. Although this already been pushed back many times, due to Nautilus' difficult financial situation. (Nautilus Minerals 2016) Recently however, the church of the PNG has spoken out firmly against deep sea mining. The impact of this position has to be seen, but it should be noted that approximately 95% of the population of the PNG is Christian. (The National 2017)

The commencement of mining for the Nautilus Solwara 1 project has been postponed from January 2012 to the first quarter of 2019. This has led the company into a very difficult financial position which had a large staff reduction as a result and the need for a monthly financing need of around US$ 2mm. (Nautilus Minerals 2017b) (Nautilus Minerals 2009)

7 Conclusions from part A

In general, it can be concluded that offshore mining still has a long way to go before it is standard practice. This holds specifically for deep-water projects, whereas the shallow water projects are in a slightly better position. Projects close to the coast have advantages over projects further away, including better legislation (i.e. they are in the EEZ of a nation) and less complex processing (i.e. it can be done on land).

Minerals

It is shown that [classified] are attractive in terms of all assessed criteria. [classified]and [classified] are promising as well. However, there is some price pressure in the [classified] market. [classified] is not seen as an attractive mineral on its own, but, when found in combination with other minerals, it can be a good addition to the project.

In general, it should be noted that offshore mining is mostly done with dredging vessels, which have large throughputs compared to conventional mining equipment. Therefore, the main minerals of interest are bulk minerals. Most minerals of interesting for shallow water offshore mining are found in placer deposits.

Processing

Designing a processing facility is a complex and opaque challenge. In most cases, a consultant is hired to design a pilot plant, in cooperation with equipment manufacturers. Each processing technique has his own basis of separation and each gangue has its own characteristics. It depends on the differences in characteristics between the mineral and the gangue which method is best. Therefore, the pilot plant is specifically designed for the location at hand: a change in gangue material changes the processing flow sheet drastically. Each processing technique has his own basis of separation and each gangue has its own characteristics. It depends on the differences in characteristics between the mineral and the gangue which method is best. The pilot plant is used to optimize all processes before building the actual processing plant.

Legislation and tax

Legislation is not present for large parts of the ocean. This is mainly due to the fact that the deep sea does not have any regulations regarding offshore mining in place, which is the responsibility of the ISA, according to the third UNCLOS. Locations for shallow water offshore mining mainly fall under national legislation and thus local laws, tax and royalty schemes apply. Most countries do not have specific offshore mining legislation, but instead, apply their terrestrial mining laws to the offshore environment. The lack of detail in these laws implies risk on the project as well as the environment. Due to lack of legislation, a large political risk is posed on prospected projects.

Environment

The main environmental impact associated with offshore mining are sediment plumes. These "dust clouds" in the sea can cover vast areas with a layer of sediment, closing them of from the outer world. Other environmental impacts include underwater noise, habitat intrusion, and risk of chemical spills. The magnitude of each effect is measured by assessing its nature, duration, size of the impacted area, and the potential for recovery.

As offshore mining projects are gaining traction, so does opposition from the public. Many projects are delayed due to extensive legal and permitting procedures originating from a lack of both legislation and precedent of well-functioning offshore mining projects. The consequences of offshore mining on the environment are not fully investigated, which gives rise to prudence with offshore mining.

Reference projects

First of all, it is clear that offshore mining is a relatively young market, as no real projects (except Pt Timah, inshore mining) have taken place. However, there is a lot of activity, especially when commodity prices are rising.

Furthermore, it should be noted that many companies currently involved in offshore mining have no background in mining, dredging or minerals all together, making them very inexperienced.

The reference projects also teach us that the lack of rules and regulations combined with the negative public opinion pose a significant threat to the viability of the project. However, a previous case study suggested a positive outcome for the viability of a phosphate project in Namibia.

Potential future research

- Filling gaps in plume forming and its implications on offshore mining (Ph.D. project of F. van Grunsven, TU Delft). As well as the development of practical tools to mitigate plume forming.
- A study into the long term effects of seabed intrusion and the potential for recovery of these areas.
- There is a task for the ISA to come up with guidelines for national legislations, for countries to follow. Furthermore, the ISA should set-up legislation for the high-seas.

From a Van Oord perspective, Classified

Part B How should the design of a shallow water offshore mining project be structured?

Introduction and reading guide

Part B will go into the design process of an offshore mining project and how this can be structured. It will also give an overview of the main design variables

The sub-questions which will be answered in part B are:

- Paragraph 8.1 – What steps should be taken to design a shallow water offshore mining project?
- Paragraph 8.2 – What are the main design variables?

8 Developing a framework for the design of a shallow water offshore mining project

As a shallow water offshore mining project will be a complex project, providing a framework is important. In this chapter, such a framework is presented for providing guidance during the design phase of a mining project. Furthermore, the key design parameters are discussed.

8.1. Issue tree framework

As stated above, a mining project is complex by nature. Therefore a method is presented to be able to grasp the complexity and provide guidance in the design process of a project. The framework which will be presented is adapted to offshore mining projects, shallow as well as deep-water. The method can, however, be used for any project.

To provide guidance to the offshore mining design process, an issue tree is constructed. An issue tree is a tree-like structure comprising all relevant aspects to answer the main question. The issue tree is constructed using the MECE principle. MECE stands for Mutually Exclusive, Collectively Exhaustive (Rasiel 1999). Mutually exclusive means that same level issues (questions) have no overlap. Collectively exhaustive means that together the same level issues provide an answer to the above lying issue. A schematic of an issue tree is shown in Figure 8-1.

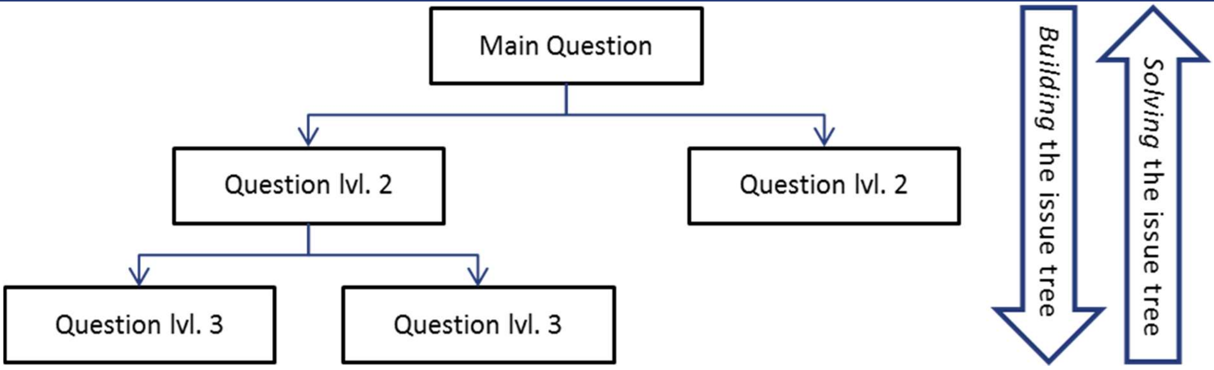


Figure 8-1: Schematic representation of an issue tree.

To illustrate the MECE principle described above, the questions at level three (lvl. 3) should have no overlap and together answer the connected question on level two (lvl. 2). An issue tree is constructed top down, increasing in detail. While solving an issue tree, in this case designing the mining process, is done bottom up, as is shown in Figure 8-1.

The issue tree constructed for offshore mining projects is not completely MECE as a result of the iterative characteristics of a design or engineering project. As can be seen from the curved arrow in Figure 6-1 there is some overlap between the mining and processing part of the issue tree. However, as much as possible, the issue tree should be worked from question 1 to 8.

The issue tree is constructed and verified in collaboration with experts from Van Oord's Engineering and Estimating department.

On the following pages, in Figure 8-2, Figure 8-3, and Figure 8-4, the constructed issue trees are shown.

It should be noted that for some projects certain steps can be obsolete.

Figure 8-2: Issue tree for an offshore mining project.

Figure 8-2, shows the issue tree as it can be used for designing an offshore mining project. The issue tree generally follows the value chain as presented in Figure 1-1. However it should be noted mining and processing are assessed in reversed order. This is done as generally, the project is undertaken to produce a *specific* amount of end product, dictated by the market. In order to determine the amount of material which should be mined, the general capabilities of the processing plant should be known.

When the productions of the mining vessel are known, the vessels efficiency can be optimized after which the maximum inputs to the processing plant are determined. Then the processing facility can be worked out in detail and optimized.

Figure 8-3: Issue tree for an offshore mining project - Processing part.

Classified

Figure 8-4: Issue tree for an offshore mining project - Mining part.

To keep track, and be able to easily reference certain locations in the issue trees, the issue tree presented in Figure 8-2 above will be simplified. The level two questions will be referred to as explained below:

Classified

8.2. Overview of main design influencing parameters

Besides providing guidance by means of issue trees, it is also important to have an overview of the projects most important design drivers. An overview of the relevant design drivers is given in the tables below. The presented variables below are applicable to any offshore mining operation, regardless of the depth.

Table 8-1: Overview of relevant design parameters for Minerals and soil, and Marketing.

Classified

Table 8-2: Overview of relevant design parameters for Market demands and Mineral processing.

Classified

Table 8-3: Overview of relevant design parameters for Mining method and Project Economics

Classified

It should be noted that in the mineral mining business the quantities are usually measured in ton or ton per hour, whereas in dredging cubic meter or cubic meter per hour is common. As quantities and throughputs play a large role in both areas of business, it is important to keep track of these units when the two share an interface. As is the case in offshore mining.

The main design variables of some processing methods are shown in Appendix C. The included processing methods are hydrocyclones, screens, and flotation.

8.3. Conclusion of part B

It can be concluded that offshore mining projects are complex by nature, due to their sheer size, a lot of design variables, and many interfaces between processes. Therefore it is advisable to set-up a framework like an issue tree. This framework offers guidance during an elaborate and complex design process.

Part C Is shallow water offshore mining a viable option, based on a case study?

Introduction and reading guide

In this part, the Classified shallow water offshore mining project is studied, based on the knowledge gained and presented in the previous two parts. The outcome of the case study will provide insight into the viability of an offshore mining project, which will answer sub question three.

The case study will be structured following the issue tree presented in Figure 8-2, Figure 8-3, and Figure 8-4. At the start of each section, the simplified issue tree shown below will show which part of the design process is evaluated.

Classified

9 Case study

Why perform a case study

The case study is executed with the purpose of gaining insights into the design and operational drivers of a shallow water offshore mining operation. These insights can be used for accessing new mining prospects.

In order to reach the goal as described above, the case study should be as realistic as possible. Therefore real deposits and locations will be chosen.

Unfortunately the case study is classified as per the request of Van Oord.

10 Discussion

This chapter will go into the applicability of this research. It will also assess the strengths, weaknesses, opportunities and threats of shallow water offshore mining in general.

Reading guide

- Paragraph 10.1 – Applicability of this research
- Paragraph 10.2 – Strengths, Weaknesses, Opportunities and Threats analysis (SWOT-Analysis)
- Paragraph 10.2 – Contributions to the offshore mining field

10.1. Applicability of this research

The applicability of this research is mainly determined by its scope, see paragraph 1.2. The conclusions, based on the case study, can't be extrapolated for any mineral or any location, without considering the issues mentioned below. The issue tree in Part B, however, can be used in any project, independent of the specific parameters.

Minerals

Part A included a description of several minerals, which could be of interest to offshore mining. The case study only assessed one: Classified. Based on the case study, it is now suggested that offshore mining is a viable business proposition. Would this be true if another mineral was mined?

This could be true. However, there are some points of attention when transferring results of the case study to other minerals:

- *Market dynamics of the mineral* – Classified
- *Size of the market* – Classified.
- *Specific processing needs* – Classified

Locations

The case study only focusses on one location. What would be the influence of a similar deposit at another location? The answer mainly relies mainly on the distance to shore, the distance to the market, the applicable legislation, and the mineral's grade.

- *Distance to shore* – If the distance to shore increases, the mining cycle will directly be affected. A larger distance could require (partial) offshore processing, which might not always be possible. Classified
- *Distance to market* – Most commodities are sold F.O.B. the location they are processed. This means the buyer is responsible for collecting, transporting and insuring the goods during transportation to another location. A location close to the location of potential buyers can lead to a competitive advantage, since the additional costs are lower. Classified
- *Applicable legislation* – Another location can also imply different legislation. This could mean different tax and royalty schemes, but also different rules with respect to environmental protection, local content requirements, and export allowances. Furthermore, it could imply a safety hazard when the project is situated in a conflict area. Classified
- *The grade of the mineral* – Due to the inherent remote (offshore) nature of the project, grades matter more when the processing plant is further away. Every cubic meter of mined material

must be transported to a processing facility. Therefore, costs could rise considerably if the grade of the mineral is too low. Transportation costs already play a considerable role in mining (onshore and offshore). They should be a point of attention when comparing locations, but could also be a point when comparing minerals.

10.2. Strengths, Weaknesses, Opportunities and Threats analysis (SWOT-Analysis)

A SWOT analysis is a structured way to evaluate a project, organization, model, etc., by means of assessing its internal and external helpful and harmful properties. The strengths and weaknesses are identified by looking at the project itself (i.e. internal). The opportunities and weaknesses are identified by assessing the project in its environment (i.e. external). The SWOT analysis is visualized as a matrix. In Figure 10-1 the SWOT matrix is shown.

Figure 10-1: Strengths, Weaknesses, Opportunities and Threats (SWOT) matrix. (Helms & Nixon 2010)

In this section, a SWOT analysis will be performed of shallow water offshore mining in general.

Strengths

- Due to the large throughputs of dredging equipment, offshore mining projects will have economies of scale with respect to conventional dry mining operations, leading to possibly lower production prices per ton.
- The footprint on land will be much less than with conventional open-pit mining.

Weaknesses

- Offshore mining using dredges does not seem to be attractive for non-bulk materials.
- Offshore mining is heavily influenced by bad weather, making the production less stable with respect to terrestrial mining
- A large initial investment is needed to start the offshore mining project. Besides a possible offshore processing plant, which would be more expensive than onshore, the mining vessel is more expensive than land based earth moving equipment, both in CAPEX as well as OPEX.

Opportunities

- A promising opportunity would be to find a method or methodology to transfer the complete processing plant offshore, while maintaining large production volumes.

Threats

- The global sentiment is against offshore mining. Legislation still needs to be drafted for most offshore locations. The sentiment could reduce the possibilities or ban offshore mining at all.
- Entering a new market as a large producer could disrupt the market and change its dynamics, lowering the selling price.
- There is not much known about the environmental effects offshore mining has.
- First-mover, no proven techniques or working methods are available. No previous projects raises questions with locals who don't want to be a Guinee pig.

10.3. Contributions to the offshore mining field

In the subsequent paragraphs, the research's most important contributions to the field of shallow water offshore mining are summarized.

In Chapter 2, 96 minerals that might be relevant for offshore mining are assessed (Appendix A). An overview of interesting minerals for shallow water offshore mining was not present in the current literature. Chapter 2 elaborates on this assessment and gives a summary of some the most important minerals. The accompanying Appendix B gives a in depth profile of some of the most promising minerals.

Chapter 6, gives an overview of the current state of marine mining projects around the world. The chapter also indicates which problems were encountered in these projects. Such an overview was not present in current literature.

In Chapter 8, a comprehensive framework to tackle complex offshore mining projects is proposed. Next to the framework, a list of key parameters to assess the viability of new project was compiled. In literature, no overview of parameters influencing the offshore mining design process was present, nor was there an overview or framework of the relevant design considerations.

The outcome of the case study was an integrated technical and financial model, which can be adjusted for future case studies. The technical model must be used in an iterative manner and shows the relations between key parameters. The financial model gives a good start to estimate the costs and benefits of a shallow water offshore mining project. The model can be used to assess future tenders, and it shows relations between the different relevant disciplines: mineral processing, dredging, finance and project management. The model and case study are described in Chapter 9.

11 Conclusion

As the scarcity of mineral deposits found on land increases and their grades decrease, many regard offshore mining as a promising alternative for fulfilling the world's need for minerals. Currently, no large-scale shallow water offshore mining projects have taken place. This research aims to provide insight into the viability and the design process of a shallow water offshore mining project. The main research question was:

Is shallow water offshore mining a viable business opportunity for Van Oord?

Based upon the provided overview of the market and industry, and the case study performed in this research, it can be concluded that shallow water offshore mining might be a viable business opportunity for Van Oord.

Sufficient interesting minerals are available in shallow water environments.
Chapter 2 shows that many interesting minerals can be found in the shallow sea. Special interest goes out to Classified. Offshore, these minerals are found in placer deposits, originating from ancient rivers. These deposits now mostly lie on the continental shelf in shallow water depths and contain large quantities and high grades of minerals due to natural separation.

These minerals become harder to extract onshore, while the demand continuously rises. Therefore, opportunities arise for new and unorthodox mining activities. Offshore mining could be a solution.

Processing is uncharted territory but can be outsourced.
Designing a processing facility depends on a vast variety of parameters and unknowns. This makes the design iterative by nature and complex to execute. The processing plant is the driving force behind the projects revenues, since it determines the quality and partially the quantity of the product

The main drivers within the design are the mined material characteristics. This set of parameters determines the basis of separation and is different for each mineral and every location on earth.

The market for processing equipment is consolidated: obtaining equipment or process specific information is therefore hard. In general, it is recommended to collaborate with a supplier or hire a dedicated consultant for engineering of the processing plant.

Legislation is virtually absent but has a major impact on the project.
Legislators can drastically impact the project. Many cases are known where legislation and the actions of legislators have led to serious delay of projects (see Chapter 6 about reference projects). This threat is worsened by the general absence of legislation with respect to offshore mining, imposing extra uncertainty on the projects.

Legislation also directly influences the projects viability through imposing tax and royalty schemes on a project. These added costs contribute significantly to the per ton costs of a project. This was seen in the case study as well as in the reference projects.

Poor public opinion and possible environmental impact form a threat.
Ambiguity in legislation and unclear environmental effects, lead to great resistance under the public regarding offshore mining. This results in delays for projects and pressure on politicians to take a stance against offshore mining.

Environmental effects are often unclear as there is relatively little knowledge of the seabed and its flora and fauna. Plume forming is a main concern because it covers vast areas of the sea with a layer of sediment. However, this is a common side effect of conventional dredging, in which Van Oord has major experience. Minimizing plume forming is in dredging a priority as well.

The issue tree functioned well for providing structure and overview.
In a complex design, project overview is of the essence. The issue tree constructed in Chapter 8 provided this overview, and was of great help in quickly clarifying specific project details to others.

Some parts of the tree might seem redundant. An example is the financing structure. However, this structure determines the WACC, which is important in evaluating the viability of the project. Especially for an offshore mining project which demands a high up-front investment and has cost and revenues streams for a long period. The case study has proven the added value of every aspect of the issue tree.

The case study resulted in a positive NPV: the shallow water-mining project did create value.
The case study showed a considerable value creation, in terms of a large positive net present value (NPV). However, it is hard to determine its bandwidth. The sensitivity of the WACC, the CAPEX, the OPEX, and the export price showed that there is considerable room for deterioration left. Therefore, it can be assumed the real project will create value as well.

Gathering reliable information to assess offshore mining is hard.
Offshore mining has (almost) never been done. Therefore, there is a lack of comparable projects, guidelines, and best practices. The research combines knowledge from two separate engineering disciplines: dredging and terrestrial mining, in order to estimate all processes for an offshore mining project.

Gathering information was further complicated by the low transparency of the processing equipment market. Equipment manufacturers keep their product information close.

Thus, the project and the case study model are built on a large variety of sources and assumptions.

Recommendations for improvements of the research

Evaluating this research, the largest gains can be obtained by improving the following issues:

- The financial model should address sensitivity studies. Aspects other than processing and mining could benefit from extra detailing.
- Equipment should be determined based on manufacturers' specifications. This could improve the details in the technical model and could verify some assumptions regarding the processing.
- Another case study would add to the variability of the results. This case study should be different on as many characteristics as possible (e.g. target mineral, location) to obtain a broader view of shallow water offshore mining.

Future research

Most of the threats originate from a lack of information about the environmental impact of offshore mining. This knowledge gap withholds legislators from drafting well-informed legislation and influences the public opinion. Specific topics that need further investigation are plume forming and the impact of dredging on the sea bed.

Furthermore, plume forming and its effects on the shallow water environment due to different mining techniques could be an interesting topic for further research. As stated in Paragraph 5.4, this is already partly being done by F. van Grunsven at the Tu Delft as a PhD study. However, research into applying the (theoretical) findings of van Grunsven to practical mitigating measures or equipment with respect to plume forming would be interesting.

Long term effects of seabed intrusions due to mining is a topic in which a lot of research is still needed to determine the long term "environmental costs" of an offshore mining operations. The research should focus not only on the deep sea, but also on the shallower waters.

There is a task for the ISA to come up with guidelines for national legislations, for countries to follow. Furthermore, the ISA should set-up legislation for the high-seas.

Finally, the other minerals which were identified as potentially interesting for offshore mining should be looked into further. These were cassiterite (tin), and hematite and magnetite (iron).

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Appendix A: Complete list of reviewed minerals

Classified

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