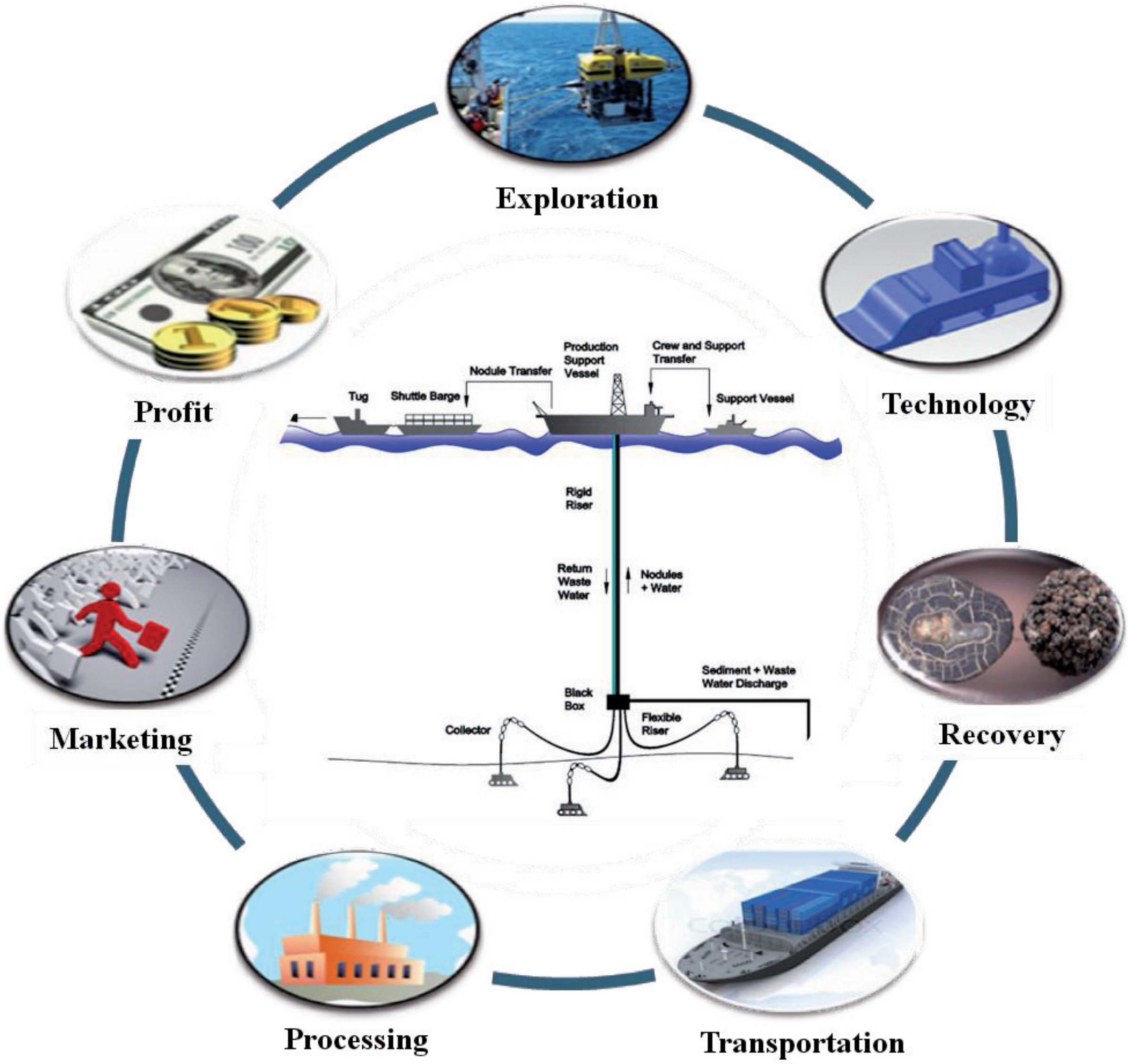
Feasibility Study on Manganese Nodules Recovery in the Clarion-Clipperton Zone



Authors: **B Agarwal, P Hu, M Placidi, H Santo, J J Zhou**

Series Editors: **R A Shenoi, P A Wilson, S S Bennett**

Lloyd's Register Educational Trust

UNIVERSITY OF Southampton

“The Lloyd’s Register Educational Trust (The LRET) funds education, training and research programmes in transportation, science, engineering, technology and the safety of life, worldwide for the benefit of all. Funding is split between four categories to provide a continuum of support. We do not fund individuals direct, in any category.

- Pre-university education – promoting careers in science, engineering and technology to young people, their parents and teachers;

- University education – supporting exceptional students at undergraduate and masters level through scholarship programmes at selected universities;

- Vocational training and professional development – funding organisations that provide training, knowledge sharing and skills development opportunities for people in work;

- Research – adding value to society by funding research programmes which address fundamental challenges that affect us all.”

Feasibility Study on Manganese Nodules Recovery in the Clarion-Clipperton Zone

Baivau Agarwal · Pan Hu · Marco Placidi · Harrif Santo · Jenny Jin Zhou

Titles in the LRET Collegium 2012 Series:

Volume 1: **A Concept for Seabed Rare Earth Mining in the Eastern South Pacific**

M B Bashir, S H Kim, E Kiosidou, H Wolgamott, W Zhang

ISBN 978-0-854-32949-6

Volume 2: **Feasibility Study on Manganese Nodules Recovery in the Clarion-Clipperton Zone**

B Agarwal, P Hu, M Placidi, H Santo, J J Zhou

ISBN 978-0-854-32950-2

Volume 3: **The deep sea energy park: Harvesting hydrothermal energy for seabed exploration**

J Parada, X Feng, E Hauerhof, R Suzuki, U Abubakar

ISBN 978-0-854-32951-9

Volume 4: **Sustainable Seabed Mining: Guidelines and a new concept for Atlantis II Deep**

L Egorov, H Elosta, N L Kudla, S Shan, K K Yang

ISBN 978-0-854-32952-6

Volume 5: **Polymetallic nodule mining: Innovative concepts for commercialisation**

W Flentje, S E Lee, A Virnovskaia, S Wang, S Zabeen

ISBN 978-0-854-32953-3

University of Southampton
Highfield, Southampton
SO17 1BJ, England

First published 2012

British Library Cataloguing in Publication Data
A catalogue entry for this title is available from the British Library

ISBN 978-0-854-32950-2

Printed in Great Britain by The Print Centre, University of Southampton

Foreword

The Lloyd's Register Educational Trust (The LRET) in collaboration with the University of Southampton instituted a research collegium in Advanced Ship and Maritime Systems Design in Southampton between 16 July and 7 September 2012.

This year's collegium has focused on The LRET's research-led education agenda. Successful ship and maritime systems design depends on the collaborative application of a broad range of engineering competences as the drive for improved efficiency and environmental performance places greater demand on the design community. This aspect needs to be reflected in the education of naval architects, marine engineers and others who are the active contributors to the ship design processes.

The aim of the research collegium has been to provide an environment where young people in their formative post-graduate years can learn and work in a small, mixed discipline group drawn from the maritime community to develop their skills whilst completing a project in advanced maritime systems design. The project brief that initiates each project set challenging user requirements to encourage each team to develop an imaginative solution, using individual knowledge and experience, together with learning derived from teaching to form a common element of the early part of the programme.

The collegium format provided adequate time for the participants to enhance their knowledge through a structured programme of taught modules which focussed on the design process, advanced technologies, emerging technologies and novel marine solutions, regulatory and commercial issues, design challenges (such as environmental performance and climate change mitigation and adaptation) and engineering systems integration. Lecturers were drawn from academic research and industry communities to provide a mind-broadening opportunity for participants, whatever their original specialisation.

The subject of the 2012 collegium has been systems underpinning seabed exploitation. The 25 scholars attending the 2012 collegium were teamed into five groups. The project brief included: (a) quantification of the environmental challenge; (b) understanding of the geo-political legal-social context; (c) possible techniques for harvesting or recovering resources from the seabed; (d) one engineering system to achieve seabed exploitation; (e) economics and logistics challenges. While all the groups addressed the items (a) to (c), each team focused on just one engineering system in dealing with items (d) and (e). This volume presents the findings of one of the five groups.

R A Shenoi, P A Wilson, S S Bennett
Southampton
2 September 2012

Preface

This book is the outcome of six weeks work carried out by a group of five individuals with widely varying backgrounds, as part of the Lloyd's Register Educational Trust (LRET) Collegium 2012. The work was conducted in association with the Fluid Structure Interactions Research Group at the University of Southampton.

Through an extensive literature review, the book looks forward to address the largest concern with respect to Seabed Exploitation: *The Environmental Concerns*. The engineering solution presented is thus based on numerous environmental considerations, apart from being technologically novel. This book is intended to develop an overall idea on the topic of *Manganese Nodule Recovery* and aims to target an outreach to the general public in terms of awareness on the potential of *Seabed Exploitation*.

This book has been very instrumental in developing a thought process towards the risks associated with the nodule recovery process. These topics have thus suitably been addressed. The investigation on past and present market trends gives a good outlook regarding the feasibility of the project and its acceptance in the industry. These analyses have encouraged the authors to bring out concepts such as *Small Modularised Design* and *Base Price*. The different background of the authors and other participants in the collegium has produced various innovative ideas.

Lastly, the authors acknowledge the fact that, with a limited timeframe available to work on such a vast topic, some gaps may exist. Constant development and future editions of this volume will be aimed at keeping readers updated on current technologies and future trends. For topics such as processing and transportation, proven facilities already exist and hence these have not been treated exhaustively. Attention has rather been directed to those topics which lead to open discussion: *Environmental Concerns*, *Technological Considerations* and *Market Analysis*.

Acknowledgement

Apart from the authors' efforts, the success of this project depended largely on the encouragement and guidelines from many others. The authors would like to take this opportunity to express their gratitude to the people who have been influential in the successful completion of this study.

The authors express sincere gratitude to the Lloyd's Register Educational Trust and especially to Mr. Michael Franklin, for such an innovative concept in the form of this collegium. The authors also thank Professor Ajit Shenoi, Professor Philip Wilson and Professor Vaughan Pomeroy for constant encouragement, invaluable guidance, excellent supervision and keen interest. The technical inputs obtained from them during the course of work have been most valuable in developing a profound interest in this field.

The authors express their deep gratitude to all the members of the Fluid Structure Interactions Research Group at the University of Southampton for their support in the form of facilities, technical inputs and feedback. Their technical suggestions and friendly interactions, together with Dr. Sally Bennett's support as group mentor, have initiated an enjoyable working environment in the group.

Gratitude must especially be extended to Ms. Mirjam Fürth and Mr. Mahesa Bhawanin, for making our stay pleasant during our tenure in this esteemed institution. The authors are also indebted to all the guest lecturers for their valuable time and painstaking efforts to convey their message to the multidisciplinary LRET-2012 scholars.

The authors would also like to thank the principal coordinator for the Collegium, Ms. Aparna Subaiah-Varma, for the tremendous perfection in making all the arrangements. Moreover, the authors would like to thank the entire LRET-2012 Scholars Group, each of whose tremendous quests for knowledge and dedication towards the work has been extremely motivating. The experience would have been quite dull had it not been for them.

Baivau Agarwal, Pan Hu, Marco Placidi, Harrif Santo, Jin Jenny Zhou

August 2012

Executive Summary

The sea occupies three quarters of the area on the earth and provides various kinds of resources to mankind in the form of minerals, food, medicines and even energy. “Seabed exploitation” specifically deals with recovery of the resources that are found on the seabed, in the form of solids, liquids and gasses (methane hydrates, oil and natural gas). The resources are abundant; nevertheless the recovery process from the seabed, poses various challenges to mankind.

This study starts with a review on three types of resources: polymetallic manganese nodules, polymetallic manganese crusts and massive sulphides deposits. Each of them are rich in minerals, such as manganese, cobalt, nickel, copper and some rare earth elements. They are found at many locations in the deep seas and are potentially a big source of minerals. No commercial seabed mining activity has been accomplished to date due to the great complexities in recovery. This book describes the various challenges associated with a potential underwater mineral recovery operation, reviews and analyses the existing recovery techniques, and provides an innovative engineering system. It further identifies the associated risks and a suitable business model.

Chapter 1 presents a brief background about the past and present industrial trends of seabed mining. A description of the sea, seabed and the three types of seabed mineral resources are also included. A section on motivations for deep sea mining follows which also compares the latter with terrestrial mining.

Chapter 2 deals with the decision making process, including a market analysis, for selecting manganese nodules as the resource of interest. This is followed by a case study specific to the location of interest: West COMRA in the Clarion-Clipperton Zone. Specific site location is determined in order to estimate commercial risk, environmental impact assessment and logistic challenge.

Chapter 3 lists the existing techniques for nodule recovery operation. The study identifies the main components of a nodules recovery system, and organizes them into: collector, propulsion and vertical transport systems.

Chapter 4 discusses various challenges posed by manganese nodules recovery, in terms of the engineering and environment. The geo-political and legal-social issues have also been considered. This chapter plays an important role in defining the proposed engineering system, as addressing the identified challenges will better shape the proposed solution.

Chapter 5 proposes an engineering system, by considering the key components in greater details. An innovative component, the black box is introduced, which is intended to be an

environmental friendly solution for manganese nodules recovery. Other auxiliary components, such as the mother ship and metallurgical processing, are briefly included. A brief power supply analysis is also provided.

Chapter 6 assesses the associated risks, which are divided into sections namely commercial viability, logistic challenges, environmental impact assessment and safety assessment. The feasibility of the proposed solution is also dealt with.

Chapter 7 provides a business model for the proposed engineering system. Potential customers are identified, value proposition is determined, costumer relation is also suggested. Public awareness is then discussed and finally a SWOT analysis is presented. This business model serves as an important bridge to reach both industry and research institutes.

Finally, Chapter 8 provides some conclusions and recommendation for future work.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ATESEPP	Impact of Technical Interventions into the Deep Sea of the Southeast Pacific Ocean
BRIC	Brazil, Russia, India and China
CCZ	Clarion-Clipperton Zone
CLB	Continuous Line Bucket
COMRA	China Ocean Mineral Resource and Development Association
DISCOL	Disturbance and Recolonization Experiment in a Manganese Nodule Area of the Deep South Pacific Ocean
DOMES	Deep Ocean Mining Environmental Study
DP	Dynamic Positioning
DWT	Dead Weight Tonnage
ECS	Extended Continental Shelf
EEZ	Economic Exclusive Zone
FPSO	Floating Production Storage and Offloading
GDP	Gross Domestic Product
HMS	Her Majesty's Ship or Her Majesty's Submarine
IKS	Institut für Konstruktion Siegen
IMCOA	Industrial Minerals Company of Australia Pty Ltd
IMO	International Maritime Organization
INDEX	Indian Deep Ocean Enrichment Experiment
IOM-BIE	Benthic Impact Experiment Conducted by the Interoceanmetal Joint Organization
IRR	Internal Rate of Return
ISA	International Seabed Authority
JET	Japan's Deep-Sea Impact Experiment
KORDI	Korea Ocean Research and Development Institute
MARPOL	International Convention for the Prevention of Pollution from Ships
MARR	Minimum Acceptable Rate of Return

METI	Ministry of Economy, Trade and Industry
NM	Nautical Miles
NOAA-BIE	Benthic Impact Experiment by the National Oceanography and Atmospheric Administration
NPV	Net Present Value
PNG	Papua New Guinea
OSP	Owner Self Perform
PSV	Production Support Vessel
REEs	Rare Earth Elements
ROV	Remotely Operated Vehicle
SMS	Seafloor Massive Sulphides
SOLAS	International Convention for the Safety of Life at Sea
SWOT	Strengths-Weaknesses-Opportunities-Threats
TML	Transportable Moisture Limit
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
UNCTAD	United Nations Conference on Trade and Development
UNESCO	United Nations Education, Scientific and Cultural Organization
USGS	United States Geological Surveys

1 Introduction

1.1 Background

Oceans are abundant in natural resources. They are home to all manner of fish, sea mammals, and other oceanic flora and fauna, and have for centuries been a major source of food for mankind. On the seabed lie abundant reserves of minerals that are arguably even richer than those present on land. These resources, if suitably extracted, can be made available for the production of tools and new technologies.

Seas cover almost three times the area of land mass and yet deep-sea mining is a relatively new mineral retrieval process. Marine resources on and below the seabed include a variety of fuels and metallic and non-metallic minerals. To date, the best-known and exploited marine minerals are fossil fuels. The seabed is also rich in various non-fuel minerals of both metallic and non-metallic types. From beach to shallow water, to deep-water and deep seabed, abundant marine minerals are deposited at various depths (Erry et al. 2002). Non-fuel mineral deposits, which are the subject of interest for the mineral market, include cobalt-rich manganese crusts, polymetallic manganese nodules, and polymetallic massive sulphides (or Seafloor Massive Sulphides, also called SMS). All three deposits are generally found at varying water depths. This report reviews past research directions and presents some feasible designs for recovery of manganese nodules.

Polymetallic manganese nodules were first discovered during the British HMS Challenger expedition in 1873. However, it was only following Mero (1965) publication *Mineral Resources of Sea* that the worldwide interest in seabed exploitation or deep-sea mining began. There have since been extensive developments in deep-sea exploration and research, with polymetallic manganese nodules being regarded as a potential candidate for the first full-scale commercial seabed exploitation. Various market forecasts were conducted to predict global land mineral shortage with increase in their demand. They further affirmed the possibility of deep-sea mineral exploitation. Unfortunately, the initial attempts failed due to the collapse of metal prices, overoptimistic assumptions on the feasibility of nodule mining technologies and controversial provisions within the United Nations Convention on the Law of the Sea III (UNCLOS III) (Glasby 2002).

Worldwide interest then turned to the other two types of minerals: manganese crusts and subsequently, polymetallic massive sulphides. After several decades, it was in 1997 that the Papua New Guinea (PNG) government granted an exploration license to a Canadian mining company, Nautilus Minerals Corporation, to explore deposits of massive sulphides off the coast of PNG (Glasby 2002). Provided that the exploration is successful, Nautilus is expected to conduct the world’s first full-scale commercial seabed exploitation in 2013. The plan was delayed by many years due to several issues, particularly persistent public protests on the environmental impacts to the local marine ecosystems and coastal communities. The latest progress update (as of June 2012) indicates further delays or cancellation of the project due to disputes with the PNG government (Jamasmie 2012). This case study illustrates how challenging and problematic it is to achieve full-scale commercial seabed exploitation.

1.2 Aims and Objectives

The vast amount of resources lying on the seabed has always been of economic interest to the world. The factors preventing their exploitation are: 1) the inability to quantify and mitigate environmental damages; 2) insufficient technological advancements; 3) sufficient land reserves, which keep the mineral prices low. These are the primary reasons why all the plans and proposals for deep seabed exploitation have died in their incubation period and now are just filling up the shelves of the libraries.

Fortunately, several promising developments and metal market trends recently have rekindled interest on this topic. The current market conditions may allow deep sea mining ventures to occur in course of few years. Favourable world economics have spurred researchers and industries to re-solve existing issues which are mainly on environmental impacts and exploitation technology. The present study reviews the issues and addresses them suitably to achieve a common goal, which is to promote for full-scale seabed exploitation by providing environmental friendly engineering system. This study has also been undertaken with an idea that deep sea mining cannot replace land based mining in the near future in terms of scale and output, but can complement it in parallel to increase its longevity.

1.3 Sea and Seabed Definition

Scientists have divided the ocean into five main layers also known as *zones*, as shown in Figure 1. The zones extend from the ocean surface to the extreme depths, where light can no longer penetrate.

The ***epipelagic zone*** is the first layer of the ocean, which covers the area from the ocean surface to around 200 m. Since most of the visible light can penetrate here, it is also known as the *sunlight zone*. The ***mesopelagic zone***, which is referred to as the *twilight zone* or the *mid-water zone*, lies below the epipelagic zone from 200 m to around 1,000 m. Only some faint lights can penetrate and a great diversity of uncommon fish inhabit here. The next layer is the ***bathypelagic zone***, or *midnight zone* or the *dark zone*. It extends from 1,000 m down to 4,000 m and the creatures themselves produce the only light in this layer. Life here is not as prominent as the zones above but it still has its traces. Creatures like sperm whales also dive down to this layer searching for food. The next layer is called the ***abyssopelagic zone***, known as the *abyssal zone,* and three-quarters of the ocean floor lies within it. It extends from 4,000 m to 6,000 m and there is no light at all. At this depth only a few creatures such as tiny squids and basket stars, can be found. This is the zone where almost all of the manganese nodules lie. The ***hadalpelagic zone*** lies beyond the abyssopelagic zone. It extends from 6,000 m to the bottom of the ocean and is mostly found in deep water trenches and canyons. However, life such as tubeworms and starfish can still be found in this layer despite the high pressure due to deep water (www.seasky.org).

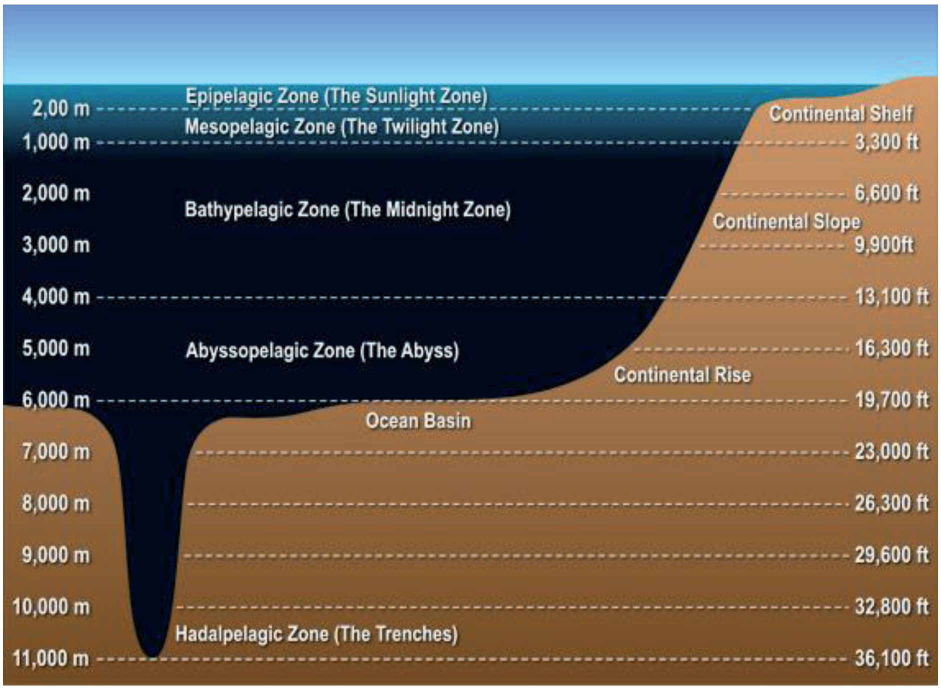


Figure 1: Diagram of the five ocean layers (source: www.seasky.org)

Having described the different layers forming the ocean from the physical and biological point of view, the next section introduces the legal characterisation of the sea.

The concept of maritime zones describes the sovereign rights a coastal state has over the offshore environment. These zones have been established in accordance with the UNCLOS 1982. Under the UNCLOS, there are four principal maritime zones: territorial sea, contiguous zone, exclusive economic zone and high sea (Figure 2). The extent of each of these zones is measured from the territorial sea baseline. The normal baseline is the low water line and the ***territorial sea*** extends to a maximum of 12 nautical miles (nm) from the baseline. The ***contiguous zone*** extends to a maximum of 24 nm from the baseline and the ***exclusive economic zone*** extends to a maximum of 200 nm. The ***high sea*** extends beyond 200 nm, and it is commonly known as ***international water***.

In terms of seabed, on the other hand, two principle zones have been defined: ***continental shelf*** and ***area*** (deep seabed). The ***continental shelf*** is a geological description and comprises the seabed and subsoil of the areas that can be shown to be the submerged prolongation of the land territory of the coastal state. It extends beyond the territorial sea and in some cases beyond the outer limit of the exclusive economic zone. The ***area (deep seabed)*** includes seabed and subsoil that extends beyond the continental shelf and beyond the limits of national jurisdiction. Manganese nodules are found scattered on deep seabed in international water.

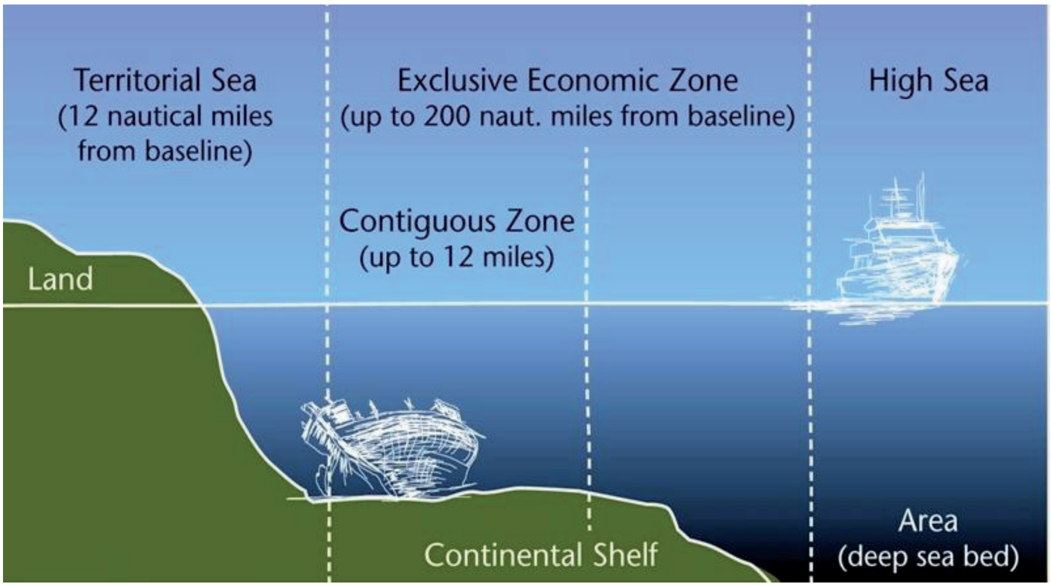


Figure 2: Maritime zones (source: www.unesco.org)

1.4 Type of Seabed Resources

The main types of mineral resources that the seabed is rich in, are:

- Cobalt-rich manganese crusts,
- Polymetallic manganese nodules,
- Polymetallic massive sulphides (SMS deposits)

The ***cobalt-rich manganese crusts*** are found at water depths of 500 – 2,000 m and occur as sheets varying in thickness from millimetres to about 25 centimetres. Cobalt-rich crusts mainly contain copper, manganese and nickel, which are deposited on rock fragments, bedrock, pebbles, blank unconsolidated sediments and sand grains. They generally have a layered cross section and characteristic regional similarities. They are widely distributed on the summits and slopes of islands and seamounts in the northwest Atlantic, Equatorial Pacific and the Blake Plateau. However, as they occur on a wide range of substrate rocks, it is difficult to distinguish them from substrate and consequently to locate. Currently, there are few studies concentrating on the impacts of mining these crusts on the biological communities, but there is indication that the collection of these crusts would destroy the local communities.

Polymetallic massive sulphides are deposited at seafloor hydrothermal vents (i.e., black smokers and hot springs) on volcanic mountains at water depths of 2,000 – 4,000 m. They are highly localised at specific sites where conditions are appropriate for their occurrence (Rona 2000). They are usually present in the form of lenticular stratiform ore bodies with more than 60% sulphide minerals. The ore bodies mainly contain sphalerite, chalcopyrite and pyrite, and different percentages of magnetite, galena, and pyrrhotite. The polymetallic massive sulphides are associated with the habitat of heat-tolerant bacteria, which form the base of a food chain. These bacteria and the species of animals feeding on them are very specific to the vent environment. Studies are being carried out to predict whether migration of these species when mining starts and relocation when mining ends, will be possible or not.

Polymetallic manganese nodules have diameters ranging from millimetres to tens of centimetres and have a characteristic potato shape. They lie on the top layer of the sediment on the seabed and are found at depths between 4,000 – 6,000 m. The exploitation of polymetallic nodules has comparatively less impact on the benthic environment as studies show that life is pretty much static at these depths.

1.5 Motivations for Deep Sea Mining

Forecasting the market for demand and supply of minerals and metals is a complex task. History has shown us the failure of the overly optimistic market forecast in the late 1970s in terms of consumption levels and prices, which effectively delayed full-scale commercial deep-sea mining for more than 30 years (Antrim 2005).

Fortunately, there have been many developments over the past two decades, which the authors strongly believe may rekindle the idea of deep-sea mining. These include improvements in political and legal issues related to international waters, the growing economies of BRIC (Brazil, Russia, India and China) and other developing nations, a growing interest in renewable energies and green technologies which triggers more demand in certain types of minerals, and rapid progress in oil and gas technologies for deep water.

These factors combined with issues such as rising demand and consequently rising prices of minerals and commodities worldwide, and uncertainty of land-based mineral supplies, contribute to our motivations for this study on deep-sea mineral recovery. Throughout this project, deep-sea mining has also been compared to the land equivalent. This has not been with the intention of justifying the environmental footprints. The goal is to highlight that for any activity to be feasible there should be a trade-off between environmental impacts and economic interests and also the environmental impacts should be within manageable limits.

The ISA Workshop in 2008 attributes the rebound in metal prices (2002 – 2003) to the modernisation of China and the rising demands created by its growing economy. It is expected that due to its economic development, the Chinese demand alone will keep on influencing and driving the global minerals market. The effect of the demand boom can be observed from the fact that the Chinese demand for copper had tripled since 1998. Today, China is the biggest consumer of copper and nickel in the world (www.isa.org.jm). Brazil, Russia, India and other developing countries are expected to follow the same behaviour as a result of their flourishing economic conditions.

The rising demand in minerals has driven metal prices up. The market trends of copper, cobalt, nickel and manganese have risen dramatically over the last 10 years. The price of copper for example, has tripled while those of cobalt, nickel and manganese have doubled since 2002 (ISA 2008a). Each of the four minerals experienced a steep rise in price before 2007 followed by a steady decline during the 2008 economic crisis. Nevertheless, as the global market is recovering, so are the metal prices. This trend of increasing metal prices makes the mineral markets an attractive investment for both private and government enterprises.

Uncertainty of land based mineral supplies is usually affected by the political and economic conditions of the mineral producing countries, for instance Democratic Republic of Congo and Russia. Here nickel-rich Russia has been taken as an example. Back in the early 1990s, the world market was flooded by a huge surplus of nickel supplied by Russia and other former Soviet nations, after the fall of Soviet Union. Those nickel-producing countries, particularly Russia, had to export nickel excessively to Western countries to cope with the decline in their domestic demand of nickel and to repair their weakened economies. As a result of high nickel availability due to increase in world supply and reduction in domestic demand, the nickel price dropped. However, with the Russian economy recovering over the last couple of years, their domestic demand in nickel is also increasing. This leads to uncertainty in terms of nickel supply to the world market, and this factor has to be considered in terms of long-term evaluation of a supply-demand balance in the nickel world market (Antrim 2005).

Renewable energies and green technologies have been developed progressively to reduce the amount of pollution. Both sectors will inevitably trigger huge additional demands in certain type of minerals once their applications are firmly commercialised. One example is the transition to hybrid (petro-electric) automobiles of green technologies. This whole design uses the concept of an on-board battery to power the propulsion. The current raw mineral for battery is nickel, and the alternative is cobalt. Either one of these two types of battery would significantly increase demand of nickel and/or cobalt (Antrim 2005).

Another interest in deep sea mining is motivated from the oil and gas sector. Rising demand and prices of hydrocarbon and shortage of shallow water reservoirs push offshore exploration and drilling to deeper water, which nowadays easily ranges from 1,000 m to over 3,000 m. Technologies in offshore engineering have been developed for deep water. One of the applications suitable for deep-sea mining is the technology of riser, a pipe system connecting a drilling platform to a reservoir well. The same technology can be applied to deep-sea mining to transport the extracted minerals vertically from the seabed to the surface for further processing.

1.6 Comparison between Land-based Mining and Deep Sea Mining

Comparing land with deep-sea mining, it is obvious that to conceptualise and execute, the latter will be more costly. There are also further challenges for deep-sea mining in terms of environmental, geo-political and legal-social issues, which will be discussed subsequently. However, there are several advantages to deep-sea over land mining, which are briefly summarised as follows:

- Smaller footprint due to less overburden

Open excavation in the case of land mining means that each operation normally leaves considerable footprints during and after the mining process. This is mainly because of the need to remove a large amount of overburden, under which the resources are locked. The footprint in the case of deep-sea mining would be smaller as most of the resources are either lying on the seafloor or buried by only several centimetres of sediments or clay.

- Less permanent infrastructure

Each land mine requires permanent infrastructure such as roads and towers. This is not the case for deep-sea mining as everything is controlled from the surface via movable floating ships or barges. Thus, there will be less permanent infrastructure needed. Once a plot of seabed has been fully mined, all the facilities can be easily moved and deployed to another area. In terms of long-term capital cost, deep-sea mining may be compatible with or cheaper than land mining.

- Less populated ecosystem to be affected

It is generally accepted that the open mining approach on land, which includes activities such as deforestation, disturbs the local ecosystem of the exploited area. Birds and other species have to find new habitats, and it is unlikely that they will be able to re-occupy the mined area due to the substantial footprint left behind after the operation. Deep-sea mining, on the other hand, will impact upon a smaller populated ecosystem near the seafloor, where the absence of light prevents photosynthesis. There will however be some effects on the ecosystems of local species, such as benthos, which manage to survive without sunlight. Nevertheless, the overall impact is significantly less in comparison to land mining; the smaller footprints left by deep sea mining could allow the ecosystem to re-occupy the habitat.

- Rich in mineral diversity

Land mining is usually conducted for one single mineral, for example coal, gold, nickel, etc. A particular type of mineral is more uniform in a certain area, such as nickel in Russia and cobalt in Congo. On the other hand, there are diverse elements in each deposit from the deep sea. Hence, multiple minerals can be obtained from a single mining operation. Manganese nodule is a clear example. Nodules are multi-mineral ores containing manganese, iron, nickel, cobalt, copper and some rare earth elements (REEs).

2 Case Study

By comparing the relative advantages and disadvantages of the exploitation methods of the three different types of mineral resources, attention has been focused on the recovery of manganese nodules. The recovery requires less digging and consequently would have less direct and indirect impacts on the bottom dwelling communities. The abyssal plains where manganese nodules occur look like vast deserts of the deep sea. The abundance of life at the abyssal seafloor is relatively low (ISA 2001). Therefore, this study will focus solely on the manganese nodules due to the environmental considerations and the concerns regarding the engineering techniques.

2.1 Manganese Nodules

Manganese nodules (Figure 3), also known as polymetallic nodules, were discovered at the end of the 19th century in the Kara Sea, in the Arctic Ocean off Siberia (1868). During H.M.S. Challenger's (1872–76) scientific expeditions, they were found to occur in most oceans of the world. According to the ISA description (ISA 2008a), "*polymetallic nodules are rock concretions formed of concentric layers of iron and manganese hydroxides around a core. The core may be microscopically small and is sometimes completely transformed into manganese minerals by crystallization. When visible to the naked eye, it can be a small test (shell) of microfossil (radiolarian or foraminifer), a phosphatized tooth of shark, basalt debris or even fragments of earlier nodules. The thickness and regularity of the concentric layers are determined by the successive stages of growth. On some nodules they are discontinuous, with noticeable differences between the two sides. Nodules vary in size from tiny particles visible only under a microscope to large pellets more than 20 centimetres across. However, most nodules are between 5 and 10 cm in diameter, about the size of potatoes. Their surface is generally smooth, sometimes rough, mammilated (knobby) or otherwise irregular. The bottom, buried in sediment, is generally rougher than the top*".

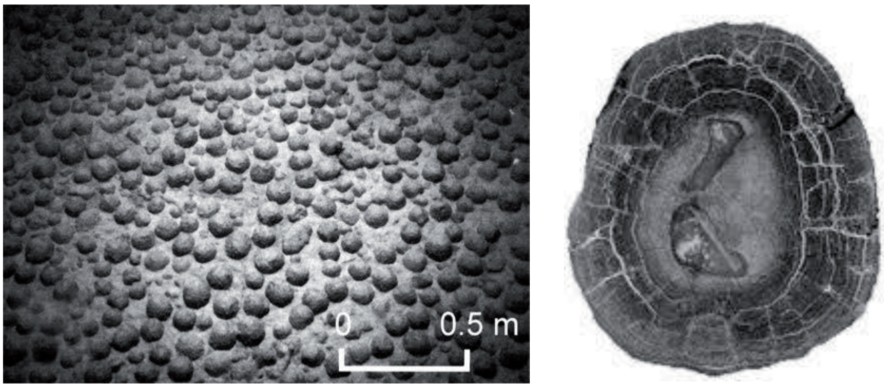


Figure 3: Manganese nodules

2.1.1 Chemical Composition

The chemical composition of these nodules varies according to the location, size and characteristics of the core. The general composition is provided in Table 1.

Table 1: The chemical composition of manganese nodules (ISA 2008a)

The constituents of nodules	Composition
Manganese	~29.0%
Iron	~6.0%
Silicon	~5.0%
Aluminium	3.0%
Nickel*	1.4%
Copper*	1.3%
Cobalt*	0.3%
Oxygen	1.5%
Hydrogen	1.5%
Sodium	1.5%
Calcium	1.5%
Magnesium	0.5%
Potassium	0.5%
Titanium	0.2%
Barium	0.2%
*nickel, copper, and cobalt are the most valuable	

2.1.2 Formation Mechanism

Several mechanisms have been proposed to explain the formation of nodules, including the hydrogenous, diagenetic, hydrothermal, halmyrolitic, and biogenic processes (ISA 2008a). Although the scientific community has not uniformly agreed, the following two theories are the most accepted:

- **Hydrogenous Process**, which involves concretions that are formed by slow precipitation of the metallic components from seawater. This is thought to produce nodules with similar iron and manganese content and a relatively high grade of nickel, copper and cobalt.
- **Diagenetic Process**, where the manganese is remobilised in the sediment column and precipitated at the sediment and water interface. Such nodules are rich in manganese but poor in iron and in nickel, copper and cobalt.

2.1.3 Geological Distribution

Nodules have been discovered in all the deep oceans and even in lakes. However, the concentration of nodules of economic interest is instead more localised. Three areas have been selected by industrial explorers: the Clarion-Clipperton Zone (CCZ) in the north central Pacific Ocean, the Peru Basin in the south-east Pacific Ocean and the north Indian Ocean. In these areas, the depth of the seabed averages between 4,000 to 5,000 metres. The bottom topography is formed of abyssal hills, elongated north to south in conformity with the scars of the ocean crust (ISA 2008a).

2.2 Target the Recovery Site: the Clarion-Clipperton Zone

Due to years of exploration and research, there is a sufficiently comprehensive database on the CCZ. Due to its well-known topography and well-documented nodule deposits of high concentration, the CCZ has been selected for the study. This area is located in the eastern central Pacific, to the south and south-east of the Hawaiian Islands. This region is considered to be the best in terms of commercial interest for manganese nodule recovery. It lies in international waters, and stretches approximately from 0°N – 23°30′N, and from 115°W – 160°W, an area of approximately 4.5×10^6 km^2 (Figure 4). The zone is bounded to the north and south by the ENE-WNW trending CCZ (ISA 2011). Presently, nine contractors have exploration contracts in the CCZ through the International Seabed Authority (ISA). The list of contractors includes China, Japan, Government of Korea, France, Interoceanmetal Joint Organization, Russian Federation, Germany, Tonga Offshore

Mining, and Nauru Ocean Resources. The physical, chemical, and biological properties of CCZ are summarised in Table 2.

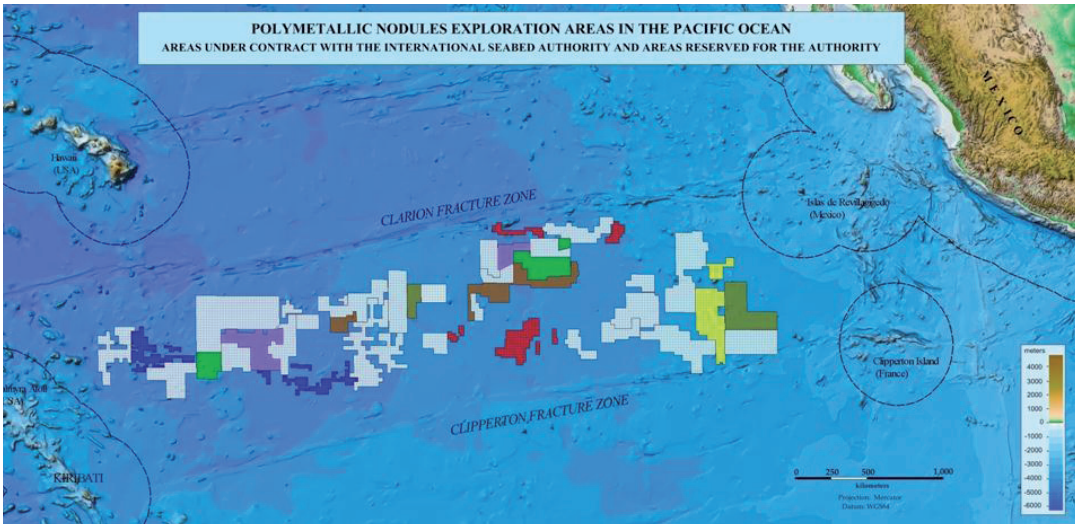


Figure 4: Clarion-Clipperton Zone management area (ISA 2011)

While the proposed engineering system (see Chapter 5) is generally applicable to the entire CCZ location, a specific location in CCZ has been chosen as a case study to provide detailed analysis. This aids selection of some location specific parameters when dealing with commercial viability, logistics and environmental impact assessment.

Several screening criteria are imposed to decide on a specific site in the CCZ. Although the detailed analysis will not be presented with this report, it covers: the metal market demand and price trends of contractors in the CCZ, data of nodule resources and finally some geological and logistical considerations.

China Ocean Mineral Resource Research and Development Association (COMRA) has been chosen as a result of this analysis. The COMRA is one of the eight original pioneer investors. In 1991, China was allocated an area for exploration located in the western part of the CCZ. China has increasingly high demand in refined metals (refer to Section 2.3) owing to its flourishing economic condition (ISA 2008a). China consumes nearly one fourth of the world's major metal production and became the largest consumer of total main metals in 2003 (Li 2007).

Table 2: The physical, chemical, and biological properties of CCZ (Amos and Roels 1977, ISA 2010)

Indicators	Descriptions
Physical properties	
Seafloor topography	Mostly between 4,000 and 6,000 m water depth; a large number of flat-floored valleys, separated by irregular, often discontinuous ridges.
Ocean circulation	Dominated by the North Equatorial Current; average speed of about 10 cm/sec
Wave	The annual maximum wave height: 6.8 m (in 1994, 1997, 2001) – 12.3 m (1988). The seasonal cycle: a peak in winter, trough in summer (with a daily average significant wave height around 4 m).
Benthic current	Calm period (0 – 3 cm/s), tidal period (0 – 6 cm/s), and benthic storm (8 cm/s, 24-h Ave.)
Sediment properties	Clays and siliceous biological casts. The bulk density: 1.1 – 1.62 g/cm^3 (mean value 1.19 g/cm^3); Moisture content: 52 – 85% (mean of about 76%); Porosity 71 – 93% (average porosity about 87%)
Chemical properties	Three layers in water column: mixed layer, thermocline layer, and deep layer
Temperatures	Mixed layer: 25°C Thermocline layer: 12 – 13°C Deep layer: 4.5°C at 1,000 m
Seawater density	Mixed layer: 1.022 g/cm^3 Thermocline layer: not reported Deep layer: 1.022 g/cm^3 at 1,000 m
Primary productivity	Affected by the solar energy input and nutrient flux.
Oxygen concentration	Mixed layer: 400 – 500 uM Thermocline layer: minima 1 uM at 300 – 500 m Deep layer: 350 uM near bottom
pH value	Decreased with depth
Nutrients	Mixed layer: 1 – 2 uM Thermocline layer: maxima 45 uM at 800 – 1,000 m Deep layer: 36 uM at 4,000 m, < 30 uM near bottom
Suspended particles	Mixed layer: 47 mg/l Thermocline layer: maxima 110 mg/l just above thermocline Deep layer: 12 mg/l within 400 m of bottom
Trace elements	Manganese: maxima 0.62 nanogram-atom/kg at the surface Copper & nickel: increase with depth
Biological properties of benthic communities	High species diversity, high variation in fauna community structure and composition

2.2.1 The COMRA Area

The COMRA contract area consists of two parts: the east and the west region located 200 km apart (Figure 5). This scattered area has both varying resources and geological conditions. Table 3 presents some of the key characteristics of the two areas for comparison.

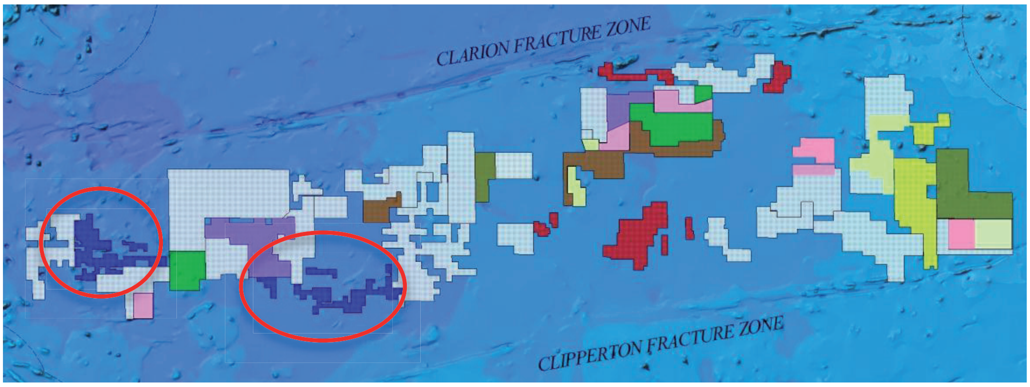


Figure 5: Allocated area for China's COMRA in CCZ (ISA 2010)

Several technical and economic criteria are applied to compare the western and eastern regions of COMRA.

Table 4 reveals that the western region has superior characteristics to its eastern counterpart in terms of abundance, grade, and spatial distribution of the nodules, as well as the seabed topographic conditions. Thus, the western COMRA area has been chosen for the location of the case study.

Table 3: The characteristics of the western and eastern regions of COMRA (Amos and Roels 1977, ISA 2010)

	West	East
Local conditions		
Area	62,000 km^2	88,000 km^2
Proximity to China	10,000 – 12,000 km	10,000 – 12,000 km
Water depth	4,900 – 5,400 m	4,900 – 5,400 m
Wave height	Max in winter (6.8 – 12.3 m) Min in summer (ave ~ 4 m)	Max in winter (6.8 – 12.3 m) Min in summer (ave ~ 4 m)
Topography	Intermountain basins & linear furrow areas; slope < 2°	isolated seamounts; slope 5 – 10°
Age of basement	Palaeocene	Late Cretaceous
Tectonic data	Mainly volcanism	Mainly faulting, followed by volcanism
Sediment data	Siliceous ooze, clay	Siliceous ooze, clay
Water column data & biological data	No specific data, similar with general CCZ characteristics	No specific data, similar with general CCZ characteristics
Resources data		
Nodule morphology	Type S (Smooth type)	Type R (Rough surface)/ Type S+R
Average Abundance	6.68 kg/m^2 74.6% of area > 5 kg/m^2	3.49 kg/m^2 30.4% of area > 5 kg/m^2
Average Grade	2.2% (Normal distribution)	2.86% (Two peaks)
Spatial distribution	798 m	418 m

Table 4: The comparison of west region and east region of COMRA

	West	East	Technique boundary	Preference
Topography	slope < 2°	5 – 10°	slope < 5°	Only west satisfied
Average Abundance	6.68 kg/m^2 74.6% of area > 5 kg/m^2	3.49 kg/m^2 30.4% of area > 5 kg/m^2	≥ 5.0 kg/m^2	Only west satisfied
Average Grade	2.2% Normal distribution	2.86% Two peaks	≥ 1.80%	Both satisfied but east preferred
Spatial distribution	798 m	418 m	Continuous distribution preferred	west preferred

2.2.2 Site Specifications in Western COMRA

According to studies undertaken by COMRA, a mining site than can yield 3 million dry tons of nodules per year for a period of 20 years could be regarded as an economically profitable mining operation. Although this figure is subjective, COMRA introduced a simple method to calculate the size of a mining depending on the reserve and its quality identified by exploration, the technology development and economic variation at the commercial time (ISA 2010).

Suppose a collection efficiency of 80%, the quantity of the mining operation needs 3.6 million dry metric tons in situ, or roughly 5.5 million wet metric tons in 20 years. Furthermore, suppose a constant grade of extracted metals, the size of the mining site needs to be 730 km^2, giving the average abundance of the nodules as 10 kg/m^2.

A detailed distribution of nodule abundance in the western COMRA is presented in Figure 6. The central part of the western area is obviously higher than that of the rest. In addition, this part is characterised by high copper and nickel grade, both important for the Chinese economy as previously discussed. Therefore, the central part of western COMRA has been identified as the specific mining site for the case study. The resource data of the mining site is listed in Table 5.

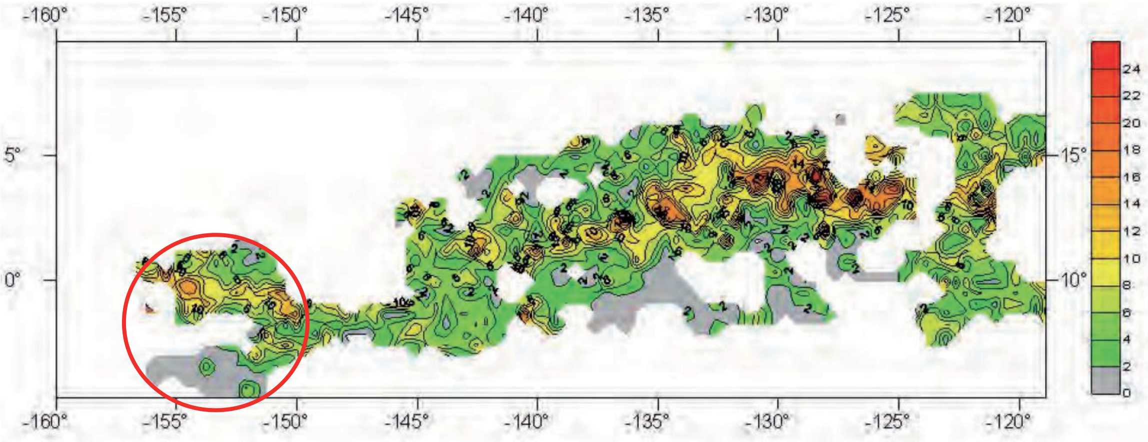


Figure 6: The distribution of nodule abundance in western COMRA

Table 5: The resource data for the central part of western COMRA

Indicators	Unit	Min	Max	Design Value
Ave abundance	kg/m^2	8.0	12.0	10.0
Ni grade	%	1.3	1.5	1.4
Cu grade	%	1.1	1.4	1.3

2.3 Market Analysis

This section will introduce the global market analysis followed by the specific evaluation for nodules' market.

2.3.1 Global Market Analysis

Recently, the world's population reached the impressive figure of 7 billion and is increasing at an even higher rate, as can be seen in Figure 7.

Developing countries such as India and China are having a significant impact on today's world economy, particularly due to their economic growth and the need to feed their continuously increasing populations. This has led to a position where 2.5 billion people are currently living in countries characterised by booming economies. This can be seen from the increasing Gross Domestic Product (GDP) of these two nations (see Figure 8), and rapidly growing middle classes exhibiting a continuous increase in demand for daily life commodities (see Figure 9).

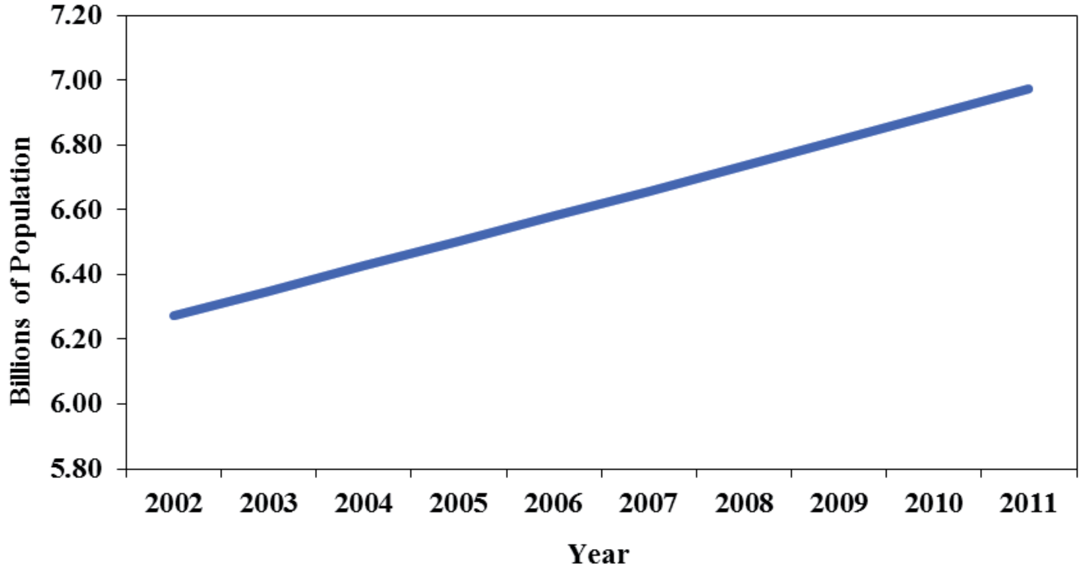


Figure 7: World's population trend in the last ten years (source: www.worldbank.org)

It can be clearly understood that the rate of growth of these two countries is much faster than any other, even more so than major developed countries such as the USA. In particular, the ISA Workshop in 2008 identifies how the modernisation of China and its growing economy created rising metal demand, which caused the price to rebound in 2002 – 2003. It is expected that due to its economic development, Chinese demand alone will keep on influencing and driving the global minerals market.

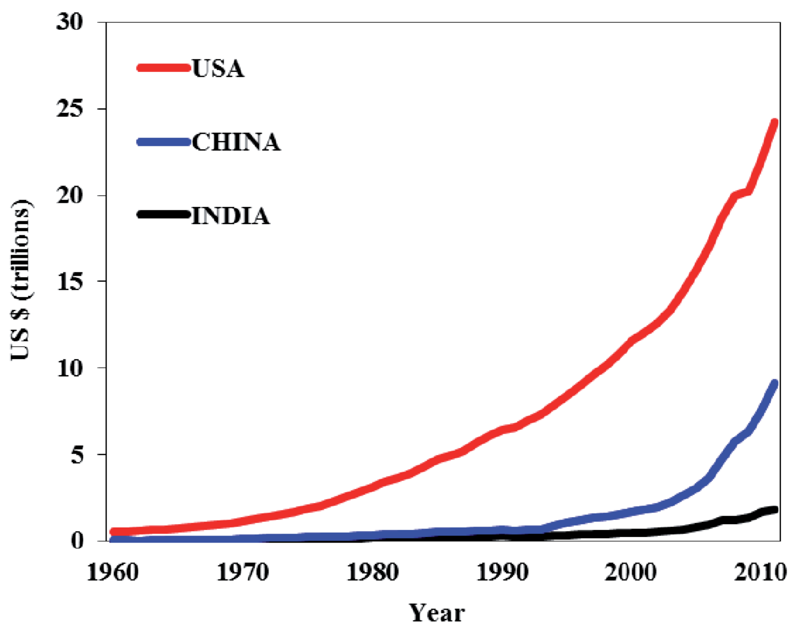


Figure 8: GDP of USA, China and India in the last 50 years
(source: www.worldbank.org)

World demand will soon surpass production. The rate of increase of demand is much higher than the rate of increase of supply that can be achieved with the current technologies and scientific knowledge.

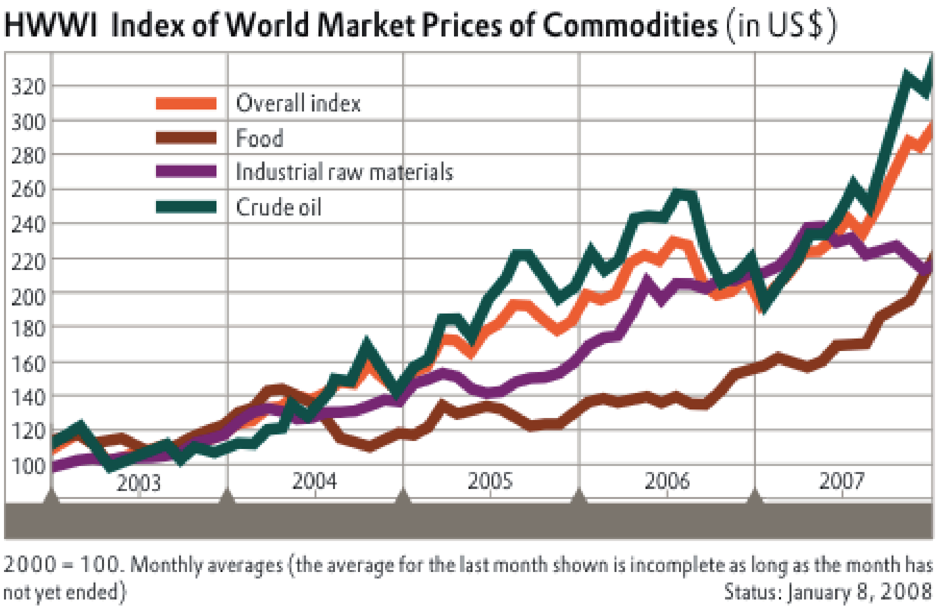


Figure 9: Index of world market price of commodities (source: www.corporate.evonik.com)

The mining industry production has in fact plateaued around its peak in extraction and processing, which leads to a discrepancy between demand and production. It is highly unlikely that the existing industry will be able to supply this ever-growing need.

The effect of demand boom can also be observed from the fact that the Chinese demand for copper had tripled since 1998. The World Bank reported that Chinese consumption of refined metal (aluminium, copper, lead, nickel, tin and zinc) has skyrocketed 17-fold since the 1990s, and it consumes 41% of the total world consumption (see Figure 10). Today, China is the biggest consumer of copper and nickel in the world (ISA 2008a). Brazil, Russia, India and other developing countries are expected to follow the same trend due to their flourishing economic conditions.

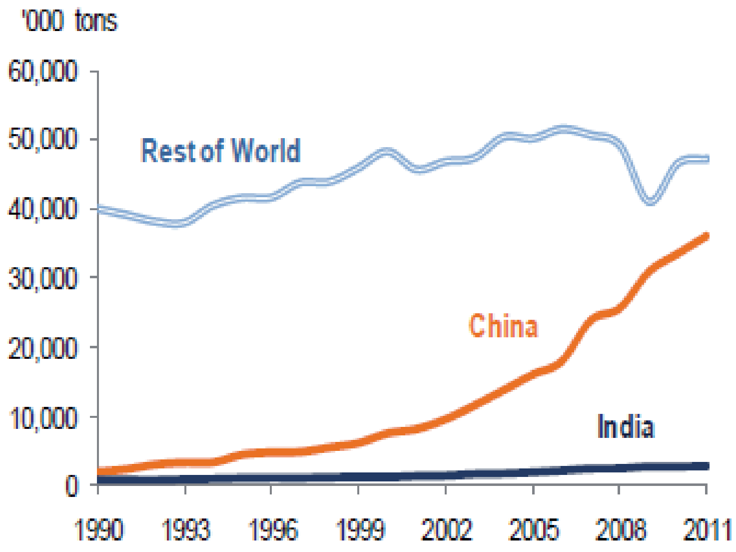


Figure 10: Refined metal consumption trend
(aluminium, copper, lead, nickel, tin and zinc)

Extrapolating the current trend to predict the future behaviour of the demand and supply trends, (future here refers to a time-frame of 10 or 20 or even 50 years), we can infer that the market is extremely volatile with quite a large degree of risk and uncertainty. Many different aspects have to be considered and unpredictable events are likely with such a long-term future plan. In this work, the market analysis is based on the current time and the present situation and assumes that demand of raw materials (metallic in particular) will follow the trend imposed by the current market. It is in fact impossible to predict if the demand for some of the materials will drastically decrease due to a revolutionary technology or invention or inverted market trend. A particular assumption is that an increased production of ferromanganese products will readily be absorbed by the markets without a sudden fall in price, as generally is the case with increased supply. The assumption is justified. In the authors' view, the increased supply can be expected at a significant time from the present, and by this time, sufficient gaps will have likely opened in the market due to increased demands.

2.3.2 Nodules Market Analysis

There are several problems in estimating the reserves of manganese nodules. Firstly, most of the analysed data derives from that collected for other purposes. Secondly, there is no universal agreement as to what grade and abundance of nodules actually constitutes a mine site. The most influential commercial studies on manganese nodules consider a concentration of 10 kg/m^2 to be the threshold of commercial feasibility. Figure 11 shows the behaviour of the grade-weighted nodule price from 1900 to 2000. The series is composed of an aggregate of average annual US prices for four metals: nickel (Ni), cobalt (Co), copper (Cu) and manganese (Mn). The prices for each metal are weighted first by average grade (the proportion of metal contained in an average nodule) and next by recoverability (the proportion that can be extracted with current technology). The price series has been adjusted for inflation and has been expressed in 1993 US dollars (Figure 11). The peak in the figure corresponds to periods of major armed conflict, which tend to result in a drastic increase in the price of metals. Manganese nodules are no exception: peaks occur during both world wars and during the Korean and Vietnam conflicts. With the exception of World War I, price controls were placed on metals in the USA during major armed conflicts, and these controls have tended to suppress the amplitude of price increases. In 1989, a smaller increase in the nodule price occurred. This increase was caused primarily by a rise in demand for stainless steels, thereby affecting the nickel market.

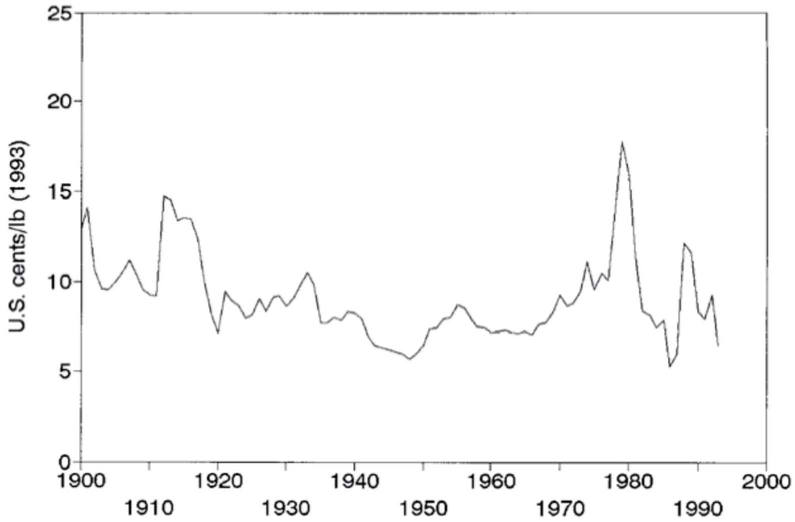


Figure 11: Dim prospects for the commercialization of deep seabed mining (Hoagland 1993)

The push of developing countries, above all China and India, has led to an increase in steel production and consumption in recent years. This corresponds to an increase in manganese demand, with a likely acceleration in the years to come.

While the future of the manganese heavy industry will continue to depend mainly on steel production, other technological applications are likely to see impressive growth. For instance, the use of li-ion and Ni batteries for consumers, the production of electric vehicles and the need for storage battery applications, will see manganese consumption rise to approximately 60,000 tons by 2020 (following the trend of Figure 12). As the market imposes in response to a rising demand, manganese production should increase in the coming years while manganese ore prices are expected to remain stable, with some occasional spikes. Reflecting these conditions, manganese prices could be 20 – 30% higher in five years.

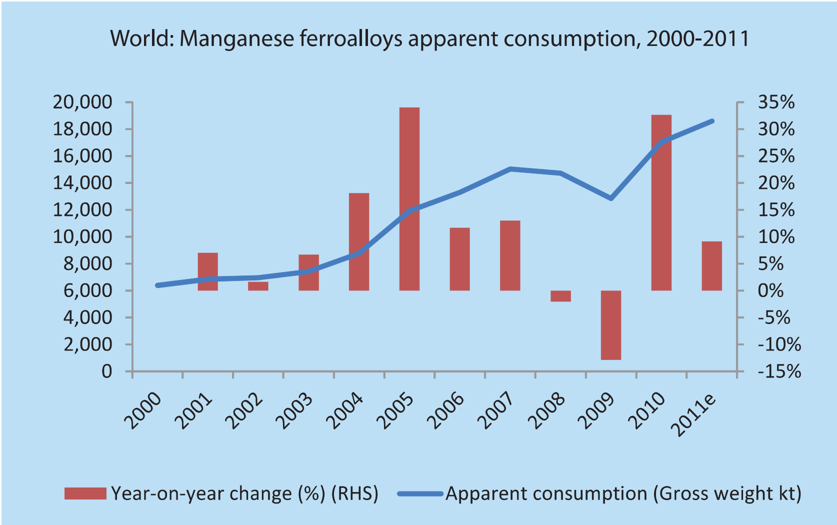


Figure 12: Manganese: global industry markets & outlook (source: www.roskill.com/manganese)

A rising demand in minerals has driven metal prices up. Figure 13 and Figure 14 show the market trends of copper, cobalt, nickel and manganese, which indicate that the prices have risen dramatically over the last 10 years. The price of copper for example, has increased more than three times since 2002 (ISA 2008a). The prices of cobalt, nickel and manganese have risen more than twice since 2002. Each of the four metals jumped steeply before 2007 and experienced steady decline during the 2008 economic crisis, but as the global market is recovering, so too are the metal prices. This trend of increasing metal prices makes the mineral markets an attractive investment for both private and government enterprises.

A different market case is instead presented for the rare earth element (REEs). There are 17 REEs, 15 within the chemical group called lanthanides, plus yttrium and scandium. The lanthanides consist of the following: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium.

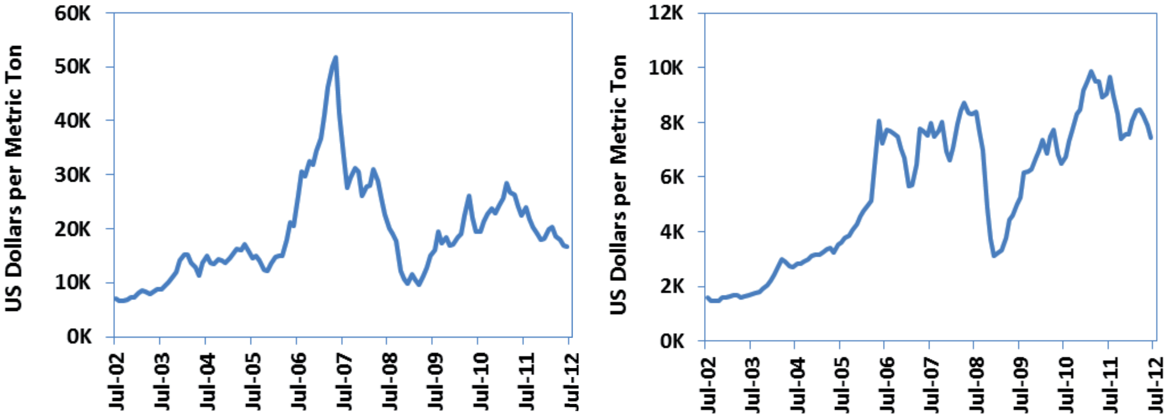


Figure 13: Left to right: nickel and copper price trends in 10 years (source: www.worldbank.org)

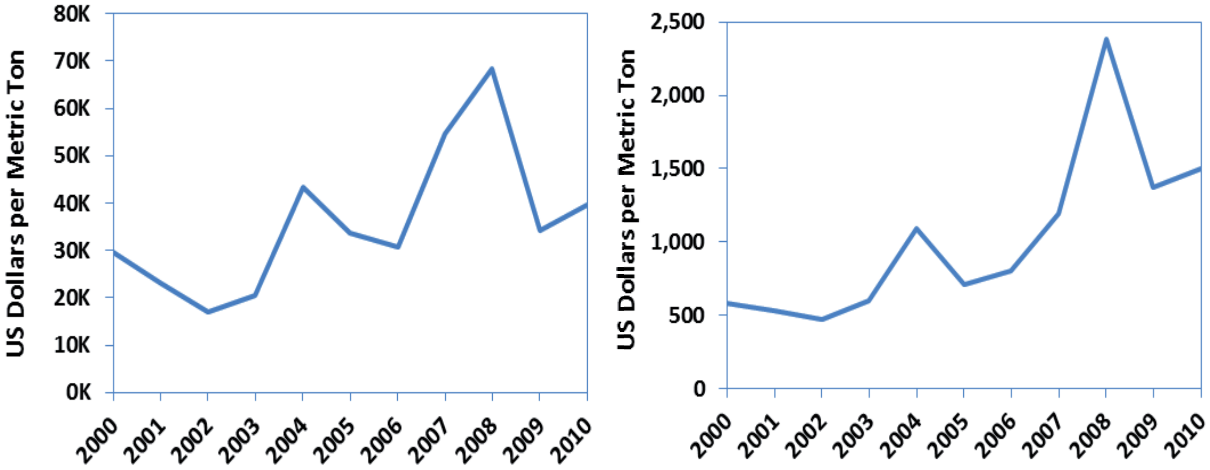


Figure 14: Left to right: cobalt and manganese price trends in 10 years (source: www.worldbank.org)

Presently, the principal utility of these elements is found to be in automobile catalysts and petroleum refining catalysts, in phosphors in colour television and flat panel displays (cell phones, portable DVDs, and laptops), permanent magnets and rechargeable batteries for hybrid and electric vehicles, and numerous medical devices (see Table 6). Important defence applications such as jet fighter engines, missile guidance systems, anti-missile defence, and satellite and communication systems are partly based on the availability of these REEs.

Table 6: USGS circular 930-N: REEs select end and uses (source: www.usgs.gov)

Light Rare Earths (more abundant)	Major End Use	Heavy Rare Earth (less abundant)	Major End Use
Lanthanum	hybrid engines, metal alloys	Terbium	phosphors, permanent magnets
Cerium	auto catalyst, petroleum refining, metal alloys	Dysprosium	permanent magnets, hybrid engines
Praseodymium	magnets	Erbium	phosphors
Neodymium	auto catalyst, petroleum refining, hard drives in laptops, headphones, hybrid engines	Yttrium	red color, fluorescent lamps, ceramics, metal alloy agent
Samarium	magnets	Holmium	glass coloring, lasers
Europium	red color for television and computer screens	Thulium	medical x-ray units
		Lutetium	catalysts in petroleum refining
		Ytterbium	lasers, steel alloys
		Gadolinium	magnets

As Figure 15 demonstrates, the price of a few REEs has risen considerably and this trend is driven by the increase in demand. With the current state of technology, today's mining industry is unable to accomplish cost-effective extraction of REEs. Adequate mining capabilities are only a part of the solution to REE supply shortfall. Additional processing, refining, and manufacturing capacity is necessary to meet growing demand. While sustained high prices may attract some investors, the technology and skills must also be upgraded to carry out the work.

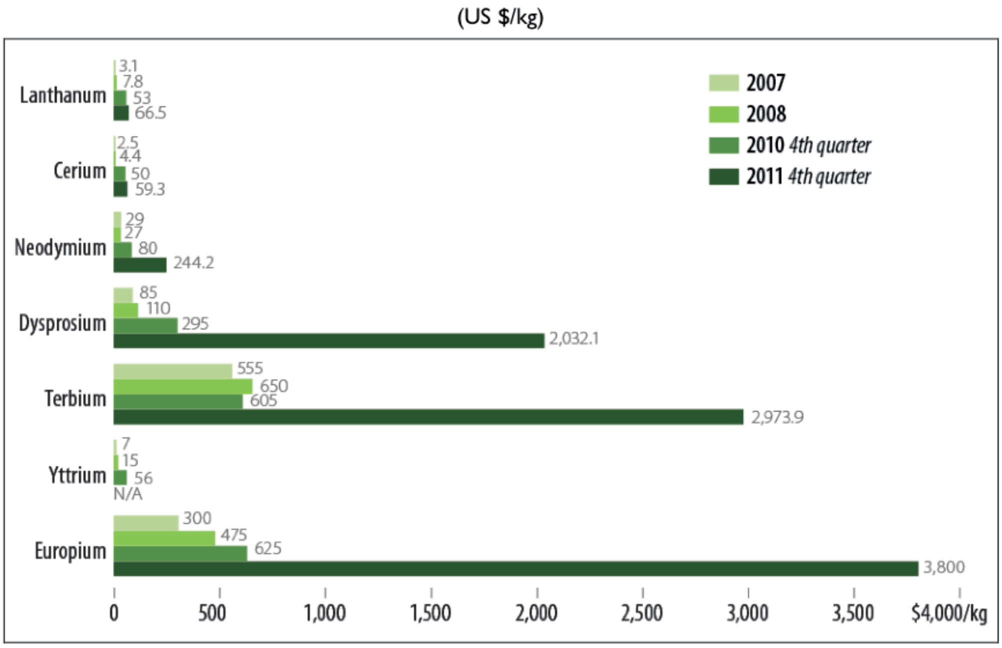


Figure 15: REEs prices
(source: www.industrialminerals.biz, www.meti.go.jp)

As Figure 16 and Figure 17 show, China is the leader both in terms of current production and predicted trend for the future. This is a commercial war that every single country will try to win in order to be independent of the Chinese influence on the supply.

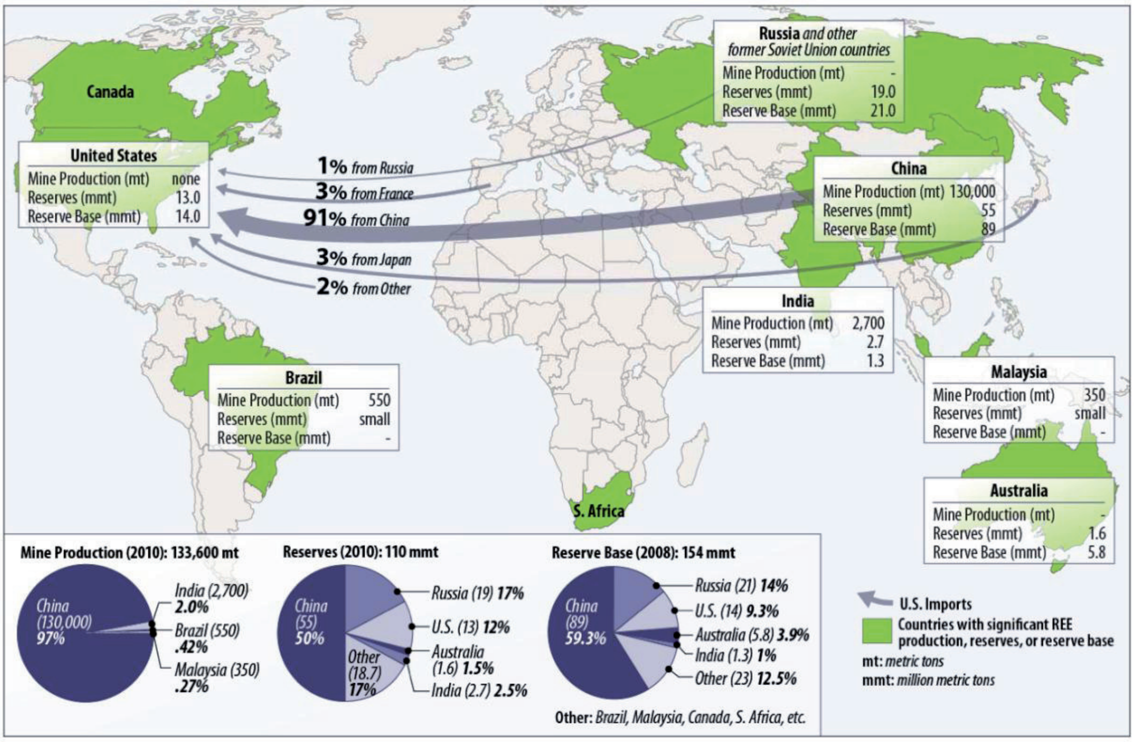


Figure 16: Worldwide export of REEs (source: www.usgs.gov)

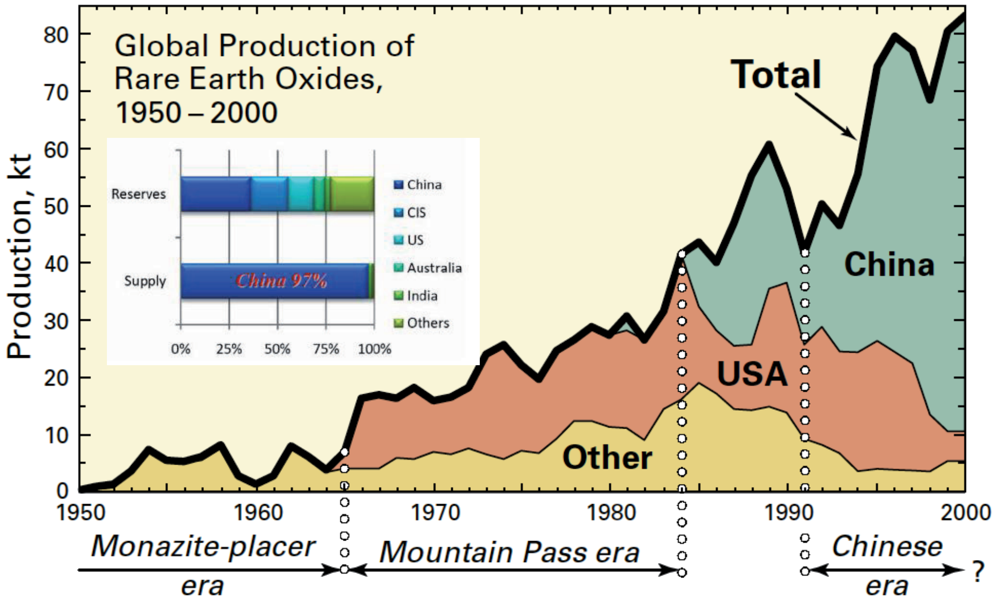


Figure 17: Global production of REEs (source: www.corporate.evonik.com)

3 Possible Techniques for Recovery

Techniques for manganese nodule exploitation have been developing rapidly since the dawn of the "New Phase", after the 1990s (Glasby 2002). Due to license distribution to major contractors by ISA in the CCZ, there have been many different techniques proposed for nodule recovery in a productive and efficient way. It is obviously a very challenging problem due to the high depths (4,000 – 6,000 m) and associated huge hydrostatic pressure and jading transfer process up to the water surface. The conceptual designs claim to be able to withstand such high pressures while working on uneven and very low bearing capacity seabed soils. Another aspect which should be considered is the environmental impact caused by the motion of each such unit (Erry et al. 2002). The resultant power supply needed to bring the nodules up to the surface is also enormous (of the order of few Mega-Watts, as shown subsequently).

The whole nodule recovery system on the seabed can be grouped into three major components: mining system, mother ship, and shuttle barge, illustrated in Figure 18. The sub-systems indicated in bold are the most challenging and need to be given particular attention. These are also the key components defining any manganese nodule recovery system. In this chapter, three basic components of the mining system are reviewed in detail, while our conceptual innovative design will be addressed in Section 5.1.

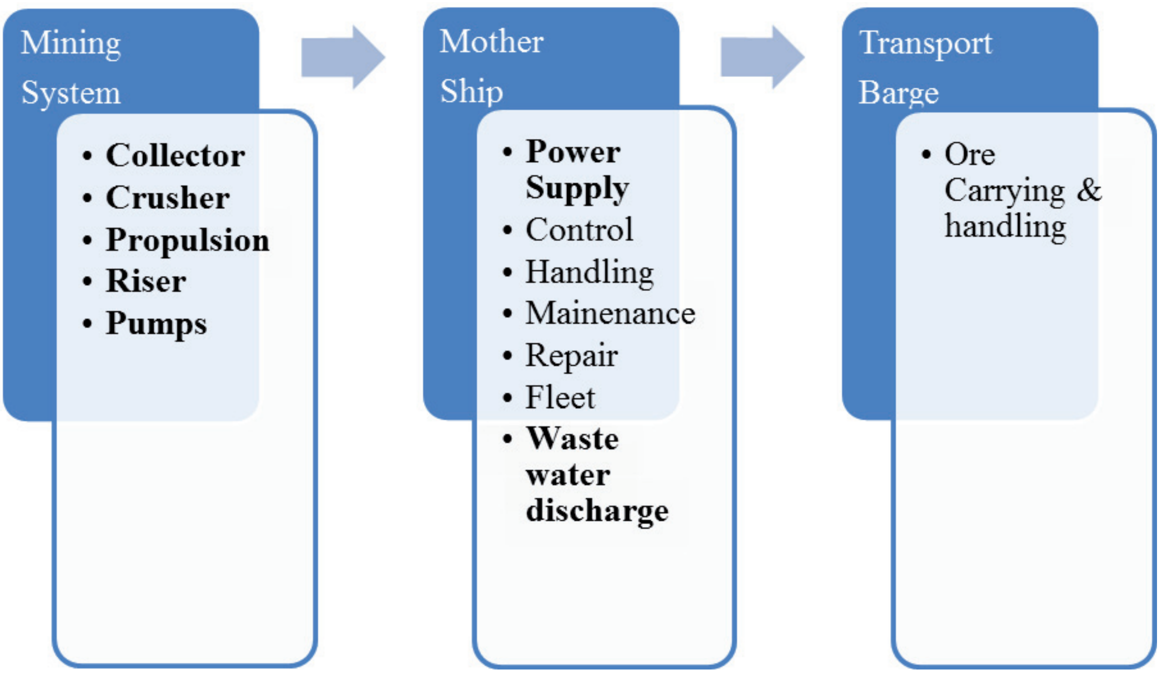


Figure 18: Sub systems for deep seabed exploitation and their functions

The two pioneering techniques of the mining system, namely the continuous line bucket (CLB) and the modular mining or shuttle system (ISA 2008a), have been abandoned. The CLB was shelved due to the high impact on the seabed environment and low efficiency (Liu 1999), while the shuttle system was discarded due to technical difficulties in the 1990s. The proposed technique that has gained the most popularity is the hydraulic mining system, which consists of a vertical riser pipe with either an active or passive collector unit. The hydraulic riser system makes use of either a centrifugal hydraulic pump or an air lift (ISA 2008a).

Reference has been made to the Proceeding of the ISA's Workshop in Kingston, Jamaica in 1999 (www.isa.org.jm), about a list of the proposed technologies for manganese nodule recovery presented by the pioneer investors and experts familiar with related industrial activities. For a more informed understanding of the entire system, the list of possible techniques is organised under three basic aspects of the mining system: collectors, propulsion, and vertical transport (Riser), as shown in Figure 19. Productivity is largely influenced by the dynamics of these three aspects and their combined efficiency.

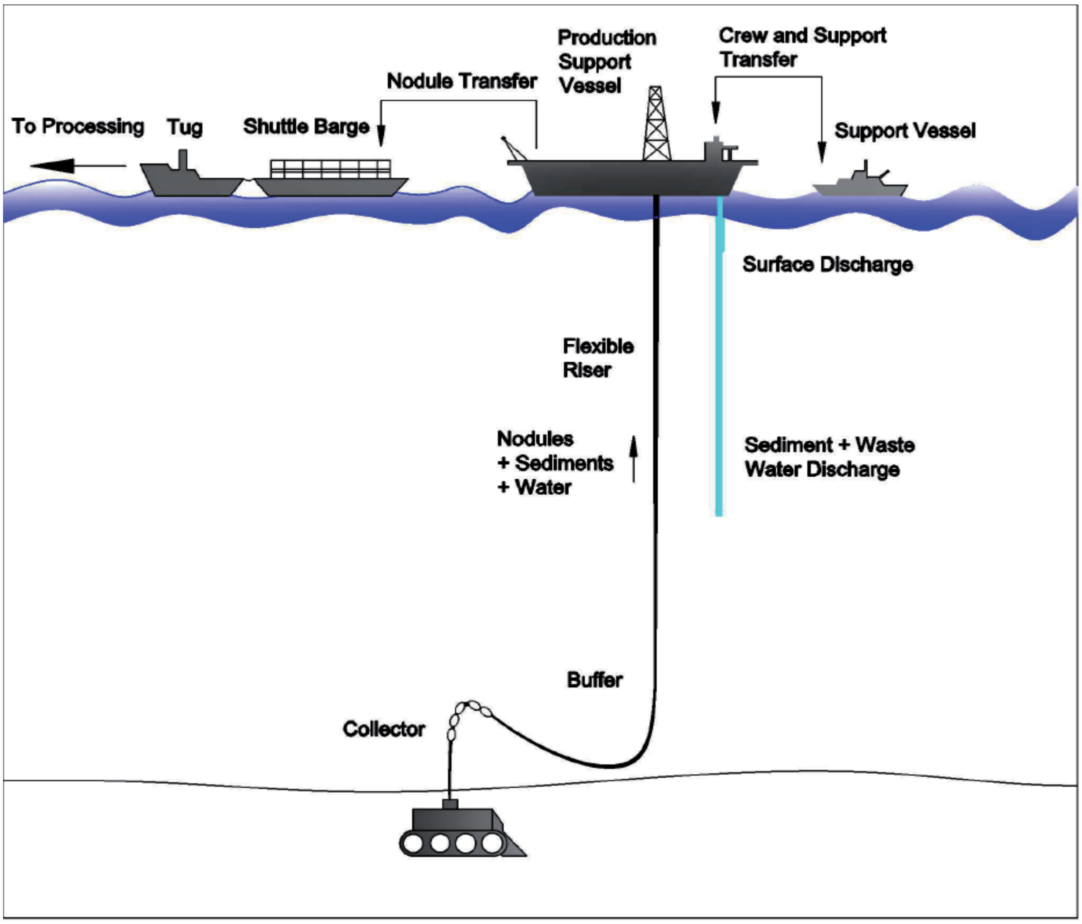


Figure 19: Conventional recovery system

3.1 Collectors

The basic function of a nodule collector is to collect nodules spread on the seafloor, clean them from sediments and supply them to the riser – pipe system for vertical transport to the surface. In performing these basic tasks, efficiency of nodule production can be prescribed in various ways. In terms of nodule collection, collection efficiency includes components such as sweep area, ratio of actual collected nodules over the total number of nodules encountered over a fixed travel distance, the amount of sediments cleaned and rejected before introducing the nodules into the riser system, the downtime of the collector and the level of redundancy. The term “redundancy” means that failure of one component does not significantly dampen the overall nodule collection (Brockett 1999). These various components affecting collection efficiency need to be considered to achieve an optimum collector design. A nodule collector is typically attached to a riser pipe for transport of collected nodules and to a power source, if the collector requires additional power to operate. Thus, in general there are two types of collector depending on whether it takes in additional power supply or not: passive and active collectors.

3.1.1 Passive Collectors

Passive collectors have a simple design, and require no additional power, offering the most obvious advantages over active collectors: low cost and simplicity. However, passive collectors have disadvantages. These include a lack of control in both quantity and quality of the nodules and sediments collected, huge sediment plumes on the seabed and a relatively large amount of sediment entering the riser system (Brockett 1999).

Most of the passive collectors have two primary functions: gathering and concentrating the nodules into an inlet and entraining them into the riser. As a passive collector is being towed across the seabed, it gathers nodules and sediments and pushes them into an inlet. Water is also forced to accelerate through a transition duct to lift and entrain the nodules and sediments into the riser (Brockett 1999).

The passive collectors lack of a sophisticated mechanism to wash the sediment off the nodules. The passive collectors also have a tendency to take in acceptable size nodules only and leave the oversized nodules out of the inlet.

Several examples of passive collectors can be found in (Brockett 1999) and two main types are shown in Figure 20 and Figure 21.

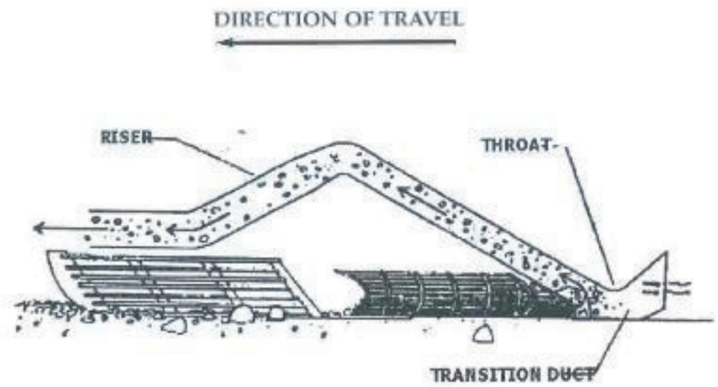


Figure 20: Passive rhomboid rake (Brockett 1999)

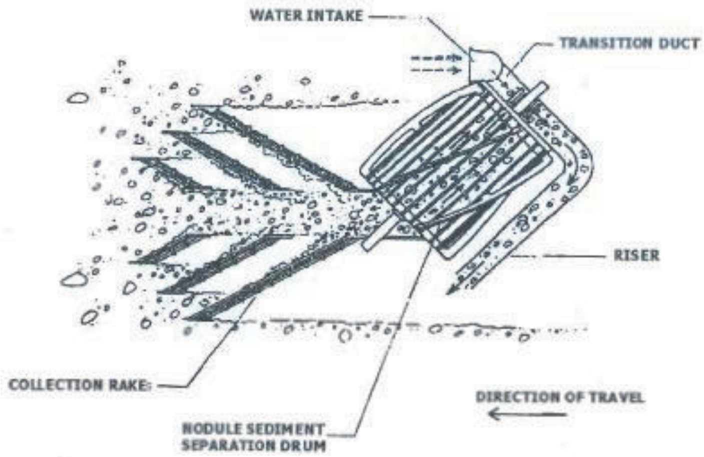


Figure 21: Hybrid passive rake (Brockett 1999)

3.1.2 Active Collectors

As opposed to passive collectors, the active ones require an additional power supply to perform the basic function of nodule collection and pre-processing. They can typically be categorised into: pure **mechanical** systems, pure **hydraulic** systems and **hybrid** systems (combination of a mechanical and hydraulic system). The design of active collectors is more complex than passive ones, but they perform the primary task of cleaning the nodules from the sediments satisfactorily. There is however a question whether purely mechanical types of active collectors are effective in nodule-sediment separation or not, which has led to the introduction of a hydraulic system (Brockett 1999).

It is also possible to handle oversized nodules with active collectors, as a crusher system can be easily incorporated into them. Thus, nodule collection efficiency is greatly improved by utilising active collectors. Three basic types of active collectors are reproduced as follows.

- **Pure mechanical system**

The pure mechanical system (Figure 22) incorporates moving parts to collect and transport the nodules to the riser system. The power consumption of an active mechanical system is higher than an hydraulic system (Brockett 1999). Due to the great complexity and moving parts of the system, pure mechanical systems are less reliable, and these factors limit their prospects.

Schwarz (1999) introduced an example of a pure active mechanical system in 1999, named the advanced collector module. The system is capable of collecting the nodules of a required size, with a moving comb mechanism as a pick-up device that cuts layers off the seafloor. It then transports the nodules to the subsequent conveyor belt, to be crushed by an integrated crusher before entering the riser system. A vibrating mechanism is installed at the base of the comb to mechanically separate the nodules from sediments.

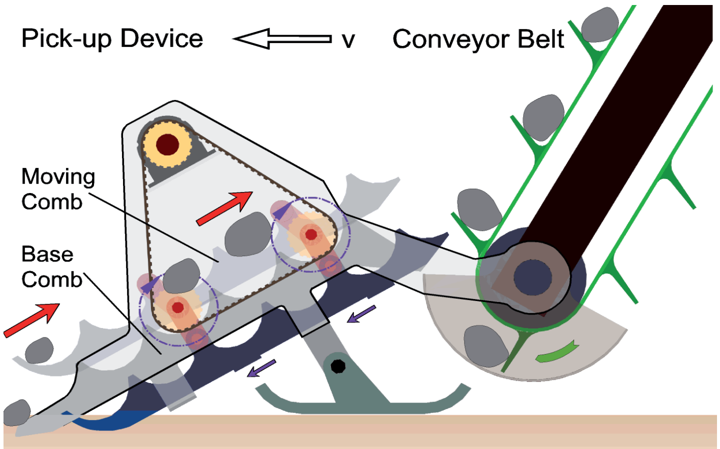


Figure 22: Mechanical collector system (Brockett 1999)

- **Pure hydraulic system**

The pure hydraulic system is the most popular in terms of nodule collection. It is more reliable and more robust than the pure mechanical system due to the limited number of moving parts and the less complicated nature of how the system performs. It also involves a very minimal seabed interaction while extracting the nodules, which obviously helps reduce the impact on the environment. While the mechanical system uses moving parts to separate a layer of nodules and sediments from the seabed, the hydraulic system utilises moving seawater for the same function (Brockett 1999). Two examples of the pure hydraulic system are reproduced as follows.

- ***Hydraulic ramp***

The hydraulic ramp (Figure 23) has a similar mechanism to the mechanical ramp. The difference lies on the cutting technique of the hydraulic ramp, which only *scrapes* sediment surfaces, and thus does not involve the removal of a layer of seabed sediment. Once the nodules and sediments have been collected, a similar concept follows: a water jet is used to perform nodule – sediment separation along the inclined ramp before the nodules enter the riser system (Brockett 1999) .

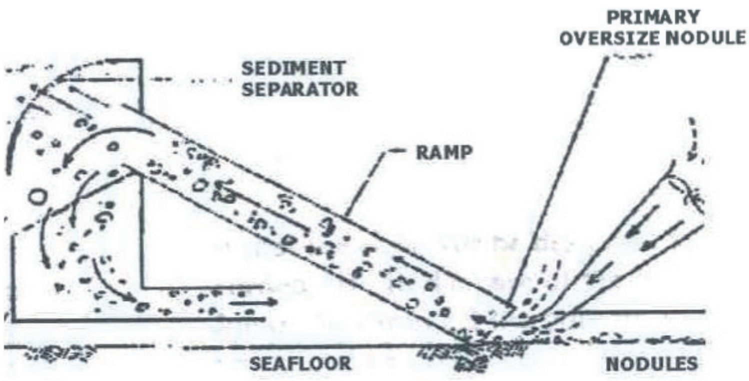


Figure 23: Hydraulic ramp (Brockett 1999)

- ***Hydraulic lift***

Similar to the hydraulic ramp and hydraulic plough mechanisms, the hydraulic lift uses a ramp-like device to transport and clean nodules before introducing them into the riser system. The only difference is that the hydraulic lift involves zero contact with the seafloor while extracting the nodules. It uses aligned nozzles to produce low pressure and a scouring action to lift the nodules off the seafloor and feed them into the riser system. It does however involve contact with the seafloor in the form of a curved base plate to align the produced jet stream and entrained water to the ramp inlet. A schematic representation is shown in Figure 24.

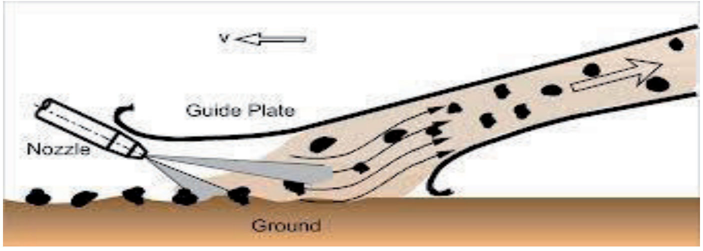


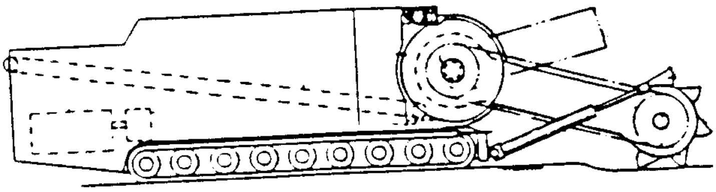
Figure 24: Hydraulic lift system (Brockett 1999)

- **Hybrid** (Combination of mechanical and hydraulic system)

The combination of a mechanical and hydraulic system exists, as a pure mechanical system is considered less effective in performing nodule-sediment separation. The addition of a hydraulic system incorporates high velocity water nozzles to wash the sediments from the nodules. Three examples of a hybrid system are reproduced as follows.

➤ ***Mechanical drum***

The mechanical drum has several scoops mounted on a drum, which rotates as the collector transverses horizontally. As a result of the rotation, the entire upper layer of the seabed (sediments and nodules) is scooped up. High velocity nozzles then wash the sediments off the nodules, and the clean nodules are deposited onto a conveyor belt, which leads to a crusher system before transferring the nodules to the riser system. A schematic representation is shown in Figure 25.



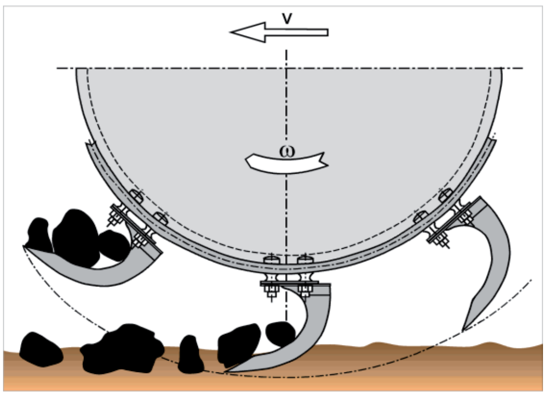


Figure 25: Mechanical drum (Brockett 1999)

➢ ***Simple hybrid lift***

A simple hybrid lift uses a hydraulic mechanism to pick up nodules and mechanical methods to transport, clean, crush and eventually entrain them to the riser system. Hydraulic systems, such as water jets, are used to lift the nodules up off the seabed. A vibrating system is incorporated in the mechanical transport system to perform the nodule-sediment separation process. Clean nodules subsequently fall into the mechanical crusher so that oversized nodules can be crushed. The advantage of this concept is that it requires virtually zero physical contact between the collector and the seabed. However, the disadvantage is that substantial sediment plumes may be created, given that there is no base guide plate to contain the water stream. A schematic representation is shown in Figure 26.

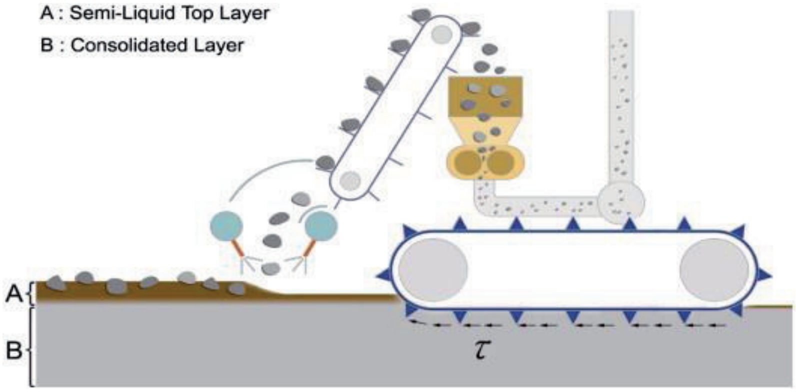


Figure 26: Simple hybrid lift (Brockett 1999)

➢ ***Hydraulic plough***

The hydraulic plough also has a ramp like mechanism to transport clean nodules to the riser system. The difference lies in the technique used to cut a layer of seabed to obtain nodules and sediments. The hydraulic plough uses a base plate at the edge of the ramp to scrape and to provide a bearing support. The tops of the nodules need to be aligned with the bottom of the base plate. As the hydraulic plough moves, it essentially scrapes a layer of nodules and sediments off the seabed through a solid entrance located below the plate. Water jets then wash the nodules as they are transported along the inclined ramp. A schematic representation is shown in Figure 27.

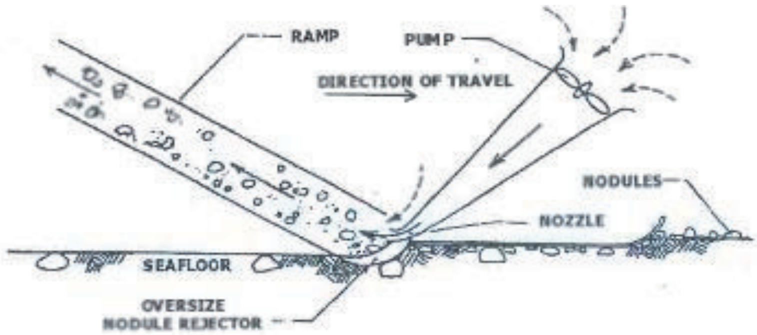


Figure 27: Hydraulic plough (Brockett 1999)

Between the two types of collectors, it is a straightforward conclusion that active collectors offer the mechanism with the smallest environmental impacts and the highest production efficiency. Of the three types of active collectors, the pure mechanical system has obvious disadvantages, such as the need for large and heavy equipment and less reliability due to the numerous moving parts. Thus, both the hybrid and the pure hydraulic seem to be the most promising concepts for a nodule collection system.

The pure hydraulic system, in the authors' view, can be more robust and reliable than the hybrid system due to fewer moving parts, and the ability to modularise the design into many small units to increase redundancy. In the case of the hybrid and mechanical systems, it can be very costly to do so.

Based on this simple analysis, a few recommendations on the collection process for the mining system can be made:

- Nodule crushing is necessary to avoid oversized nodule rejection, thus boosting the collection productivity;
- A light weight collector design would be beneficial from a stability point of view;
- A mechanism which allows minimum physical contact between the collector and the seafloor would be ideal;
- A mechanism to contain or suck sediment plumes up during the collection process should be incorporated;
- A mechanism for the collector to move freely and flexibly on a very low bearing capacity seafloor with the suitable ground contact system;
- A modularised system design, which contains many small collectors that contributes to high redundancy in nodule collection activity.

3.2 Propulsion

The propulsion system describes the way a collector moves while recovering the nodules on the seabed. Nodule collection efficiency is greatly related to propulsion, manoeuvrability and speed of travel. Manoeuvrability refers to the ability of a collector to move around on the seabed floor. Two basic forms of propulsion have been proposed: towed and self-propelled, which are discussed as follows:

3.2.1 Towed Collectors

These kinds of collectors are dragged along the seabed floor by means of a mother ship. Passive collectors belong to this category and, as these have been previously discussed, will therefore not be reviewed in this section.

3.2.2 Self-propelled Collectors

Self-propelled collectors have their own propulsion system in order to manoeuvre. The collector unit can be further categorised on the basis of the propulsion system used.

- **Wheel mounted collectors**

The collectors in this category are simply wheel mounted and the movement mechanism creates minimal sediment plumes. Wheeled collectors score well in this respect. The major problem with this class of collectors is the insufficient contact area with the floor and hence the weight support issues. The soil on the seabed is composed of soft clays with low bearing capacity. The collector units are usually very heavy (15 tons), so to be properly supported on the loose soil, the contact area between the collector unit and the seabed soil should be maximised. This reduces the pressure on the points of contact on the seafloor (Pressure on the soil = $\frac{\text{Weight}}{\text{Contact Area}}$). If the contact area is not sufficiently large, it may lead to high levels of local stress and consequently sudden soil collapse. This problem makes wheeled collectors obsolete.

- **Archimedes screw driven collectors**

This type of collector has been built and tested in China since 2005 in different water densities and on soils characterised by different shear strengths. The overall results for the movement of the collector have been very satisfactory (Li and Jue 2005). The stability of the vessel in soft soil is exceptionally good. During motion, the movement screws penetrate through the top few centimetres of soil. This effect makes the whole environment hazy, thus reducing the visibility and threatening most of the local flora and fauna. Thus, even though they provide good grip, the amount of sediment dispersed in the water is unacceptable. Moreover, while descending down a slope, there is a chance that the vehicle may slip and tip over. Its power consumption is almost twice as much as that of an equivalent tracked collector (Li and Jue 2005). The heavy loading capacity of the vehicle is also brought into doubt due to the screwing mechanism. A schematic representation is shown in Figure 28.

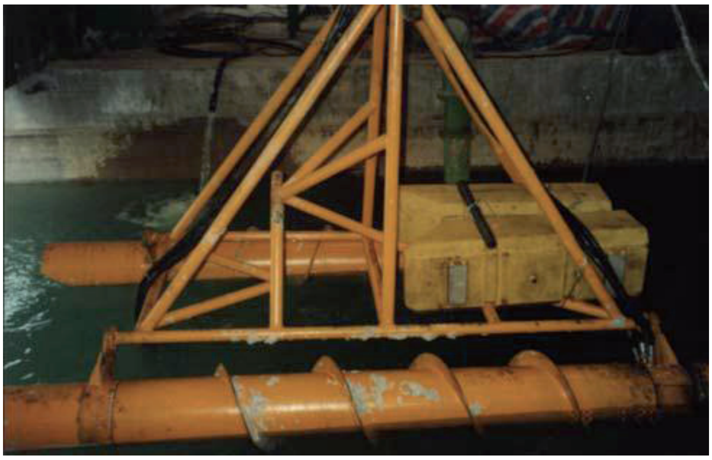


Figure 28: The Archimedes screw vehicle designed by China (Li and Jue 2005)

- **The tracked vehicle**

This is the most successful movement mechanism tested so far. The most important design characteristic of this family of vehicles (referred to as crawlers) is the good manoeuvrability in soft grounds. The ground contact area is sufficiently large, which results in less pressure under the contact area. Hence, a large weight can be easily supported. The performance on slopes is also satisfactory. Owing to the large contact area, the loading capacity is high. The power consumption of the machine is lesser than the Archimedes screw driven collector as previously discussed. An example is provided in Figure 29.

Figure 29: The crawler vehicle designed by China (Li and Jue 2005)

3.3 Vertical Transport

Vertical transport refers to the process of transporting nodule and water mixture (slurry) through a riser system to the water surface. The overall production efficiency has several components, such as optimum concentration of nodules in the slurry, riser friction factor, and the chosen type of lift system.

To achieve optimum concentration of nodules in the slurry, nodule pre-processing is recommended. Chung and Tsurusaki (1994) suggested an additional buffer weight system to be attached at the end of a riser-pipe system for two purposes: firstly to control the slurry mixture ratio for multi-phase flow and to prevent the occurrence of nodule flow blockage, and secondly, to restrain steady-state horizontal sway of the bottom end of the pipe system.

A common design of the lifting system can be divided into three different categories, which are summarised in the following paragraphs.

3.3.1 Continuous Line Bucket

This refers to a system where buckets are fixed to a continuous line in such a way that, when towed across the seafloor, they collect loose material. This line is dragged via two ships, both of which are connected to the ends of the line. The separation between the ships dictates the sweep area attained. After collection, the buckets can be recovered using a conveyor system. The main disadvantages are lack of manoeuvrability, and hence lack of production control, and heavy sediment disturbance. A schematic representation is shown in Figure 30.

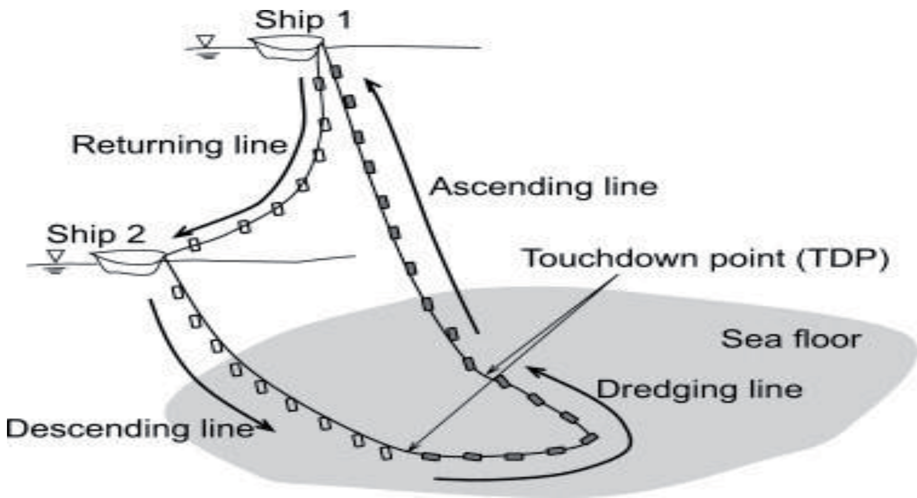


Figure 30: The line bucket system in operation (Brockett 1999)

3.3.2 Air Lift System

The air lift system utilises a process of injecting air into the collection line to reduce the density of the slurry and to induce a flow driven by the pressure difference between the nodule feed point and the end on the mother ship (Brockett 1999). It is a three-phase flow (nodules, water and air), and consumes more power than the hydraulic lift system (Chung and Tsurusaki 1994). A schematic representation is shown in Figure 31.

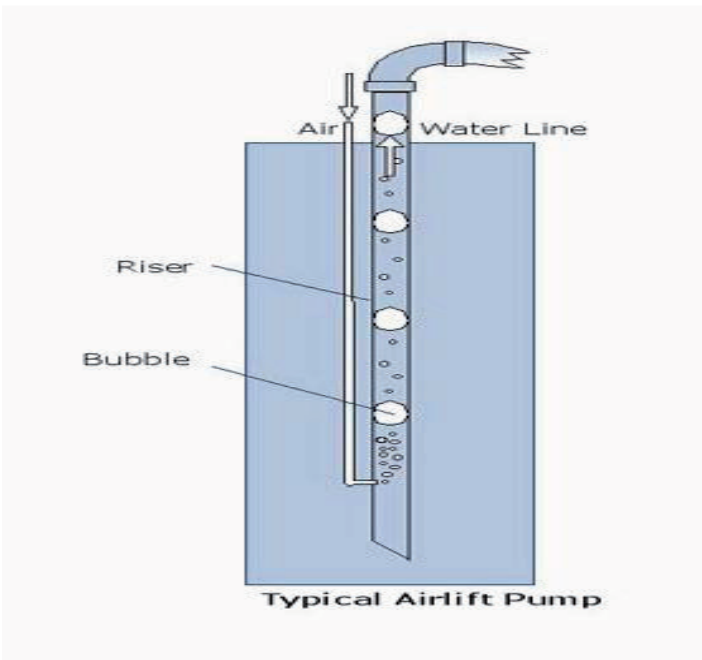


Figure 31: Air lift system (Brockett 1999)

Compressed air is injected at the lower portion of the pipe and its lifting force is used to transport the slurry. The air, which is less dense, rises by buoyancy. The design is based on the principle of entraining the slurry to move along with the air bubble. The mechanism is simple but has the disadvantages of frequent clogging and high power requirement to send air down to a depth of greater than 4,000 m.

3.3.3 Hydraulic Pump System

The hydraulic pump system design is based on a series of pumps (Figure 32) along a riser system, which transports the slurry (nodules and water) to the surface (Chung and Tsurusaki 1994), as can be seen from Figure 33.

This is probably the simplest of all the systems for lifting the nodules to the surface. The slurry is transported to the surface through pumps installed along the lifting line. The advantages are: a simple concept design, a high lifting efficiency and reliable operation. The pump and the associated components have to be designed for operation at high depths.

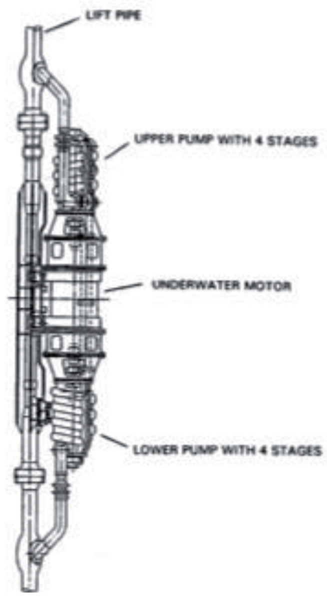


Figure 32: Deep-submersible pump with underwater electric motor (TRAM 1991)

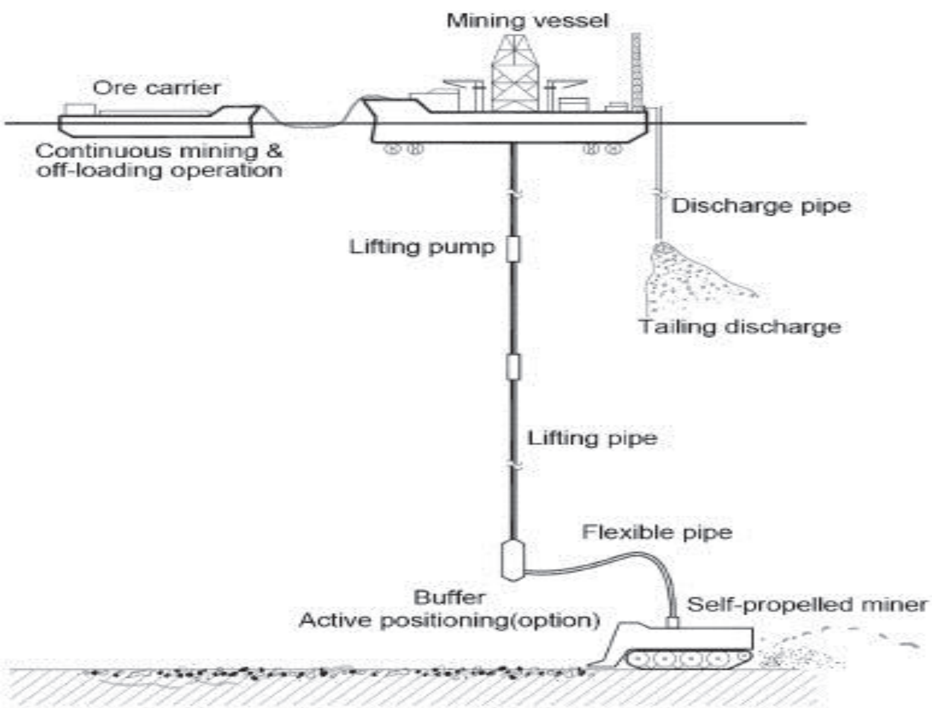


Figure 33: The pump system (TRAM 1991)

.

4 Current Issues and Challenges

This section will introduce and briefly discuss some of the common issues and challenges related to the design and the prospective of seabed exploitation. It will begin with an analysis of the engineering challenges faced in designing such a system, followed by a consideration of the environmental issues. Finally, an overview of the geopolitical and legal-social aspects will be presented.

4.1 Engineering Challenges

The seabed surface represents an inestimable source of resources for humanity, not only in terms of the available minerals, as this study discusses, but also in regards to oil and gas, which have been exploited since the 1970s. A discussion of the latter two resources is beyond the scope of this work, and thus they will not be considered any further. Further aspects not taken into account within the present study are the resources in terms of energy extraction (refer black smokers or mid-ridges) and the biodiversity that characterises the deep seas. A critical analysis of the biodiversity and the environmental impact of the exploitation will however be included and discussed later in the context of nodule exploitation. These will not however be treated as resources to be exploited themselves.

Before we can introduce and discuss the engineering challenges of a full-scale nodule commercial recovery operation, it is important to clarify the critical distinction between the terms resource and reserve, which are frequently confused. As Mickey Fulp from the Mercenary Geologist explains, a mineral resource is a geologic inventory of a mineral abundance in the ground; a reserve on the other hand, is a mineral deposit that can be mined at a profit. A reserve is characterised by an economic parameter that has been applied to it through a feasibility study, showing that it can be mined, at a profit, at this particular time (www.mercenarygeologist.com). This difference is of particular importance here, because the engineering challenge itself is the factor that contributes to distinguishing between the two categories. If the challenges cannot be overcome, then a resource cannot be exploited at the present time. It will therefore not be considered a reserve and hence will not have a direct commercial interest. Some of the main engineering challenges with regards to manganese nodules are summarised below and feasible solutions are presented following the introduction of the proposed design.

Seabed exploration and potential commercial exploitation offer a multitude of challenges to overcome, both in terms of the hostile marine environment and the biological hazards that are directly connected to the exploitation. As previously discussed, the nodule deposits, being connected to the formation mechanism, are highly concentrated in the middle of the oceans (refer Section 2.1) and strictly fall within high depth seas. This makes the exploration and exploitation processes particularly challenging, complex and expensive. Fuel consumption is one of the main parameters that must be considered in the commercial viability of exploiting these deposits. Assuming the possibility of exploitation, the minerals still have to be transported thousands of miles away to be sold in the market and the mother ship continuously has to be refilled with fuel.

The location in which these deposits are found incites various problems. Firstly, these minerals have to be brought up to the water surface, provided the excavation can be accomplished. This comprises a long journey in a potentially highly unpredictable environment. A high depth involves a high hydrodynamic pressure. The pressure under water increases roughly 1 atmosphere for each 10 metres in depth, so an easy estimation of the pressure at 6,000 m depth reads around 600 atm. Such a high pressure constitutes the principal difference between the land based and deep sea mining machineries. All the system's components have to withstand such a high water pressure. As a result, the weight of every single one must increase proportionally, given that a stronger and more robust component is required. A further issue connected to the high depth is the need to supply power to the machines. Even after adopting high voltage connections, the losses due to the joule's effect must be considered given that long cabling is required. The result is an over-dimensioning of the power system in order to meet the requirements. Moreover, due to high depths and safety issues, the mining operation cannot involve manned vehicles. The entire mining operation has to be controlled from the water surface and it is strictly based on unmanned machineries.

The salinity and acidity of the seawater are further important considerations. This is an unforgiving environment for metal components to be operating in: frequent maintenance and use of special alloyed steel must be considered to prevent oxidation and/or mechanical failure of the components. Moreover, the non-uniformity of the temperature gradient has to be addressed for fatigue related issues and for defining optimal operating temperatures for the different parts of the system.

Regarding the machinery control, the seabed is characterised by an absence of light (refer paragraph on environment in the deep sea). The zero visibility of the environment dictates that control of the machines must be based on alternative auxiliary tools (sensors, GPS, radar, etc). These systems have to be developed or adjusted to function within a high spatial range. The productivity and the cost of the nodule recovery operation are strongly based on the seabed topography, which continuously has to be monitored and overcome through the aid of smart machinery and sophisticated mining techniques.

All these aspects come under the design umbrella and must be addressed for the final design to be approved and to have a high efficiency. The classical engineering approach makes prominent use of previously proven designs in order to make the design loop smaller and more cost effective and hence faster and more efficient (see Figure 34). This particular case, being a completely new concept, has no proven designs available as a benchmark and hence requires intense brainstorming and investments to tackle the problem of designing an efficient system.

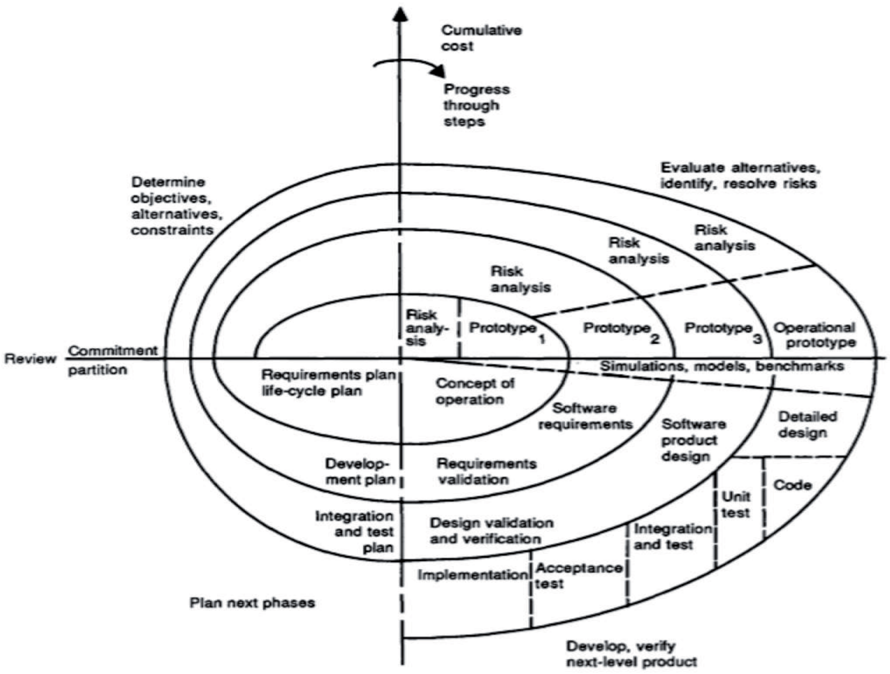


Figure 34: Classical design engineering loop (Boehm 1988)

Ideally an efficient and cost effective engineering system has some level of redundancy built in so that the production does not have to be stopped in case of maintenance requirements or failure of a single component. The designer tends to use a parametric design concept so that in the case of a slightly different system, a proven design can just be applied and scaled to the new needs, cutting down the costs and time to produce the new system. In this particular situation however, the redundancy is limited by the maximum space available on the mother ship and the design is highly dependent on the location where the system is to be used. This goes against the normal engineering loop design notion.

Despite all the engineering challenges, every system needs to be environmental friendly. It is also required to be cost effective and hence, commercially viable. This usually involves a high level of compromise between different requirements and a multidisciplinary approach. It becomes then necessary to compromise for feasible engineering system between the production scale, the power consumption, the efficiency, simplicity and the environmental footprint, which the system would inevitably leave on the local marine ecosystem. These aspects will be analysed in detail in next sections.

4.2 Environmental Challenges

To discuss the environmental challenges connected with the nodule recovery process, the entire operation has been divided into the following sub operations:

- **Collection of** the polymetallic nodules and separation from the fine-grained seabed mud/clay that host them;
- **Lifting** them by 4,000-6,000 metres to the ocean surface;
- **Separation** from the seawater (de-watering process) and sediment entrained in the lift operation and transporting them to a metallurgical processing facility.

Initial environmental impact studies were conducted during pilot-scale mining tests for manganese nodules in the 1970s. These were followed by several experiments in the last decade by intentionally creating benthic disturbances in the Pacific and the Indian Oceans. The related studies are summarised in Table 7. As is apparent from the table, the majority of previous studies only investigated the impact of collection activity on the deep-sea dwellings. It is important to note that the studies showed widely different degrees of detrimental effects caused by the collection. The differences can be attributed to the experimental assumptions or the onsite conditions. It is rather too early to conclude that nodule exploitation causes serious environment consequences. Further efforts are required to characterise the regional environment and to monitor the effects of industrial pilot-scale tests since the results are strictly location dependent.

A more comprehensive discussion on environmental impacts of nodule mining is presented as follows, divided into two groups based on basic operation activities.

4.2.1 Environmental Impacts Associated with Collection Activities

A clear impact of a commercial recovery is the removal of the nodules themselves from the ecosystem. Nodule growth is one of the slowest of all geological phenomena – in the order of a centimetre over several million years. A nodule with 4 cm in diameter may be 10 – 20 million years old (Glover and Smith 2003). Manganese nodule is a clear example of non-sustainable seabed resource. Adequate management and planning are essential to control the commercial nodule recovery rate until new resources are discovered.

Table 7: Summary of reviewed studies

Studies	Scale	Ref	Results
The Deep Ocean Mining Environmental Study (DOMES)	Pilot-scale (1972 – 1981)	(Amos and Roels 1977)	No significant surface discharge impacts. Near-bottom sediment plumes will occur but their behaviour is greatest unknown.
The Disturbance and Recolonization Experiment in a manganese nodule area of the deep South Pacific Ocean (DISCOL)	Large-scale (1988 – 1998)	(Thiel 1991)	Severe decrease in the density of deep-dwelling macrobenthos, and species diversity.
Impact of technical interventions into the deep sea of the Southeast Pacific Ocean (ATESEPP)	Experimental scale (1997)	(Thiel 1992)	Heavy impacts on the geochemical regime after disturbance of the top 20 cm of the deep seafloor's sediment structure.
Japan's Deep-Sea Impact Experiment (JET)	Experimental scale (1994 – 1997)	(Fukushima 1995)	No significant difference in the density of macrofauna, but a decrease in polychaete abundance, and increase of crustaceans.
The benthic impact experiment by the National Oceanographic and Atmospheric Administration (NOAA-BIE)	Experimental (1991 – 1993)	(Trueblood et al. 1997)	No significant impact on species diversity that, but a decrease in some of the meiobenthos abundance and an increase in the numbers of macrobenthos
Benthic Impact Experiment conducted by the Interoceanmetal Joint Organization (IOM-BIE)	Experimental (1995)	(T.Radziejewska et al. 2003)	No significant change in meiobenthos abundance and community structure in the re-sedimented area, but alteration in meiobenthos assemblages within the disturbed zone
Indian Deep Ocean Enrichment Experiment (INDEX)	Experimental (1997)	(Sharma et al. 2000)	Reduction in macrofaunal density

Fortunately, substantial reserves can be found in the deep sea. Mero (1965) estimated that the total amount of polymetallic nodules lying on the sea floor was more than 1.5 trillion tonnes. He subsequently calculated that about 11 billion tonnes of manganese, 115 million tonnes of cobalt, 650 million tonnes of nickel, and 520 million tonnes of copper could be supplied by the nodules from the North Pacific high-grade area (Mero 1977). On this basis, the nodules could provide an inexhaustible supply of metals such as manganese, cobalt, nickel, and copper (Glasby 2002).

Another concern about the collection activity is the disturbance on the deep-sea floor habitats. The organisms which live on the surface of the manganese nodules include foraminifera, bryozoans, coelenterates, and serpulid worms (Morgan et al. 1999). According to the Kaplan project, the near bottom communities are dominated by polychaetes, nematodes, and foraminifera (ISA 2008b). All the seabed dwellings have a low level of productivity, biomass, and physical energy, but species diversity, in terms of the number of species per sample, is relatively high (Glover and Smith 2003). All these characteristics make the seabed habitats susceptible to environmental change near the sea floor. The detailed direct and indirect impacts are discussed below.

A direct impact on the deep-sea dwellings is the removal of the top few centimetres of sediment (5 – 12 cm) during the nodule-collecting activities. It is known that the whole of the abyssal fauna lives on the sea floor or within the upper few centimetres of the sediment (Amos and Roels 1977). Therefore, many bottom-dwelling communities in the direct path of the collector will be put in danger.

The indirect effects of nodule-collecting activities may also be deleterious. The collector propulsion system during the collection process will stir up sediments and create bottom sediment plume. Amos and Roels (1977) estimated a CLB system would re-suspend as much as 50,000 m^3 of sediments for every ton of nodule removed. Similar considerations are found in hydraulic studies, which claim that between 2.5 – 5.5 t of sediments would be brought into suspension for every ton of nodule removed (Morales-Nin and Ramos 2009). Morgan et al. (1999) assumed a production of 5,000 t/day of dry nodules in their study, the suspended sediments from the sea floor would then be 52,000 t/day. An advanced polymetallic nodule mining system proposed in the Indian Ocean (Sharma et al. 2000) reported 3369.6 t of nodules would be mined each day and about 57,602 t of sediment would be mobilised from the sea floor as a result. The substantial amount of mobilised sediments would affect the collection area, depending on regional conditions. The possible deleterious consequences include burying and subsequent suffocating the bottom communities and clogging the filter apparatus of the suspension feeders.

Extreme caution is needed in extrapolating these results to the impacts of commercial exploitation, since the reviewed studies produce disturbances that are much lower in intensity and many orders of magnitude smaller in scale. For example, the operation time of IOM-BIE (Benthic Impact Experiment conducted by the Interoceanmetal (IOM) Joint Organization), which lasted for 18 – 88 hours, is much shorter in comparison to a large-scale mining operation expected to last for about 300 days per year over a 30-year period. The distances covered by the paths of disturbers for different Benthic Impact Experiments vary from 33 to 144 km in a narrow width of 200 – 300 m, and the equivalent areas are much smaller than the area to be covered during commercial mining (in the order of 300 – 600 km^2 per year). Hence, the amount of sediment mobilised during these experiments is far below the actual amount during a commercial mining operation. Effectively, previous studies can be considered micro-scale experiments in terms of sediment re-suspension. In the future, it may be advisable to conduct a relatively large-scale or better full-scale experiment to study the impacts of such a disturbance on the benthic ecosystem.

In addition, there is also an issue of re-colonisation effects. Marine habitats are nearly continuous across ocean basins, which may make the fauna more resistant to extinction caused by local exploitation. Amos and Roels (1977) suggested that no more than 40% of a given area would be mined to facilitate the re-colonisation process from adjacent, untouched zones. The idea of preserving certain areas was recommended in a workshop at Manoa, Hawaii (Smith 2007). In this area, nodule mining would be prohibited in order to the leave the natural environment intact. As recommended by ISA, the dimensions of the preservation reference area should be 400 × 400 km^2, including a 200 × 200 km^2 core area surrounded by a 100 km^2 buffer zone (Smith 2007).

4.2.2 Environmental Impacts Associated with Lifting and Separation Activities

There has been significantly less discussion on the environmental impacts associated with the lifting and separation process compared to the collection activity. To be economically feasible, a mining unit (single mining ship or platform) must harvest enormous amounts of nodules per day. After the nodules have been collected from the sea floor, they are transported through more than 4,000 metres of a water column to the surface-mining vessel. Substantial amount of energy is required to lift up the nodules from the sea floor. Despite the continuous efforts in exploring various renewables to supply the energy demand for lifting, fossil fuels remain the dominant source. Therefore, the major concern with the lifting process is not the resultant impacts on the water column, but more about the air emissions associated with fossil fuel combustion, such as carbon dioxide, sulphur dioxide, nitrogen oxides, hydrocarbon compounds, carbon monoxides, and particular matters.

Nodules brought up to the surface via a riser system have to be separated from mud, sediments and water that do not contribute to the production. A separation process is thus necessary. Common practice is to discharge the waste material directly to the surface layer. This surface discharge means introducing additional surface-water suspended materials that have different physical and chemical characteristics, as well as temperature. Amos and Roels (1977) reported two or three orders of magnitude increase in surface-water suspended material compared to an undisturbed condition. The surface discharge creates surface plumes that are a more serious problem than the near bottom sediment plumes due to their comparatively higher radius of influence. Depending on the water current regime and the sinking properties of the particles, plumes can spread over far distances prior to resettling.

Surface plumes discharged on the surface in the epipelagic zone can reduce and block sunlight penetration essential for photosynthetic activities of the phytoplankton and other flora and fauna. Surface plumes are also likely to affect the pelagic community by clogging the filter feeding apparatus of zooplankton and reducing the floating capabilities of plankton due to the adhesion of sediment particles to body surfaces. Because of the potential huge amount of environmental damages in the depth zone from the surface to 1,000 m, it is strongly recommended that discharges be released below the depth of the oxygen-minimum layer (e.g. in 1,000 m in many parts of the Pacific Ocean) (Chung 2002).

If the environmental aspects of deep seabed mining are properly handled, it will represent no new source of environmental impacts in comparison to land based mining, but rather an alternative source of supply of the same end products. In fact, the environmental consequences to a great extent will depend on the chosen engineering system. Hence formulation of rules and regulations to protect the environment will have to be based entirely on the engineering system being used. Fortunately, the impacts of deep seabed nodule mining systems are highly localised.

4.3 Geo-political and Legal-social Status

"Like the oceans themselves, the Nation's marine interests are vast, complex, composed of many critical elements, and not susceptible to simplicity of treatment. ... The plan must provide for determined attack on immediate problems concurrently with initiation of a long range program to develop knowledge, technology, and a framework of laws and institutions that will lay the foundation for efficient and productive marine activities in the years ahead (USNO. 1969) "

As clearly stated in the above, the topic of seabed exploitation, especially in international water, is a delicate and complex topic. Mining or exploration in international waters inevitably provokes issues of geo-political and legal-social dimensions. These two aspects interact with each other and are largely responsible for the long delay of the first commercial seabed exploitation. As international waters do not belong to a single nation, the rules and regulations for the activities in the area are commonly agreed by every nation on a consensus basis. The ISA was set up for this purpose (the reader is advised to refer www.isa.org.jm for further information).

Two provisions set up by ISA are currently in use with regards to deep-sea mining operations in international water:

- 1982 United Nations Convention on the Law Of the Sea (UNCLOS) III a.k.a. Law of the Sea Treaty

There is a lengthy history behind how the arguments between United Nations (UN) and non-treaty members arose in deciding how to operate in international waters in terms of deep sea exploration beyond the Economic Exclusive Zone (EEZ). UNCLOS III requires every contractor to share half of its profits and also the technical knowhow with the Rest of the World (represented by ISA) (Glasby 2002). This whole process is intended to describe the use of deep sea resources as the "common heritage of mankind", a concept adopted by ISA to protect the interest of the Treaty members (mainly Third World Countries a.k.a. Group of 77 in the UN) (Glasby 2002). The misconception here was that the seabed mining would be so profitable that the developed countries would be keen enough to share the technologies and profits to the Third World Countries (Glasby 2002).

Major developed nations, led by the United States, refused to sign the UNCLOS III treaty, the Law of the Sea Treaty in 1982, by counter-arguing that it is up to the individual's freedom to mine at deep-sea under customary law, which is the Geneva Convention on the High Seas. It is important to mention that seabed mining was not included as one of the activities in the Geneva Convention, for not being technically ready when the Convention was formed. It is also apparent that the Convention was not free-market friendly and was in favour of the economic system of the Communist states. This also led the U.S. to declare unilaterally in 1983 the usage of the EEZ to extend the borders for shallow water mining in the short run (Glasby 2002).

- 1994 International Agreement a.k.a. Final ACT

This international agreement revoked the provisions of the 1982 UNCLOS Treaty on the transfer of technology and financing of the Third World countries. Due to such changes, it has now been recognised by the U.S. This eased the tensions between the UN and non-treaty members, and also opened up more opportunity for seabed exploration. Nevertheless, the U.S. has still not acceded as a member of the ISA (www.isa.org.jm). It has been suggested that the reason for this is largely a matter of domestic politics (Wood 2007). Perhaps the main concern for the U.S. if they were to ratify the Convention is the loss of part of the revenue previously amended to the U.S. Treasury and now to ISA for the oil and gas exploration in the Gulf of Mexico at the extended continental shelf (ECS), which goes beyond EEZ (200 nm). The estimate of the loss may be billions, if not trillions of dollars (Groves 2011).

These two provisions result in strict characterisations of the seabed environment where different laws govern different areas. International organisations are in place to guarantee that international laws are abided by every member and certify consortiums or entreprises to explore and exploit their contract areas in international water.

The current legal status of the usage of international waters is that almost all of the nations have ratified and signed the Convention, except for the U.S. and some other countries (www.isa.org.jm). It is the goal of the Convention to achieve universal participation, which has not yet been reached.

The Convention allows members to obtain a license from ISA to perform activities in international waters with equal rights, and such activities include seabed mining. The provision envisaging the seabed mining activity was realised in 2001/2002 with currently 10 major contractors signing a 15-year license contract each with ISA. The area of interest concentrates on the CCZ near Hawaii and on the Central Indian Basin of the Indian Ocean. Each area is limited to 150,000 square kilometres of which half is to be returned to ISA after eight operational years. ISA imposes several obligations on every contractor in the exploration and development of seabed mining. Firstly, they should conduct extensive survey on resources in their area of interest and report their activities to ISA on an annual basis. Secondly, they are obliged to give away half of their contract area to ISA which will be put under ISA management for the rest of the world to benefit from. The remaining half of the area will be an exclusive right of the contractor for further exploration, which will eventually lead to commercial benefits (www.isa.org.jm). It is worth noting that both mandatory technology transfer and limitation on seabed production have been dropped since the 1994 International Agreement, and this has since encouraged more commercial exploration to take place.

Social-related issues that may arise from seabed mining activities are often related to the environmental impact. The environmental and social issues overlap with one another. Public rejection emerges when the local environment and community are potentially disrupted due to seabed mining activities. There is always a concern on the generated pollution and the treatment of the mining waste to the environment, which can lead to health implications for the local population.

The study of this social issue draws on valuable lessons learnt from the case of Nautilius Mineral Inc. It was the first commercial mining company to be granted a license from the government of PNG (1997) to conduct seabed exploration at the floor of the Bismarck Sea. At present, there are many environmental and social issues still to be addressed, which further implicates the delay of the full mining operation (Rosenbaum 2011).

Nautilius Mineral Inc. intended to extract massive sulphide deposits for commercial purpose. However, the operation received strong objection from the local community and citizens of PNG. Part of the complications arises from an insufficient environmental and social impact assessment. Due to this perceived lack of scientific data available to the public, public scrutiny emerged. A technical paper drafted by Rosenbaum (2011) clearly summarises the possible environmental and social impacts from the high level of uncertainty about the risks posed by the seabed mining to marine environments and local communities.

The concerns surrounding the social impacts in the case of PNG centre on the detrimental health impact on local communities from pollution of the mining and waste discharge activities on the marine environment and ecosystem, which forms the marine food chain. Many local communities settling in the coastal region near to the exploration site rely heavily on seafood and such pollution is likely to expose the communities to dietary contamination (Rosenbaum 2011).The associated pollution might also have an impact on the local economy if local communities harvest the local fish and marine resources for commercial purposes. Disruption to the marine ecosystem will inevitably pose a risk to the local economic contribution (Rosenbaum 2011).

Essentially, local communities are more comfortable with those who understand how to operate and co-exist with oceans in a good way, not with corporations who are only interested in a quick solution and profit. More thorough and transparent studies are thus imperative to determine whether such mining and water discharge activities are causing social-economic and ecological impacts. Rosenbaum (2011) strongly encourages every mining activity to go through public and expert scrutiny in the first phase before actual operation can take place. This process will hopefully provide public and local communities a convincing solution and transparent engineering system, which addresses all the concerns raised by them.

5 Proposed Engineering System

This chapter introduces an innovative recovery engineering system for seabed nodules recovery. Firstly the new conceptual design is introduced, followed by a detailed discussion and analysis of the different components. Subsequently, some of the calculations and ideas behind the design process are presented and discussed. Power consumption, mass flow rate of the system and economic viability are some of the aspects taken into consideration.

5.1 Concept Design

As presented in the previous section, many different concept designs of mining subsystems for the collector, its propulsion and vertical transport exist. The optimum nodule recovery system, in the authors' view, is obtained by assembling the best performing subsystems into an integrated system. Currently the most convincing system in existence is represented in Figure 35 and discussed below.

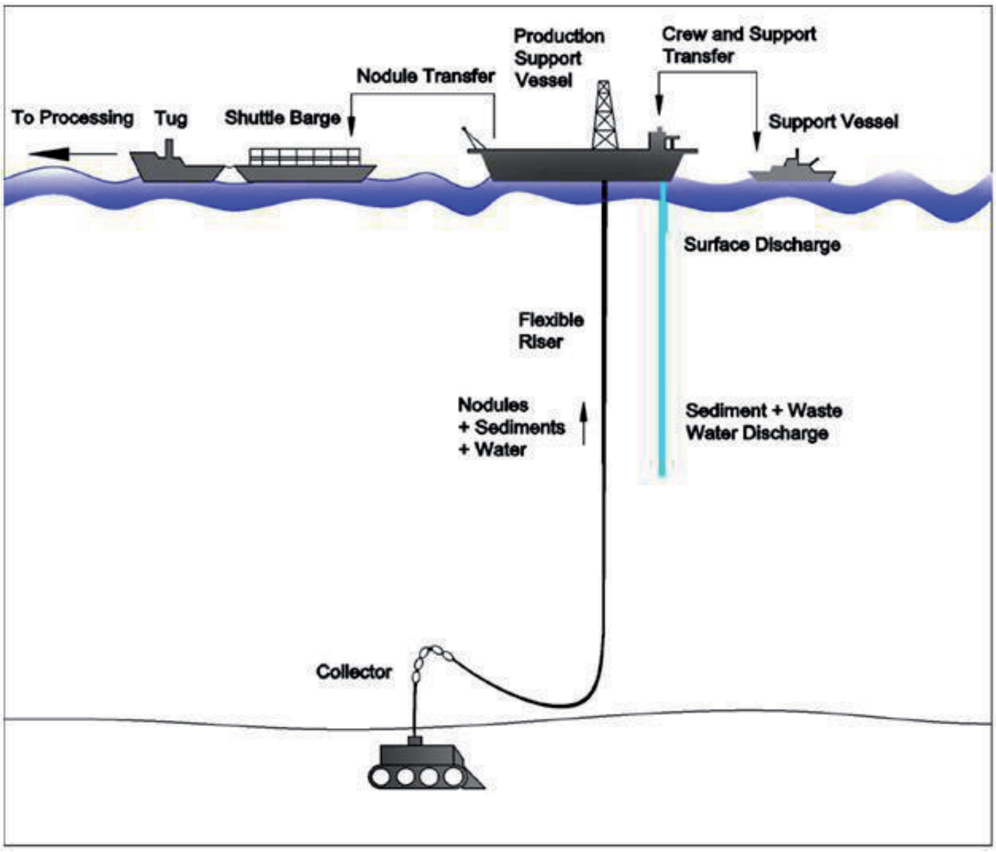


Figure 35: Existing nodule recovery concept

The existing system uses a single large collector connected to a mother ship (or Production Support Vessel, PSV) through a riser system (rigid or flexible). The collector is of a mechanical or hybrid type with a crawler type of propulsion. There are pumps located on the riser system at various water depths to transport nodules with clay, sediment and water (slurry) to the PSV on the surface. Cleaning and dewatering of the nodules is accomplished in the mother ship, which also regulates the moisture content of the nodules and brings them to Transportable Moisture Limit (TML). The nodules are then transferred to a transport barge (or an ore carrier). Wastewater and sediments are discharged from the mother ship, on the surface or at a suitable water depth.

Our proposed engineering system is based on similar concepts but incorporates modifications. Novel ideas are suggested at various levels of the subsystems. A schematic diagram of the proposed nodule recovery system is illustrated in Figure 36.

Starting from the seafloor, the proposed system is based on the use of multiple small collector units instead of a single large collector unit. This modularised subsystem is intended to introduce more redundancy into the system. Breakdown or maintenance of one of the collectors does not halt the entire nodule recovery system. A modularised subsystem permits much less effect on the integrity of the system when one subsystem fails. One additional collector will remain on standby on the PSV as a backup. This will not only help filling in the gap in production but also facilitating maintenance of all the collectors at regular intervals. A modularised subsystem also has an added advantage of boosting the production rate described in the following way. Two of the most common methods for a single subsystem to increase the production rate are either to increase the subsystem efficiency or to increase the area swept by the collector, but not both. Increasing the subsystem efficiency needs a reduction in speed of the collector and hence reduction in swept area. Consequently there will be a decrease in production rate, as the latter effect is more dominant. Fortunately, a modularised subsystem on one hand can afford a lower collector velocity to have high individual efficiencies, and on the other hand can possibly maintain a high swept area as the total area swept is the sum of areas swept by three collectors. Thus, the modularised subsystem can be expected to have a relatively higher overall productivity compared to the existing single subsystem.

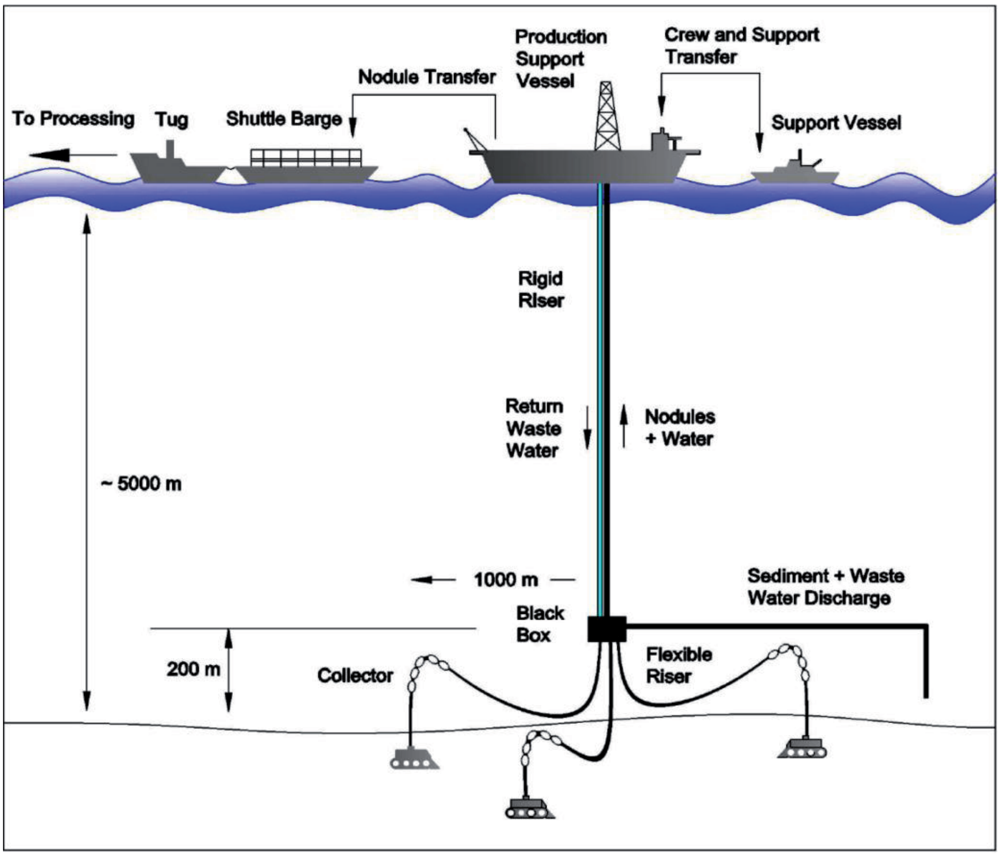


Figure 36: Proposed nodule recovery concept

Above multiple collector units, a buffer system named the Black Box (BB) is introduced. Flexible risers are used to connect this component to the collector units. The BB is a simple box type of submersible structure added to the whole system to perform several specific functions. The main function is to perform nodule – sediment separation so as to clean nodules. With the BB, sediments collected can be possibly discharged at a much deeper water depth compared to the existing nodule recovery concept, thus limiting the impacts on the environment to a local scale. The riser system cannot distinguish between the types of solids that it is carrying. For any amount of nodules and water it transports, it would also have to transport a certain amount of sediments. By making the slurry free from sediments, the power required to pump it to the PSV can be reduced.

Other functions of the black box include: optimising the waste treatment system, controlling the slurry concentration before transferring it to the PSV, and regulating mass flow when one of the collectors is down for maintenance or an extra collector is used to boost productivity. More details on the black box and its functions are presented in section 5.1.3.

A further improvement is on the utilisation of wastewater. The suggested engineering system uses the BB to separate sediments from nodules and water. Therefore, only nodules and water will be pumped to the PSV, and the wastewater from the on-board pre-processing is used for cleaning nodules inside the black box, before discharging the whole mixture at a much lower water depth. The remaining portion of wastewater will be pumped up together with clean nodules and subsequently forms part of the next wastewater return cycle after on-board pre-processing. It is important to mention that the return wastewater from the PSV will be comparatively clean as sediments have already been separated from nodules.

The following presents in detail the core subsystems of the proposed engineering system.

5.1.1 Collector

This subsection provides a detailed design of a collector unit and its propulsion mechanism. A schematic representation of a collector unit is illustrated in Figure 37.

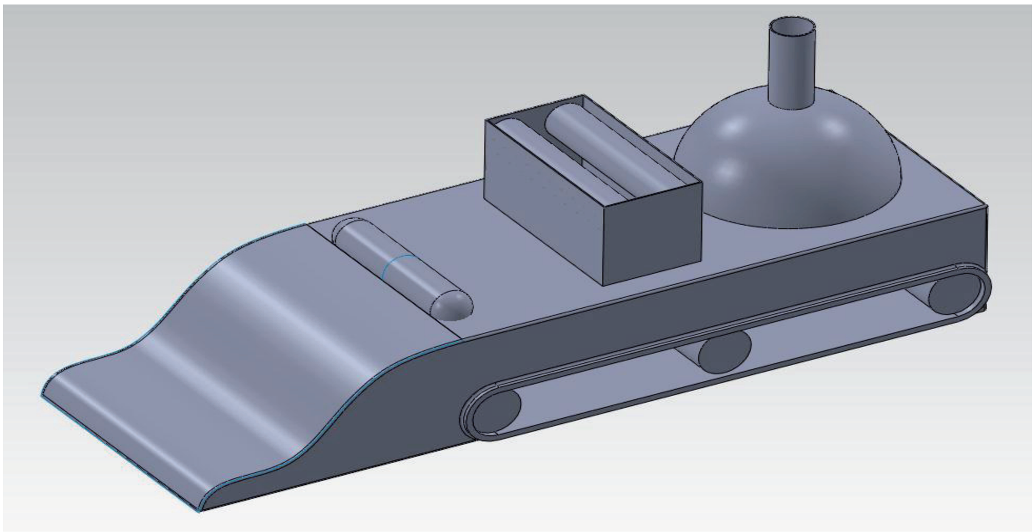


Figure 37: Representation of a collector unit

The main components of the collector unit are the crusher, pump, crawler, collection mechanism and the port for the lift system. The key dimensions and design parameters of the collector unit are as follows:

Speed while collecting nodules:	0.2 m/s
Speed while traversing without collecting:	0.5 m/s
Collecting width/maximum width:	1.0
Assumed downtime:	35 days per year

Width:	2 m
Length:	≈ 6 m
Height:	≈ 2 m (modifiable while in construction)
Total weight including all components:	5 tons (in air)

A detailed description of each of the subsystems is presented below:

- Collection Mechanism

The hydraulic lift mechanism is chosen for collection of nodules. This reduces the number of moving parts and thus the downtime in case of failure of the component. A schematic representation of the collection mechanism is shown in Figure 38.

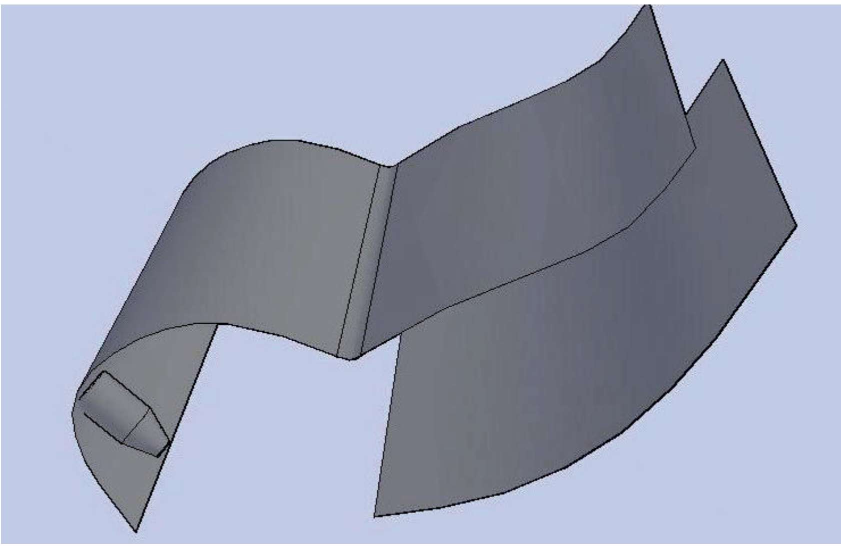


Figure 38: Representation of the hydraulic lift mechanism

A series of water nozzles are fitted along the width of the forward part of the collector, in such a way that the nodules can be lifted up through water jet action, virtually without any physical contact with the seafloor. This mechanism has been chosen as it involves minimum sediment disturbance. The forward curve shape is intended to contain the sediment plume generated while collecting nodules. Presented here is preliminary idea, the exact shape has to be designed depending on the movement characteristics of the collector in water. Experimental studies are needed in order to pick an optimal design.

This collector mechanism uses pressurised water jets through an open cycle pumping system. A pump is fitted at the end of the collection manifold to guide the nodules along the way up.

- Pump

As previously discussed, a pump is installed at the end of the collection manifold to aid the nodule movement upwards. This is a simple hydraulic pump capable of working at a high ambient pressure at a water depth of 5,000 m. Two such pumps are intended to be used to operate water nozzles in each collector.

- Crusher

This component plays an important role in defining the efficiency of a collector. If a crusher is not implemented in the design, oversized nodules will have to be rejected, as they cannot be carried along in the riser system. Furthermore, if the crusher is designed to crush all nodules, it contributes to unnecessary power wastage. Thus the rollers of the crusher have to be separated by a suitable distance, allowing only the nodules over a specified required size to be crushed. Fortunately, it is easy to crush wet nodules as they are generally porous and hence contain lots of water (ideally, about 30% w/w). A representation of a crusher is shown in Figure 39. Since 99% of the nodules in the CCZ area are estimated to be under 6 cm in diameter (Mero 1965), the crusher is designed to only be used on those 1% oversized nodules. This minimises power consumption.

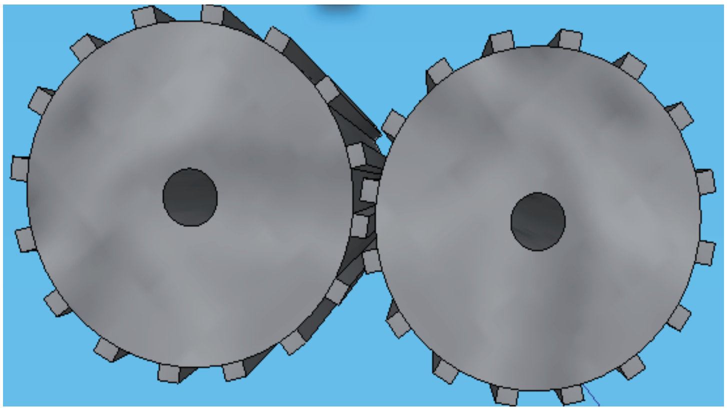


Figure 39: Representation of the crusher

- Crawler

A representation of the crawlers is provided in Figure 40. This type of movement mechanism has several inherent advantages.

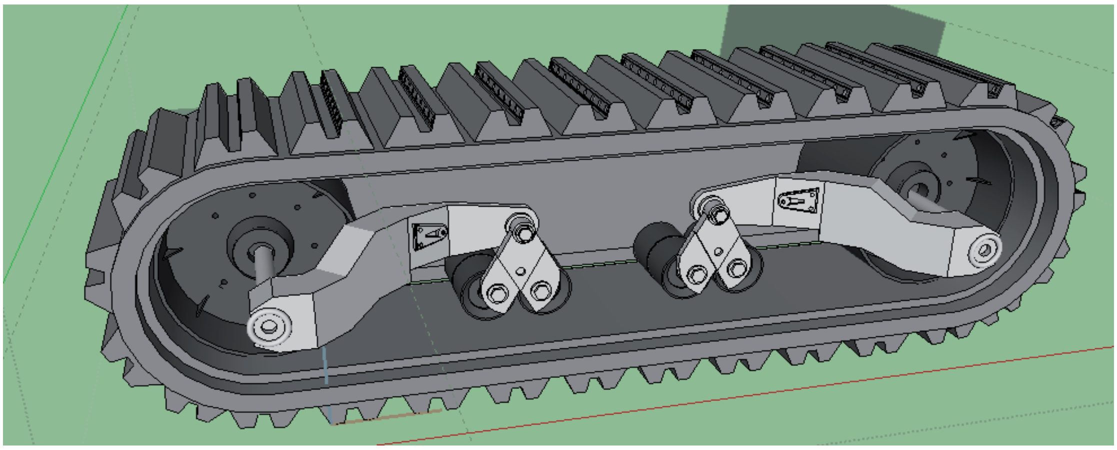


Figure 40: Representation of the crawler subsystem

The biggest advantage of this mechanism is that it provides sufficient contact area with soft seafloor soil, and hence it is able to support a heavy collector unit. It also has a lower penetration depth into seafloor soil as compared to the Archimedes screw mechanism, thus inflicting less of an environmental impact. The manoeuvrability of crawlers in soft seafloor soil is excellent. It possesses fewer stability issues while moving along seafloor slopes, during collecting nodules and when pumping out slurry via the flexible riser system.

Soil Bearing Capacity Analysis

Low movement speed and high collection width to maximum width ratio have been considered to give the collector subsystem a higher efficiency. The dimensions of the collector are governed by soil stability and manoeuvrability. The seafloor soil is characterised by a soft and sticky layer with low bearing capacity, and hence the weight and the dimensions of the collector unit have to be designed according to the soil specification. The top layer of the seafloor typically consists of an extremely soft semi-liquid sediment type with a thickness of up to 10 cm, while below the top layer there is layer of cohesive soil with almost a constant strength. Melcher (1986) and Rehorn (1994) suggested that the shear strength, s_u, ranges between 0 and 7.4 kPa with an optimal design parameter of about 2.5 kPa. The internal friction angle, ϕ, for design purpose can be approximated to be zero (Schwarz 1999). This value has been chosen for this analysis. The bearing capacity at the limit of manoeuvrability is calculated according to Terzaghi (1943), who proposed a soil bearing capacity equation for shallow footing as follows:

$$q = c \times N_c + \gamma \times D \times N_q + 0.5 \times \gamma \times B \times N_\gamma$$

where c = cohesion of soil; γ = unit weight of soil; D = depth of footing; B = width of footing; N_c, N_q, N_γ = Terzaghi's bearing capacity factors depend on soil friction angle, ϕ. For $\phi = 0^{\circ}$, $N_c = 5.7$, $N_q = 1$, and $N_\gamma = 0$.

Due to the previously introduced water jet method to lift the nodules up, the surface soil and sediments will be blown sideways and the crawler is expected to sit on the cohesive soil with a penetration depth = 0.1 m. The ground pressure exerted by the contact area of the crawler must not exceed the soil bearing capacity, to ensure the crawler's mobility regardless of the buoyant material that can potentially be added to the design. The crawler therefore has to be designed as light as possible, or with a contact area as large as possible to distribute the ground pressure. The soil bearing capacity, q, is found to be 14.85 kPa for the case of 0.1 m penetration depth. Based on the soil bearing capacity and an appropriate factor of safety, the minimum contact area of the crawler is calculated and presented in Table 8. The dimensions of the collector are then designed according to the minimum contact area for different weights of the collector. As presented earlier, the chosen dimensions of the collector unit are 6 m × 2 m × 2 m with contact area of 6 m x 1 m = 6 m^2 > 3.67 m^2 (Table 8 for weight of 5 tons in air).

Table 8: Soil bearing capacity with different collector's weight consideration

Penetration depth (m)		0		0.1		0.2	
Bearing capacity (kPa)		14.25		14.85		15.45	
Weight (tons)	**Gravity (kN)**	Minimum Contact area of crawler (m^2)					
		*1	*1.1	1	1.1	1	1.1
5	49.05	3.44	3.82	3.30	3.67	3.17	3.53
6	58.86	4.13	4.59	3.96	4.40	3.81	4.23
7	68.67	4.82	5.35	4.62	5.14	4.44	4.94
8	78.48	5.51	6.12	5.28	5.87	5.08	5.64
9	88.29	6.20	6.88	5.95	6.61	5.71	6.35
10	98.10	6.88	7.65	6.61	7.34	6.35	7.06

*assuming no factor of safety and then a factor of safety of additional 10%

Assuming that the collector is made of titanium as a prototype, the weight of the collector in water can be calculated as follows

$$W_{submerged} = W_{air} - W_{buoyancy}$$

Where, $W_{submerged}$ = the weight of the collector in water, W_{air} = the weight of the collector in air and $W_{buoyancy}$ = the buoyancy force from the submersion of the collector.

The average static soil pressure, σ of the collector in water comes to

$$\sigma = \frac{W_{submerged}}{0.5 \times 2 \times 6} = 6.31\text{kPa} < 14.85\text{ kPa}$$

The denominator here represents the contact area. The width of the collector is 2 m and it is assumed to have two tracks of width of 0.5 m each, extending all along its length. As the contact pressure of the collector on the soil is smaller than the soil bearing capacity, it is safe to operate the collector with the chosen dimensions and weight in this soil condition.

Having determined suitable values for different parameters related to the collector, key computations for the production rate of the system are presented as follows:

Velocity of the collector, V_C	$= 0.2\text{ m/s}$
Width of the collector, b	$= 2\text{ m}$
Area sweep rate, A_S	$= V_c \times b = 0.4\text{ m}^2/\text{s}$
Average nodules abundance in CCZ, α	$= 10\text{ kg/m}^2$
Collection efficiency, η_c	$= 0.8$
Acceptance ratio, α_r	$= \alpha \times \eta_c = 8\text{ kg/m}^2$
Wet nodules pick up rate per collector, Δ_{WC}	$= A_s \times \alpha_r = 3.2\text{ kg/s}$
	$= \dfrac{3.2 \times 3{,}600 \times 24 \times 330}{1{,}000}$
	$\approx 91{,}300\text{ tons/year}$
Production rate for a three-collector system, Δ_W	$= 91{,}300 \times 3$
	$\approx 274{,}000\text{ tons/year}$

This represents the productivity in terms of wet nodules. Before processing, these have to be dewatered and then dried. Assuming suitable reference values for concerned efficiencies, which account for loss in mass, we get the total productivity in terms of dry tons, as follows:

Dewatering efficiency, η_{dw}	$= 0.98$
Drying efficiency, η_{dr}	$= 0.67$

Thus, system production rate in terms of dry tons, Δ $= \Delta_W \times \eta_{dw} \times \eta_{dr}$

$= 274{,}000 \times 0.98 \times 0.67$

$\approx 180{,}000$ dry t/y/system

A production rate of 0.5 M dry tons of nodules per year is targeted, which is smaller compared to the common benchmark of 1.5 M dry tons. The main reason for a small production scale is to avoid oversupplying refined metals to the instability-prone metal world market and breaking the metal prices, and also to reduce initial capital cost (Martino and Parson 2012). From the production rate computation shown earlier, one system of three collectors can yield about 180,000 dry tons per year, so to achieve the targeted rate of 500,000 dry tons per year, we need three systems of three collectors each.

Having determined the production rate of a system per year, the frequency of movement of the PSV, required to achieve the target production rate, must be estimated. Assuming the PSV and all the associated mining subsystems have to be moved once the nodules at a particular site are completely recovered, the frequency of such a movement can be obtained as follows.

Length of the flexible riser, l $\approx 1{,}000$ m

Height of the black box from the seabed, h ≈ 200 m

Hovering radius for each collector, r $= \sqrt{(l^2 - h^2)}$

≈ 980 m

Area swept by the collectors without ship movement, A $= \pi r^2$

$\approx 3{,}016{,}000$ m^2

Area sweep rate, A_S $= 0.4$ m^2/s

There are 3 collectors per system sweeping the seafloor continuously at the above-mentioned rate.

Thus, time interval between each movements, T $= A/(A_s \times 3)$

$$= \frac{3{,}016{,}000}{(0.4 \times 3) \times (3{,}600 \times 24)}$$

≈ 30 days

The whole system has to be moved 2 km approximately every 30 days. Two approaches for towing the PSV and all the subsystems are presented:

- Approach 1: The PSV is towed 2 km every 30 days, and the rest of the time it can be positioned stationary with the aid of a dynamic positioning (DP) system (Figure 41). When the PSV is towed, no mining activity takes place. However, in the authors' view, towing the whole system at such velocity in a constrained time is unlikely to be feasible.

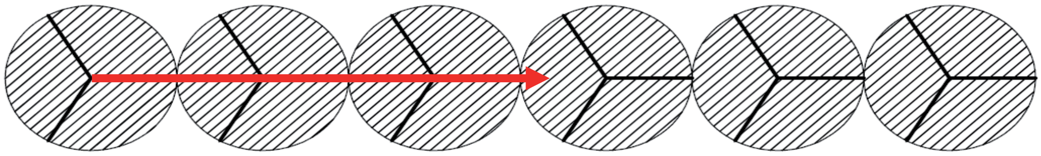


Figure 41: Representation of the approach 1

- Approach 2: The PSV is towed at a much slower velocity, almost continuously. In this case, the mining operation can be run continuously and the PSV is dragged infinitesimally slowly along with the whole system ahead in the mining area (Figure 42).

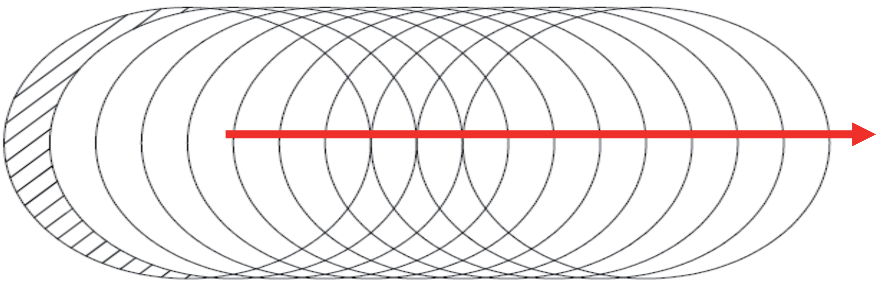


Figure 42: Representation of the approach 2

5.1.2 Riser

Following the production rate computation presented earlier, the mass flow rate of slurry can be obtained to determine the riser dimensions and the pump's capacity. Figure 43 shows the mass flow rates for the whole system.

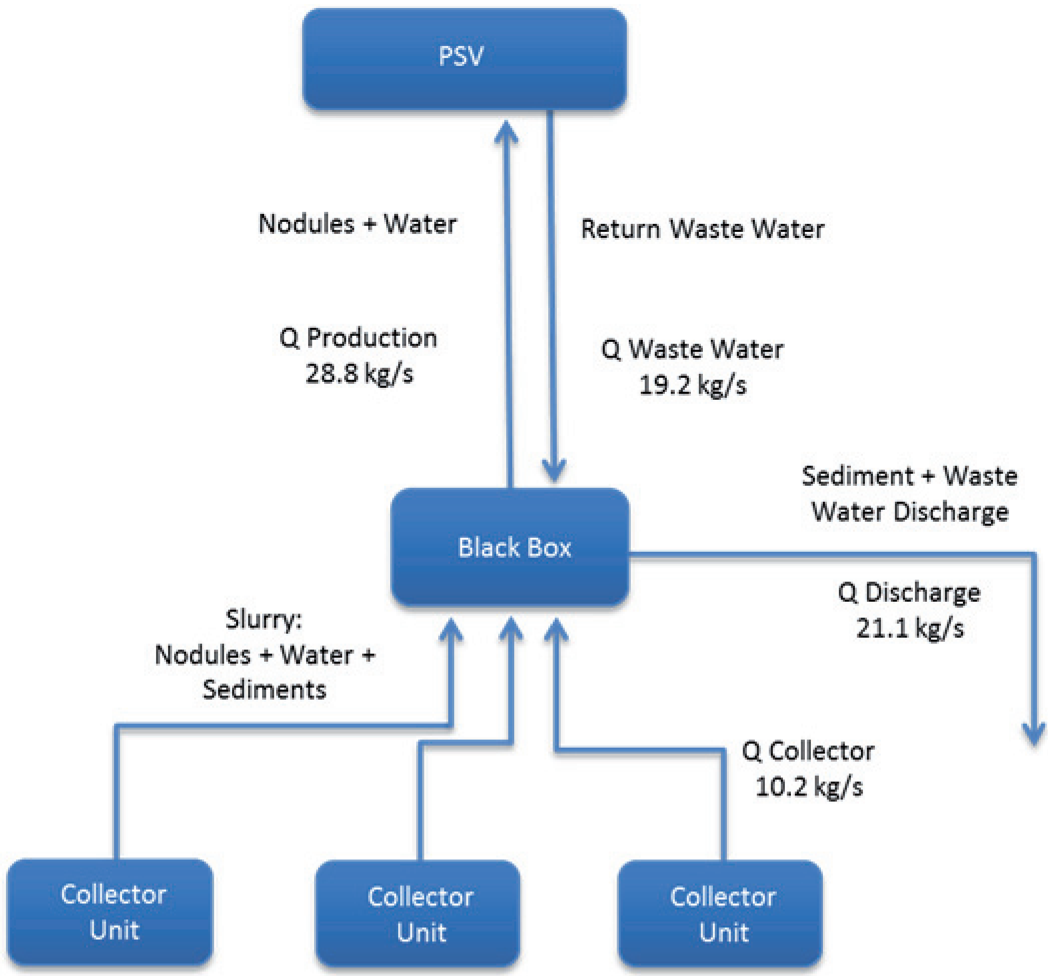


Figure 43: Mass flow rate of the whole single production system

Several key assumptions had to be made in estimating the mass flow rate of the system and are listed as follows, together with some of the key design parameters:

Mass flow rate of collected nodules (a)	= 3.2 kg/s
Assumed volumetric concentration of nodules in slurry	= 20% v/v (Herrouin 1991)
Specific gravity of nodules	= 2 tons/m^3 (Herrouin 1991)

Mass concentration of nodules in slurry	= 33.3% w/w
Mass flow rate of collected water (b)	= 6.4 kg/s
Assumed sediment to nodule weight ratio	= 4% (Herrouin 1991)
Associated mass flow rate of collected sediments (c)	= 0.128 kg/s
Assumed concentration of sediments with water	= 20% w/w (Khadge and Valsangkar 2008)
Mass flow rate of water associated with sediments (d)	= 0.512 kg/s
Total mass flow rate from each collector (a + b + c + d)	= 10.2 kg/s (Q Collector)
Total mass flow rate to black box	$= 10.2 \times 3 = 30.6$ kg/s
Total mass flow from black box to PSV (a + b)	$= 9.6 \times 3 = 28.8$ kg/s (Q Production)
Mass flow rate of return waste water to black box	= 19.2 kg/s (Q Waste Water)
Mass flow rate of sediments and waste water discharge	= 21.1 kg/s (Q Discharge)

From the flowchart in Figure 43 it can be clearly identified that the whole riser system can be deconstructed into the following major subsystems:

- Subsea flexible riser
- Main rigid riser
- Return waste water riser
- Waste discharge riser

Two different types of riser are used to transport the slurry vertically to the PSV. From each collector unit to the black box, an S-shaped subsea flexible riser is used to allow the collector more flexibility in manoeuvring along the seafloor while transferring the collected nodules. From the black box to the PSV, a main rigid riser is used instead. A rigid riser system needs to be incorporated to support the BB a few hundred metres above the seafloor, while at the same time provides a medium for slurry transfer. A rigid riser type is also used for the return wastewater and waste discharge riser, to transport wastewater from the PSV to the black box and to transport sediments and wastewater for in-situ discharge, respectively.

Both the main and subsea riser systems consist of two individual risers, one to support an umbilical carrying electromechanical optical cable, and the other to provide a platform for slurry transfer. All the riser designs are based on the existing technology used in the oil and gas industries.

Subsea Flexible Riser

The subsea flexible riser has a length of about 1,000 m spanning from the bottom of the black box to a port on the collector. It provides a medium for the transfer of slurry in the form of nodules, water and sediments collected during recovery operation.

To keep the subsea flexible riser from dragging on the seafloor and to provide greater flexibility in manoeuvring, synthetic buoyancy modules are put in place from the end of the port of the collector at about 2/3 of the entire length. The shape of the flexible riser eventually forms an S-shaped configuration. This configuration is similar to the dynamic subsea flow systems extensively used to connect subsea wellhead to floating bodies (e.g. FPSO) in offshore industry. According to Schwarz (1999), the inner diameter of the subsea flexible riser has to be at least three times the largest nodule size after going through a crusher system in the collector. Thus, with the largest nodule size of 60 mm, the inner diameter is designed to be 180 mm.

The mass flow rate of slurry going through the subsea flexible riser based on the production rate of a collector is found to be 10.2 kg/s. A pump with a capacity greater than the calculated mass flow rate is needed to drive the slurry transfer from the collector to the black box. A simple hydraulic pump is installed in each collector, with a slurry flow rate capacity of 15 kg/s.

Main Rigid Riser

The main rigid riser is about 4,800 m long and connects the PSV to the black box. Its main purpose is to transport slurry of nodules and water upwards for on-board pre-processing. Umbilicals are attached together with the main rigid riser for power supply and control mechanism. It is mounted together with the return wastewater riser.

The main rigid riser dimension is considerably bigger than the subsea flexible riser, as it is expected to transfer approximately three times the mass flow rate of each flexible riser. As a consequence, bigger pumps are needed. The inner diameter of the main rigid riser is designed to be 315 mm.

The mass flow rate of slurry going through the main rigid riser is 28.8 kg/s. Pumps with a similar capacity to the one used in the subsea flexible riser but with a much bigger power requirement can be deployed in series to further enhance the total driving capacity.

Return Waste Water Riser

The return wastewater riser transports wastewater from on-board pre-processing back to the black box for nodule – sediment separation, as well as in-situ discharge. The amount of wastewater produced is therefore estimated based on the amount of water content in the production slurry carried by the main rigid riser. The mass flow rate of the wastewater is found to be 19.2 kg/s. It has the same length as the main rigid riser.

The inner diameter of the return wastewater riser is 100 mm. The inner diameter of all the risers is designed in such a way that the expected flow velocity is 3 m/s. The same is also applied in determining the inner diameter of the waste discharge riser. The water density is taken to be 1,000 kg/m³.

Waste Discharge Riser

The waste discharge riser, used to dispose of sediments and muddy water, should ideally have a length, which allows the waste to be discharged at a suitable distance, so as not to affect the mining operation (see Figure 36). This decision has to be made in situ. The waste discharge riser is positioned away from the recovery area to minimise interference between the recovery operation, the discharge sediments and the associated plumes. The estimated mass flow rate of the waste is 21.1 kg/s.

The inner diameter of the waste discharge riser is 100 mm, based on a 3 m/s expected flow velocity. The average density of the slurry mixture is taken to be 1,050 kg/m³. Two pumps of similar capacity, with the one adopted for the subsea flexible riser will be used. Both pumps are located inside the black box.

5.1.3 Black Box

The recovered nodules need to be separated from clay, sediments and muddy water before drying them for further metallurgical processing. A proper and reliable waste treatment system is therefore important in order to minimise, as far as is possible, the impact and footprint on the marine environment.

Two separate waste treatment systems are proposed: the black box and on-board pre-processing. The black box waste treatment is performed near the seafloor (submersible), while the on-board pre-processing takes place on the PSV. Below we elaborate further on the details of black box design.

The concept of the black box is an innovative idea that allows in-situ waste discharge close to the mining operational depth and optimises the cycle of the waste treatment system. The conventional method is to pump all kinds of waste onto the water surface, pre-process them on board and send them back as discharge at the surface or at a certain water depth. As shown in the proposed engineering system diagram, the black box is mounted directly below the rigid riser at 200 m, right above the seafloor (for a typical 5,000 m water depth operation).

The in-situ operation performed in a black box is a nodule – mud separation process in slurry flow. The mud is typically a mixture of clays and sediments collected together with nodules during the mining operation. The conventional way is to discharge the muds back at surface level, which raises concerns about the consequences for the environment. For more discussion on the impacts from conventional waste discharge, refer to Section 4. In-situ waste discharge permits a better settling of sediments and clays with a localised plume effect, thus significantly reducing the radius of influence. It is the objective of this study - to minimise the impact on the environment – that leads to this novel black box concept design.

Centrifugal pumps are used to perform nodule – mud separation, which work based on the principal of centrifugal force, which is able to separate different weighted solids from fluid. Lighter solids (sediments and clays) tend to settle near the centre of rotation, while heavier solids (nodules) are held bonded against the wall of the rotating drum due to the rotational action. Two separate pipes and pumps are then used to transport a mixture of the cleaned nodules and water and another mixture of muddy water (sediments and clays). This concept of separation was developed by IKS in 1999 (Schwarz 1999). Figure 44 presents a flow chart schematic for the black box:

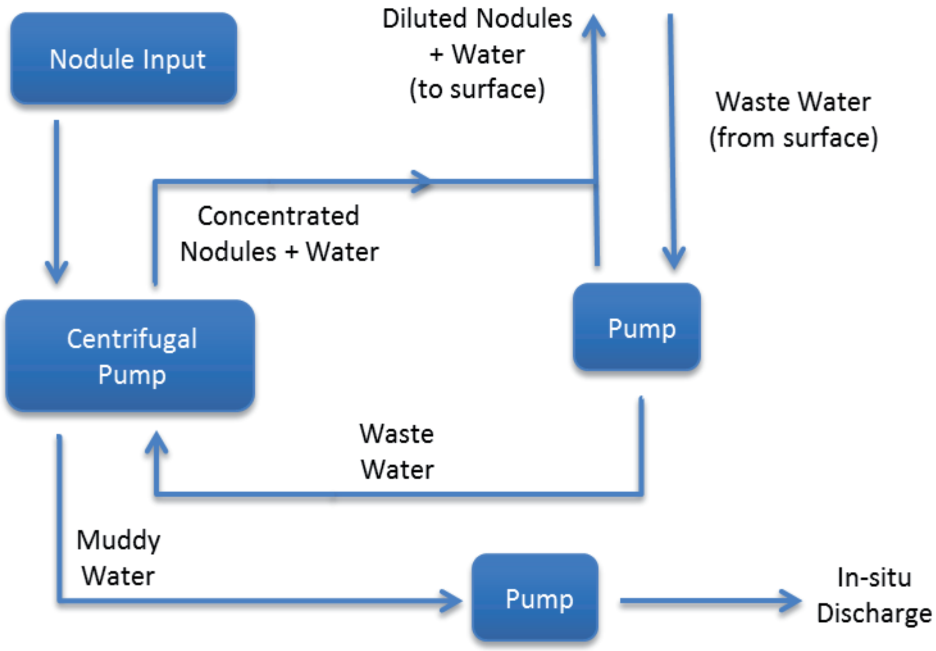


Figure 44: Flow chart of black box. (Centrifugal Pump from Schwarz 1999)

For each centrifugal pump, there are two inlets: a nodule input and one for recycled wastewater (from the surface), and two outlets: for muddy water and for the concentrated mixture of nodules and water. After the nodule – mud separation process, a discharge pump for in-situ discharge, which contains a mixture of sediments, clay and water, will suck the muddy water out. The separated product is a highly concentrated mixture of nodules and water, which needs to be diluted for further vertical transport to the surface by the riser system. Thus, to control the final slurry concentration, recycled wastewater (from the surface) is directed and mixed into the concentrated mixture.

A closed loop of wastewater flow is designed so that it runs between the black box and the on-board pre-processing: waste water discharged after on-board pre-processing is sent down to the BB to clean muds and sediments from the nodules. A portion of wastewater will be discharged directly from the BB, while the remaining portion will be pumped up to the surface together with nodules as slurry. This portion will form part of the subsequent cycle of discharged wastewater after on-board pre-processing. This utilisation of wastewater is another step of improvement to reduce unnecessary amount of wastewater discharge to the marine environment.

Following the mass flow rate calculation shown earlier, the mass flow rate for the waste discharge can be further broken down into that of sediment and wastewater:

Mass flow rate of sediments and waste water discharge	= 21.1 kg/s (Q Discharge)
Mass flow rate of sediments handled and discharged	= 0.384 kg/s
Mass flow rate of waste water handled and discharged	= 20.7 kg/s
Amount of sediment handled by black box every day	= 33.2 tons
Amount of waste water handled by black box every day	= 1,792 tons

It is important to note that the mass concentration of sediments in the wastewater has now decreased to less than 2% (w/w) from the initial intake of 20% (w/w) collected together with nodules and water. The collected sediments are actually further diluted in the BB to help proper resettlement by minimising large plume effects due to the sudden release of huge amounts of suspended sediments in water. This requires a large amount of wastewater to help the dilution process, which is about 1,800 tons per day.

To manage this quantity of waste discharge each day, a robust and reliable pump system with a high capacity is required. Two centrifugal pumps of 15 kg/s capacity each are used to clean nodules from sediments, and two hydraulic pumps of the same capacity are used to pump waste for discharge purpose.

In summary, the black box performs two basic and integrated functions. Firstly, it provides a platform for in-situ waste treatment and discharge; secondly, it controls the end slurry concentration for vertical transport to the surface. Thanks to the in-situ nodule-clay separation, the BB offers potential power consumption reduction. The power required previously to bring the clay and the sediment to the surface or to dump them back in the water is no longer needed as everything is performed inside the BB. Furthermore, in achieving in-situ waste discharge, the black box permits the utilisation of wastewater. Together with in-situ waste discharge, this helps to limit and reduce the negative impacts on the local marine environment. The innovative idea of the black box is definitely a big leap towards an environmentally friendly solution.

5.2 Other Components

This section provides details on other more conventional components, which are not the core part of the proposed innovative engineering system, but are still important to consider.

5.2.1 Production Support Vessel

The PSV a.k.a. mother ship will be positioned on location for the entire duration of the mining operation. It supports all mining recovery, waste treatment, dewatering and offshore loading activities while providing a source of power supply on board. The same concept for the mining system will be applied to the PSV as well, i.e. to modularise all equipment and facilities to reduce ship interference and time required for commissioning.

To maintain the ship stability and minimise drifting action due to waves, currents and wind, DP will be used for station keeping of the vessel. Four sets of two azimuth thrusters are used: two sets at the forward port and starboard, the remaining two sets at the aft port and starboard.

The vessel will be equipped with a large clear aft deck as a platform for mining spread. It will be fitted with a large moon pool for riser deployment and recovery. In addition, there will be three production storage tanks:

- The slurry main tank, which is connected to the riser system to screen and process the instantaneous variation in slurry density prior to its transferral into the dewatering system;
- A storage tank to contain dewatered nodules ready for metallurgy processing with a tank capacity of a few days production.

In general, the PSV will be fairly similar to the offshore type of floating vessels used in the oil and gas industries.

5.2.2 Ore Shuttle Barge

More details on the shuttle barges used to transport dried nodules to land for metallurgical processing is described in paragraph 6.2.

5.2.3 On-board Pre-processing

Nodules brought up to the PSV need to be pre-processed before being offloaded to shuttle barges and shipped for on-shore metallurgical processing. Two pre-processing activities have to be performed: dewatering and drying.

The dewatering of nodules can be performed in a dewatering plant. The main functions of this module are to dewater nodules, to provide sampling for grade control, to return excess water to the wastewater riser, and to provide a transitional platform for nodule-drying processes later on.

Dewatered nodules need to undergo a drying process as the final pre-processing stage. The aim is to bring the moisture content below the TML and also to reduce their weight contribution from water content, thus increasing the net amount of nodules that can be transported in a given size of the chosen shuttle barge. The TML defines the highest moisture content of a bulk solid granular ore material for safe transport (Jankowski and Heymann 2010) Various methods can be applied in the dewatering plant, such as vibrating screens, a centrifugal pump, hydro-cyclone, etc.

5.2.4 Metallurgical Processing

Morgan et al. (1999) presented the primary difference between manganese nodules and most of the land based metals: manganese nodules are oxides, and not sulphides. Thus, there are differences in processing techniques required for manganese nodules as compared to the conventional techniques for land-based metals. Laterites are one of the land-based ores, which have the closest similarity with nodules, and hence the proposed processing methods for nodules in the past have been based on modifications of techniques previously developed to process laterites (Morgan et al. 1999).

The key problem in processing nodules is how to effectively dissolve or reduce the manganese dioxide to release the economical amount of cobalt, nickel and copper in the process. Two techniques are described in short: hydrometallurgical and biohydrometallurgical processes.

The hydrometallurgical process uses acid or ammoniacal as a medium for leaching. It has gained popularity due to relatively low cost and energy requirements. Unfortunately, a high concentration of hydrochloric acid is needed to obtain economic recovery (> 90%) of Co, Ni and Cu, and this high acid consumption leads to problems of disposal. There are two ways to improve both the acid and ammoniacal leaching process: either by increasing pressure and/or temperature, or by adding some organic and inorganic compound to facilitate the metal recovery process. Many more techniques based on these two improvement methods also exist (Mukherjee et al. 2004).

Another option is the biohydrometallurgical process, even though it is commonly used for copper, gold and uranium recovery. The idea is to introduce organisms and/or microbes to process bio-reduction of manganese dioxide (Mukherjee et al. 2004).

In this feasibility study, we do not consider in detail the processing techniques used for recovery of our nodules. However, the acid leaching method has been chosen in the Section 6.1 for computational and illustrational purposes.

5.3 Power Supply

Having presented and discussed an innovative concept design and its main components, the next logical step is to provide detailed information regarding the power supply needed to drive the whole system. Here the power consumption for collectors, the riser, the black box, and also for the PSV is described. A notable point is that the PSV provides continuous power supply to the whole system from the surface.

5.3.1 Power for Collector Unit

As the development of collectors is still in a conceptual and experimental stage, there is no information available on the exact power consumption of a full-scale collector unit. However, as the chosen collector unit in the proposed engineering system is considerably smaller than the conventional unit, we can obtain the order of magnitude by looking into an experimental collector unit, which has roughly the same configuration/dimensions as the one suggested.

One experimental collector unit, which has the closest similarity with the proposed unit is MineRo, recently developed by Korea (KORDI) (Hong et al. 2010) and represented in Figure 45. The side-by-side comparison between MineRo and the proposed unit is provided in Table 9.

Table 9: Side-by-side comparison between proposed unit and MineRo

Component	Proposed Unit	MineRo
Size (L × W × H)	6 m × 2 m × 2 m	5 m × 4 m × 3 m
Mining Capacity (wet nodules)	3.2 kg/s	2.39 kg/s
Contact Pressure (average)	~ 4 kPa	5.6 kPa
Collector Type	hydraulic	hybrid

The only difference is the type of collector: MineRo is a hybrid type, while the unit proposed here, is a purely hydraulic type. It is unclear yet which type of collector will consume more power, however, we believe the order of magnitude will not be far different. The power consumption reported for MineRo is 3.3 kVA, 135 kW (hydraulic), and 15 kW (electric). Assuming the power consumption is approximately the same, the total power needed for 3 collectors in operation per system is 405 kW (hydraulic), and 45 kW (electric).

Figure 45: MineRo collector unit (Hong et al. 2010)

5.3.2 Power for Riser System

There is no comprehensive information available about power consumption of a 5,000 m long riser system, as the development of nodule mining is still in its conceptual and experimental stage. However, by rough approximation it is possible to evaluate the scale of power consumption for the proposed riser system.

The power consumption can be estimated from the following relationship between power, operational water depth, slurry flow rate and pump efficiency, as follows:

$$\mathrm{HP} = \frac{Q \times h}{76 \times \eta_{pump}}$$

where: HP = Power consumption needed in terms of horse power

Q = Production slurry flow rate in litre/s

η_{pump} = Efficiency of pump, taken as 0.6

h = Operational water depth, expressed as total head in metres

In terms of the main rigid riser, which extends for about 5,000 m, for a production slurry rate of 28.8 kg/s, with a density of slurry of about 1,222 kg/m³, the total power requirement is about 3 MW. Two sets of pump systems will be used in the main rigid riser to deliver pump capacity greater than the production slurry rate, and the total power requirement is about 6 MW. Similarly for the return wastewater riser (mass flow rate of 19.2 kg/s), the total power requirement is about 1.7 MW. Two sets of pumps will be used, with a total power requirement of about 3.5 MW. For both the subsea flexible riser and waste discharge riser, assuming that the differential head in which the pumps need to work on is about 300 m, the power requirement for such pumps is 50 kW for the subsea flexible riser and 130 kW for the waste discharge riser. Two sets of pumps will be used to deliver pump capacity greater than the required slurry rate. Thus, the power consumption of 100 kW is expected for pumps in the subsea flexible riser for each collector and 260 kW is required for pumps in the waste discharge riser. Furthermore, there will be an additional two pumps of 100 kW installed in each collector to operate water nozzles for hydraulic lift, and two additional centrifugal pumps of 100 kW in the black box to clean sediments from the nodules.

In total, there are 4 pumps totalling 200 kW in each collector for the nodule transport and hydraulic lift, 2 pumps totalling 200 kW in the black box for nodule-sediment separation, 2 pumps totalling 260 kW in the black box for waste discharge, 2 pumps totalling 3.5 MW for the waste water return line, and 2 pumps of 6 MW for the production line. For a single system composed of three collectors, a complete riser system and a black box, the total power requirement for the riser is approximately 10 MW.

5.3.3 Power for Black Box

Ideally, no extra power is needed to drive the operations of the black box, other than for the centrifugal pump to perform the nodule – sediment separation process, and for a hydraulic pump to discharge wastewater and sediments in-situ.

It is possible to evaluate the amount of power saved by utilising the black box to separate the sediments and the nodules at the bottom instead of transporting all of them together to the PSV. From Equation "Power consumption needed in terms of horse power", it is shown that the power requirement is proportional to the amount of production slurry flow rate. Thus, reducing the unnecessary flow of sediments and the associated water in the production slurry will save power required to operate the riser system.

From Figure 43 of the mass flow rate of the entire system, one can easily deduce that the mass flow rate of sediments is 0.384 kg/s and that of the associated water is 1.536 kg/s. Without the black box, the production slurry flow rate will be 30.6 kg/s instead of 28.8 kg/s, having to account for the sediments and the associated water. This mass flow rate difference of 1.9 kg/s leads to a power saving of about 200 kW per system, assuming the same set of parameters used. For the proposed three multiple systems, the total power saving amounts to 600 kW. This results in a total power reduction of 1.2 % in the case of a small production scale of 0.5 M dry tons of nodules per year. For a bigger production scale of nodules recovery, the amount of power saving will increase consequently.

5.3.4 Power for Production Support Vessel

Reference has been made to the case study report by Solwara 1 (Hong et al. 2010) about the typical electrical power demand for the PSV in operational condition. PSV provides a platform for on-board power generation, which are used to support the following operational duties:

- Production / mining operation
- DP thrusters
- Ship services
- Auxiliary ship systems

For a 170 × 40 m DP ship with a total of 8 thrusters, electrical power demand for normal operational condition requires 450 kW for each thruster, and 1,100 kW for ship services (Hong et al. 2010). Thus, the total power demand from the PSV is approximately 4.7 MW.

5.3.5 Total Power Requirement

The total power requirement for a single system of three collectors is approximately 11.5 MW for the collectors and the riser system plus 4.7 MW for the PSV, which yields 16.2 MW per system. For the proposed three multiple systems of three collectors each, the total power requirement is about 50 MW.

The power source on-board is from diesel generators placed on each PSV, and each of them is expected to run continuously by burning fuel throughout the recovery operation.

6 Risk Assessment

This chapter discusses a commercial viability analysis in relation to the system previously introduced, then provides details on logistic and economic analysis, and finally presents the environmental impact and safety assessments.

6.1 Commercial Viability

A production of 0.5 million tons of dry nodules per year is set to be the target of this feasibility study. While a bigger production scale might sound favourable in terms of higher revenue, the effect of oversupplying refined metals such as cobalt and nickel would consequently bring the prices of these metals down, as their market occupancy is small. Martino and Parson (2012) highlighted a possible solution to prevent a sudden surplus in the supply of cobalt and nickel and to reduce excessive initial capital costs by targeting a smaller production scale, such as 0.5 million tons of dry nodules per year as chosen in this study. In this case, produced refined metals can be expected to suit market supply and demand.

There have been numerous studies conducted on the economic feasibility of manganese nodules, such as by Yamazaki (2008) and Soreide et al. (2001). Table 14 compiles four different economic feasibility studies and summarises the key components such as: production scale, capital and operating costs. To allow for a fair comparison between the different studies, each of their total capital and operating costs have been made equivalent to the costs of 2010 by using the US producer price index, as provided by Martino and Parson (2012). Averaging the capital and operating costs weighted on production scale of all the four studies will provide an idea as to the scale of capital and operating costs needed for a production scale of a million dry nodules per year. From the four studies, it is found that the average capital cost is approximately $1,000 M/1 M dry nodules, and the average operating cost (per year) is about $220 M/1 M dry nodules. These two figures have been used as reference values to approximate the total cost of the targeted production scale of 0.5 million dry nodules. The authors acknowledge that this is a crude approximation, as details of each component have not been considered. Furthermore, the cost of the particular mining and processing method might differ from the averaged value. However, this approximation gives some idea about the economic feasibility on a broad scale. Assuming all the metal contents of a manganese nodule can be of commercial interest, Table 10 illustrates the gross revenue from the production of 0.5 million dry nodules, with the average metal prices from 2010 – 2011 taken as reference. The gross revenue is recorded to be about $459 M, where the major source of revenue of more than 80% comes from manganese, nickel, copper, and cobalt.

This illustrates the reason why for economic feasibility studies in the past, only these four metals are considered for commercial interest.

Table 10: Gross production revenue of all metal contents

Metals	**% of Nodules**	**Total Production / Year (Tons)**	**Metal Prices* ($ / kg)**	**Gross Revenue (M $ / Year)**
Manganese	24%	116,640	1.32	153.96
Iron	10%	48,600	0.48	23.33
Aluminium	3.10%	15,066	2.45	36.91
Nickel	**1.44%**	**7,000**	**23**	**161**
Copper	**1.12%**	**5,443**	**8.3**	**45.18**
Cobalt	**0.20%**	**972**	**39.2**	**38.10**
Zinc	0.05%	243	2.35	0.57
Total	39.91%	193964		459.05

*Metal Prices at 2010 – 2011

In the recent studies however, the contribution of manganese to the revenue has been dropped due to its much smaller market size. With a small market size, oversupplying manganese will affect the stability of the manganese price in world metal market. Hence, the recent studies only consider cobalt, nickel and copper. In this study, we opt for the same approach for the worst case scenario. It is worth noting that other than the three aforementioned metals, manganese nodules also contain other minerals such as iron, lead and a few REEs. Considering the best case scenario, every single one of them would contribute to the production revenue.

Technical Setting

The same efficiency rates, which were used in calculating the production, have been adopted here in the present economic feasibility study. Additional efficiency, called leaching efficiency, is introduced for metallurgical processing. This efficiency is assumed to be 0.90 for cobalt, 0.97 for nickel and 0.94 for copper (Yamazaki 2008). In the case of this study, cobalt is chosen to be the target mineral (benchmark) as it has the smallest market among the three minerals under consideration (Soreide et al. 2001). However, the assumed optimal cobalt production scale of 2,500 tons per year could not be achieved in our case, as the production scale of this study is much smaller in comparison to the earlier ones. The quantity of all minerals extracted can be obtained by multiplying their respective concentrations with the dry tonnes produced after processing.

The entire development period is assumed to be 20 years. The exact location for this study is the Western COMRA area from which the dry nodules have to be transported to China (approximately 10,000 km). The Chinese tax for corporate profit is assumed to be 20%.

A flow chart of manganese nodule development is shown in Figure 46.

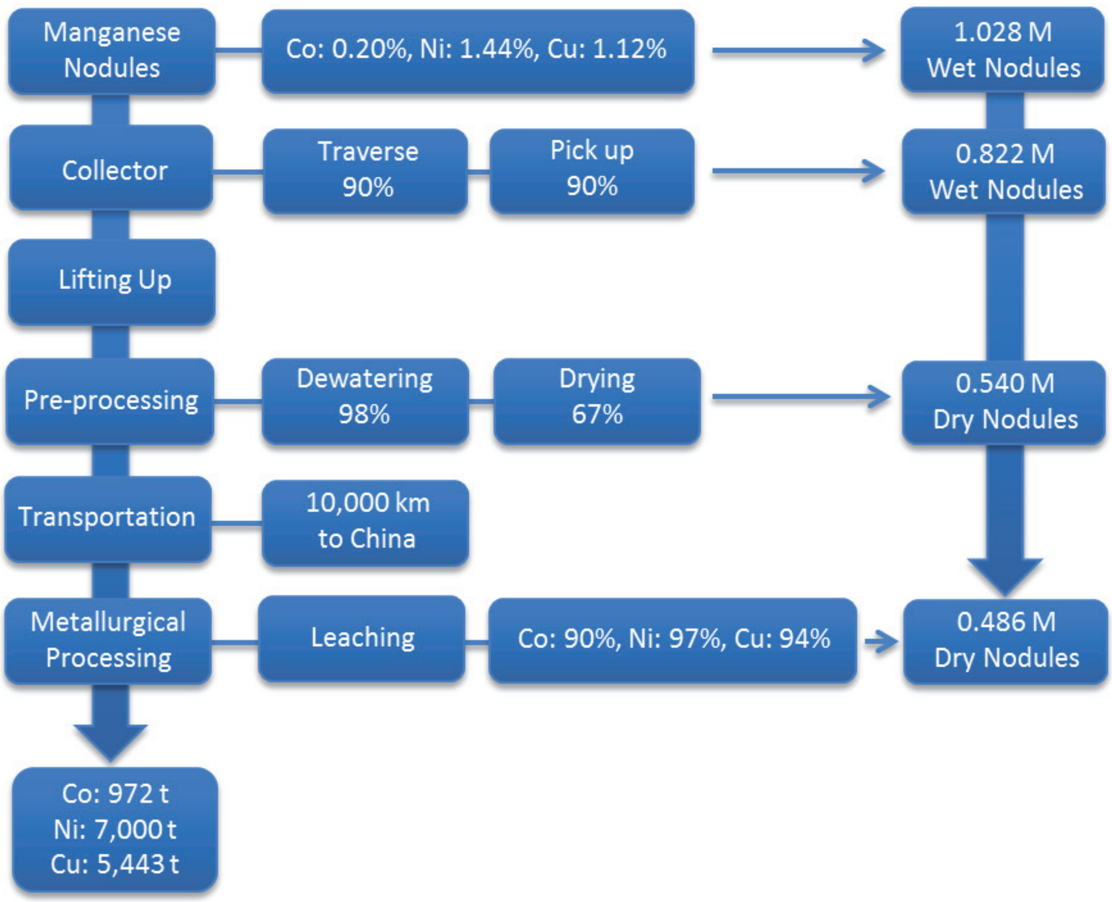


Figure 46: Flow chart of manganese nodule development

The 2010 prices for the three metals of commercial interest are used to compute the production revenue. The cost and revenue for manganese nodule production is presented in Table 11 and Table 12 respectively. The cost calculations are based on production of ~0.6 M tons of dry nodules before processing (instead of 0.540 M tons, to get an overestimate in terms of costs, which will be a conservative approach). An additional 10% is added to the total costs, to be on a conservative side, to yield $660 M for capital cost and $145 M for the operating cost per year.

Table 11: Manganese nodule production cost

Components	Mining (wet)	Transportation (dry)	Processing (dry)
Production (t/y)	0.822 M	0.540 M	0.486 M
Capital Cost (M $)	198	132	330
Capital Cost Ratio	30%	20%	50%
Operating Cost (M $)	53.65	36.25	55.10
Operating Cost Ratio	37%	25%	38%
Metal	**Price**		**Production**
Co	$ 45,496/t		972 t/y
Ni	$ 27,016/t		7,000 t/y
Cu	$ 7,788/t		5,443 t/y
Total Capital Cost (M $)	660		
Total Operating Cost (M $)	145/year		

Table 12: Manganese nodule production revenue

Price ($/ton)	Value
Cobalt	45,496
Nickel	27,016
Copper	7,788
Revenue per year (M $)	
Cobalt	44.22
Nickel	189.11
Copper	42.39
Total Revenue per year (M $)	275.72

Three measures of economic return for an investment are presented: payback period, net present value (NPV), and internal rate of return (IRR). The payback period is the time needed for an investment to yield exactly the same amount which had been incurred as initial expenditure (to break even on capital cost). The shorter the payback period the better the investment. NPV is a method of comparing the capital cost and the subsequent profit earned in the future, discounted to present terms. A positive figure of NPV indicates an excess amount of cash flow (profit) in present value terms. A discount rate of 8% is chosen in this study, as suggested by Yamazaki (2008).

IRR is the interest rate for NPV to be zero. Higher IRR reflects higher profitability of an investment. A benchmark rate for IRR is called minimum acceptable rate of return (MARR), or hurdle rate. An investment project is attractive when its IRR is higher than the hurdle rate. Usually the MARR is set to be 12%, and a typical return for the S&P 500 is between 8% – 11% annually. The S&P 500, or the Standard & Poor's 500, is a stock market index based on the common stock prices of 500 top publicly traded American companies, as determined by S&P.

The evaluation of the economic feasibility is summarised in Table 13. The payback period of the project is 10 years, the NPV is $361 M, and the IRR is 14.75%.

Table 13: Manganese nodule economic feasibility

Components	**Value**
Capital Cost (M $)	660
Operating Cost/year (M $)	145
Revenue (M $)	275
Annual Profit (M $)	130
Profit after Income Tax (M $)	104
Payback Period (year)	10
NPV at 8% Discount Rate (M $)	361
IRR	14.75%

This rough economic feasibility study for small production scale of 0.5 million dry nodules reveals that such a production scale is still a profitable investment, and that the adverse effect of oversupplying refined metals on the world market can be kept under control.

Table 14: Past economic feasibility studies on manganese nodule

	Yamazaki (2006)			Soreide et al. (2001)			Charles et al. (1990)			Andrews et al. (1983)		
	Mining (wet)	**Transportation (dry)**	**Processing (dry)**	**Mining (wet)**	**Transportation (dry)**	**Processing (dry)**	**Mining (wet)**	**Transportation (dry)**	**Processing (dry)**	**Mining (wet)**	**Transportation (dry)**	**Processing (dry)**
Production (t/y)	2.2 M	1.5 M	1.5 M	1.1 M	0.7 M	0.7 M	2.3 M	1.5 M	1.5 M	2.3 M	1.5 M	1.5 M
Capital Cost	202 M$	142.7 M	417 M	127 M$	93 M$	271 M$	282 M$	188 M$	470 M$	180 M$	176 M$	513 M$
Capital Cost Ratio	26%	19%	55%	26%	19%	55%	30%	20%	50%	21%	20%	59%
Operating Cost	71.5 M$	57.5 M$	74.2 M$	21.8 M$	13.5 M$	22.9 M$	48 M$	36 M$	156 M$	45 M$	25 M$	165 M$
Operating Cost Ratio	35%	28%	37%	38%	23%	39%	20%	15%	65%	19%	11%	70%
Metal	**Price**	**Recovery**	**Product**	**Price**	**Recovery**	**Product**	**Price**	**Recovery**	**Product**	**Price**	**Recovery**	**Product**
Co	$ 35,200/t	90%	2,363 t/y	$ 44,000/t	83%	2,652 t/y	$ 14,960/t	85%	3,525 t/y	$ 12,100/t	85%	3,375 t/y
Ni	$ 22,000/t	97%	18,340 t/y	$ 7,326/t	98%	2,548 t/y	$ 7,920/t	95%	19,730 t/y	$ 8,250/t	95%	18,525 t/y
Cu	$ 6,600/t	94%	13,823 t/y	$ 22,00/t	97%	1,890 t/y	$ 2,090/t	95%	17,810 t/y	$ 2,750/t	95%	15,675 t/y
Mn							$ 660/t	93%	38,2500 t/y	$ 880/t	93%	404,550 t/y
Taxes	30%			10%						46%		
NPV	902 M$			- 81 M$								
IRR	23%			9.60%			12%			6.40%		
Priced at 2010												
Total Capital Cost	1,487 M$			800 M$			1,570 M$			1,752 M$		
Total Operating Cost	223 M$			96 M$			401 M$			474 M$		
Average Capital Cost Weighted on Production Rate		1,500 M$/1.5 M dry nodules		or	1,000 M$ / 1 M dry nodules							
Average Operating Cost Weighted on Production Rate		330 M$ / 1.5 M dry nodules		or	220 M$ / 1 M dry nodules							

6.2 Logistic Challenges

The dry nodules will be firstly transported to a coastal port in China, and then offloaded to an onshore storage area, followed by inland transportation. The last two steps are planned in the well-established current approach. This section will therefore focus on the challenges associated with the ocean transportation, including the selection of coastal ports and the ocean transport route, and bulk identification, and the operation strategy.

6.2.1 Port Selection

Table 15 lists the most important ports in China and the cargo throughput present there. The locations of China's major ports are shown in Figure 47.

Table 15: Growth in cargo throughput at the top ports in China (in million tons) (Brooks and Cullinane 2006)

Port	1990	1995	2000	2002
Shanghai	139.59	165.67	204.40	263.84
Ningbo	25.54	68.53	115.47	153.98
Guangzhou	41.64	72.99	111.28	153.24
Tianjin	20.63	57.87	95.66	129.06
Qingdao	30.34	51.30	86.36	122.13
Qinhuangdao	69.45	83.82	97.43	111.67
Dalian	49.52	64.17	90.84	108.51
Shenzhen	4.80	11.74	56.97	86.67
Fuzhou	5.61	10.32	24.26	39.07
Lianyungang	11.37	17.16	27.08	33.16
Rizhao	9.25	14.52	26.74	31.36
Yingkou	2.37	11.56	22.68	31.27
Xiamen	5.29	13.14	19.65	27.35
Yantai	6.68	13.61	17.74	26.89
Zhanjiang	15.57	18.95	20.38	26.27
Shantou	2.79	7.16	12.84	13.80
Haikou	7.56	7.85	8.08	10.73
Total	**483.20**	**801.66**	**1256.03**	**1666.28**

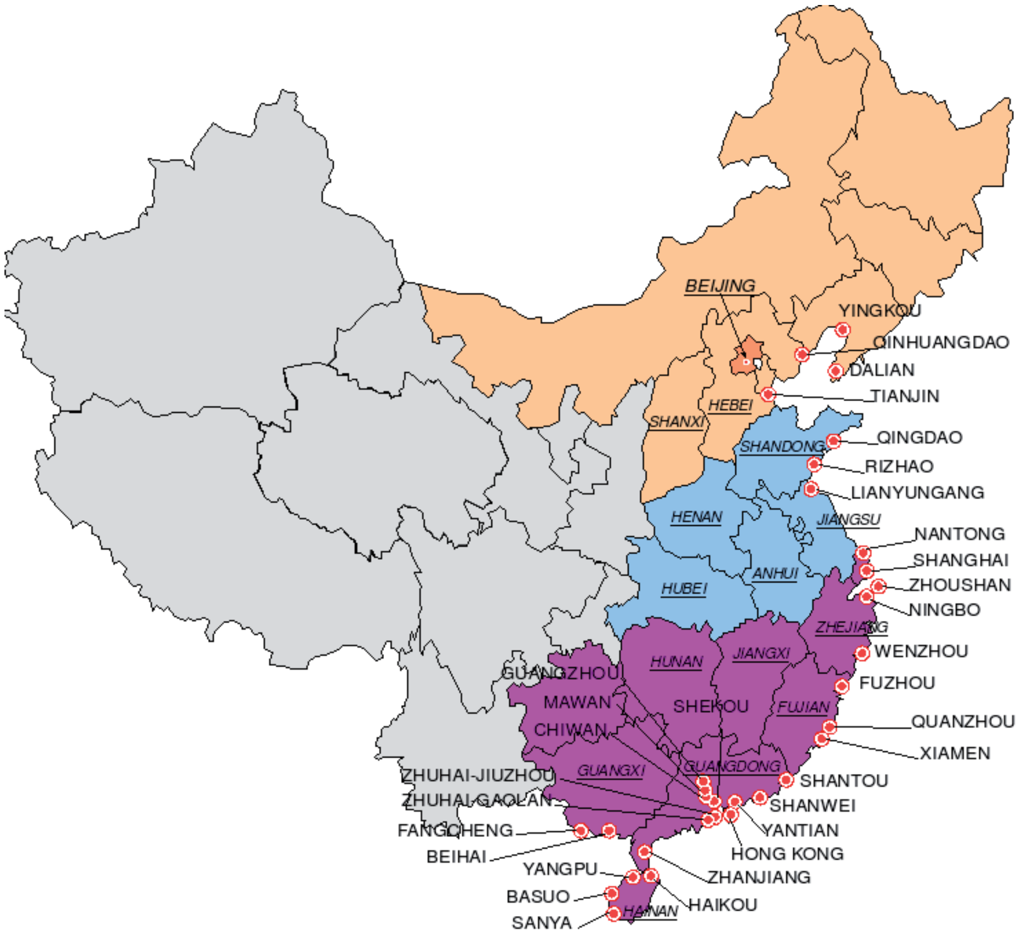


Figure 47: The locations of the major ports in mainland China
(source: www.p-s-central.com/PS-Central-China-Ports-Index.php)

Although all major and some minor ports in China handle dry bulk cargo, we have selected the Qingdao port as the ore handling port, given that it is the largest ore importing port in the world, with ore throughput of 41 million tonnes in 2004 (Brooks and Cullinane 2006).

6.2.2 Transportation Route Selection

The ocean transport patterns are indicated in Figure 48. The nearest route from the mining site to Qingdao port is highlighted in red. The distance is approximately 12,000 km.

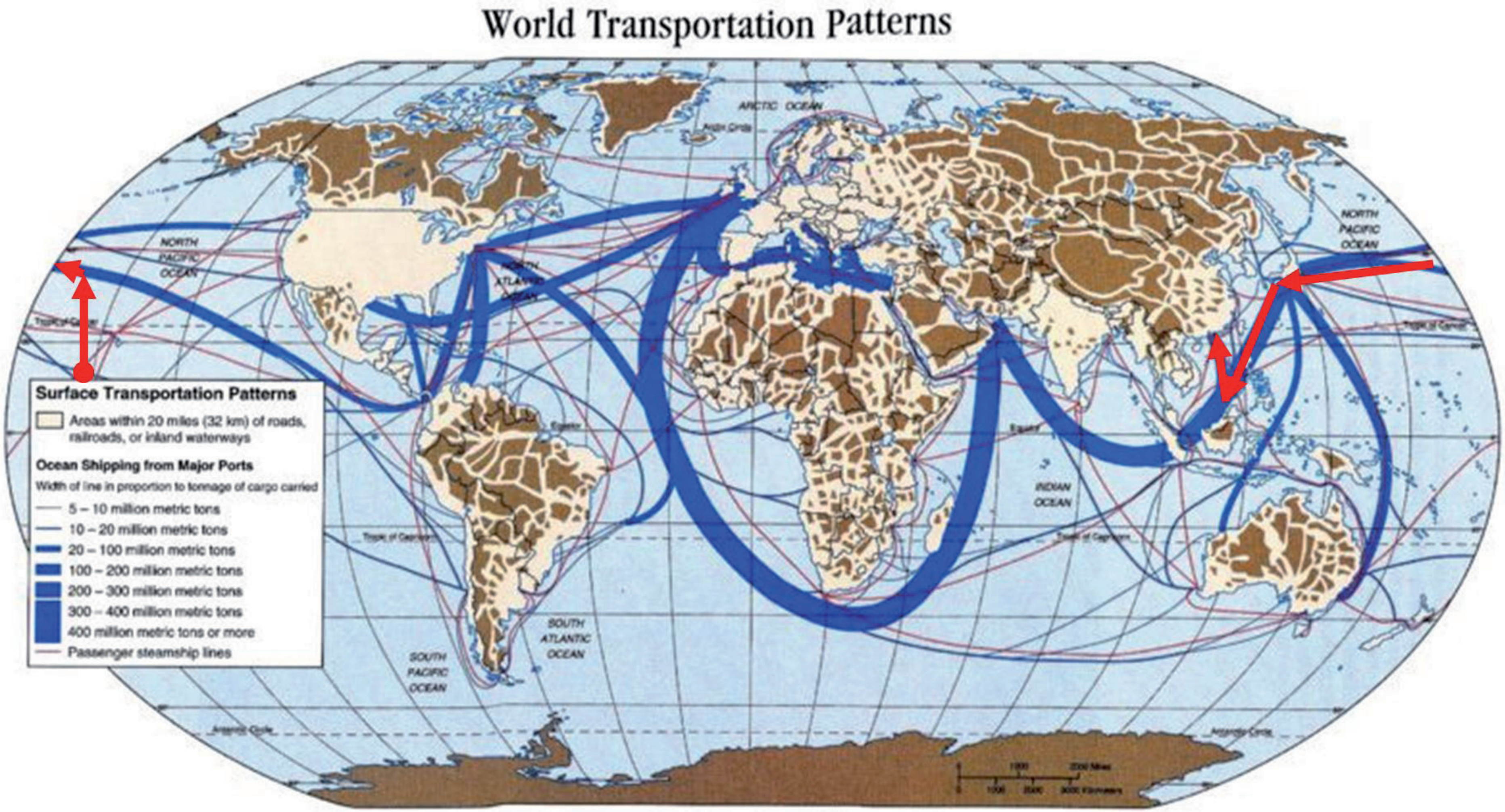


Figure 48: The world transportation patterns (COOP-COAST 2010)

6.2.3 Identification of Bulker Carrier

The calculations for the turnaround time and bulker carrier capacity are listed in Table 16.

Table 16: The calculation of turnaround time and bulker carrier capacity

Parameters	Amount	Unit
Annual productivity (wet)	274,000	metric ton/yr
Annual productivity (dry)	180,000	metric ton/yr
Total operation days	330	d
Daily productivity (dry)	545	metric ton/d
Transport distance	12,000	km
Speed	14.5	knots
	27	km/h
Travel time	18.5	d
Port time	20	d
Total turnaround time	57	d
Factor of safety	100%	
Bulker capacity	62,222	metric ton

The above calculations are indicated for a single system and it has already been proposed to use three such systems. So there will be a requirement of three vessels of capacity as indicated. The major bulk carrier size categories are indicated in Table 17. According to the production capacity, two Panamax bulkers (60,000-80,000 DWT) per system can be used for transportation. The characteristics of each Panamax bulker are indicated in Table 18.

Table 17: Major bulker carrier size categories (UNCTAD 2011, MAN 2010)

Name	Size in 10^3 DWT	New price	Used price
Handysize	10 – 35	\$25M	\$20M
Handymax	35 – 59	\$25M	\$20M
Panamax	60 – 80	\$35M	\$25M
Capsize	80 and over	\$58M	\$54M

Table 18: The characteristics of selected Panamax bulker (MAN 2010)

Characteristics	Value	Unit
Ship size (at scantling draught)	65,000	DWT
Crew	26	capital
Speed	14.5	knots
Scantling draught	14.2	m
Length overall	225	m
Length between pp	217	m
Breadth	32.26	m
Design draught	12.6	m

6.2.4 Identification of the Operation Strategies

A number of available options for commercial operation of the barging transport system are being considered:

- Charter and Contract Operation (C&CO), where tenders are received from various barging contractors for the supply and operation of the barging vessels on a charter basis;
- Purchase and Contract Operation (P&CO), in which the project procures the barges, with equipment operation and servicing being supplied by a third party;
- Owner Self Perform (OSP) of both the procurement and the operations of the transport barges.

Table 19: The comparison of different commercial operation options of the barging transport system

Commercial operation options	C&CO	P&CO	OSP
Schedule	Acceptable	Acceptable	Acceptable
Performance risk	Low	Moderate	High
Annual cost (million US$/ship)			
Max	9.9	9.6	15.0
Min	0.8	2.3	11.0
Ave	5.0	5.6	13.0

Table 20: Total annual cost of "Owner Self Perform" transportation strategy

Indicators	Value	Unit
Total capital cost	35	Million US$
Project year	20	yr
Ave real interest rate	2.7%	--
Daily fuel cost		
daily fuel cost, at sea		
Max	43	Thousand US$
Min	24	Thousand US$
Ave	32	Thousand US$
daily fuel cost, in port		
Max	2.4	Thousand US$
Min	1.3	Thousand US$
Ave	1.8	Thousand US$
Total season days	330	d
days at sea	214	d
days in port	116	d
Fuel consumption		
primary propulsion (at sea)	43	metric ton/d
auxiliary (at sea)	2.5	metric ton/d
auxiliary (in port)	2.5	metric ton/d
Fuel price (heavy viscosity oil 2007-2011)		
Max	950	US$/metric ton
Min	530	US$/metric ton
Ave	720	US$/metric ton
Annual capital cost	2.3	Million US$
Fixed annual operating cost	3.1	Million US$
crew cost	1.6	Million US$
lubes and stores	0.15	Million US$
maintenance & repair	0.87	Million US$
insurance	0.33	Million US$
administration	0.16	Million US$
Annual fuel cost		
Max	9.4	Million US$
Min	5.2	Million US$
Ave	7.1	Million US$
Total annual cost		
Max	15	Million US$
Min	11	Million US$
Ave	13	Million US$

To determine the optimum delivery strategy, three key issues are identified: schedule, performance risk, and cost. As indicated in Table 19, all of the proposed delivery strategies are acceptable in terms of schedule. The C&CO option is considered as it has the least potential for performance risk due to less requirement of procurement. According to the preliminary cost assessment (Table 20, Table 21, Table 22), the C&CO and P&CO options require a lower annual cost. Based on these assessments, either the C&CO or P&CO strategy can be adopted in this study.

Table 21: Total annual cost of "Charter and Contract Operation" transportation strategy

Indicators	**Value**	**Unit**
yearly chartered rate (max)	30	Thousand US$/d
yearly chartered rate (min)	2.5	Thousand US$/d
yearly chartered rate (ave)	15	Thousand US$/d
Total annual cost (max)	9,900	Thousand US$/d
Total annual cost (min)	830	Thousand US$/d
Total annual cost (ave)	5,000	Thousand US$/d

Table 22: Total annual cost of "Purchase and Contract Operation" transportation strategy

Indicators	**Value**	**Unit**
total capital cost	35	Million US$
annual capital cost	1.7	Million US$
chartered annual operation cost (max)	7.9	Million US$
chartered annual operation cost (min)	0.66	Million US$
chartered annual operation cost (ave)	4.0	Million US$
Total annual cost (max)	9.6	Million US$
Total annual cost (min)	2.3	Million US$
Total annual cost (ave)	5.6	Million US$

6.3 Environmental Impact Assessment

One of the objectives of this feasibility study is to provide an integrated engineering system which minimises disturbance to the environment. The assessment on the environmental impact is conducted for three major potential pollutions, i.e. water, air and noise.

6.3.1 Water Pollution

It has been argued that the most significant impact to the environment during deep sea mining will be at the seafloor, where most of the mining operation is conducted, and at the depth of the waste discharge. Here an assessment on water pollution from sediment mobilisation and wastewater discharge has been provided with reference to the International Convention for the Prevention of Pollution from Ships (MARPOL).

Mobilized sediment (sediment plume)

The volume of mobilised sediment depends mainly on the penetration of the crawler during nodule recovery, and on the type of collector mechanism. To minimise the amount of mobilised sediment, the water-jet technique and the hydraulic type of collector are adopted. An estimate on the volume of sediment displaced during the collection mechanism by using a water-jet technique is as follows:

Key parameters used to estimate the sediment displacement, are as follows.

Width of the collector, b	$= 2$ m
Velocity of the collector, V_C	$= 0.2\ \mathrm{m/s}$
Specific gravity of nodules, γ_N	$= 2\ \mathrm{t/m^3}$ (Herrouin 1991)
Average nodules abundance in CCZ, α	$= 10\ \mathrm{kg/m^2}$
Penetration of the water-jet technique on seafloor, D	$= 0.01$ m (Herrouin 1991)

The volume of sediment mobilized is calculated as follows:

The volume of mixed sediment and nodule, $\forall_M$ $= b \times V_C \times D = 0.004\ \mathrm{m^3/s}$

Since the nodules are half buried in the sediment, the embedded volume of nodules, $\forall_N$

$$= \frac{b \times V_C \times \alpha}{1000 \times \gamma_N \times 2}$$

$$= 0.001\ \mathrm{m^3/s}$$

The volume of sediment plume, $\forall_S$ $= \forall_M - \forall_N = 0.003\ \mathrm{m^3/s}$

and per day it will be $= 259.2\ \mathrm{m^3/d}$

With an average specific gravity of the sediment of 1.4 t/m^3, the volume of sediment plume created is 362.88 tons/day for each collector unit. For the proposed three multiple systems of three collector units each, the amount of sediment produced by each combined is 3,266 tons/day.

Table 23 provides a comparison of the estimated sediment plumes between previous studies and this feasibility study. It can be observed that our proposed engineering system manages to reduce the amount of sediment plumes created during the recovery operation, which is reflected by small sediments to dry nodules ratio. One obvious reason is due to the choice of a hydraulic water-jet as a collection mechanism, which minimises the footprints on the seafloor. Another reason is the use of smaller collector units, which operate at a slower velocity. This promising outcome, coupled with our innovative black box design, further reinforce our objective to minimise the impact on the marine environment. Also, the modified forward shape is intended to contain the sediment plume and to prevent it from spreading.

Table 23: Comparison of the estimated sediment plumes

Recent Studies	Daily Production of Dry Nodules	Estimated Suspended Sediments from Seafloor	Sediments/Dry Nodules
Herrouin (1999)	6,000 t (dry)	~ [a]19,155 t	3.19
		~ [b]54,519 t	9.09
Morgan et al. (1999)	5,500 t (dry)	~ 54,000 t	9.82
The Proposed System	**1,636 t (dry)**	**~ 3,266 t**	**2.00**

a = 2 cm penetration of the collector; b = 5 cm penetration of the collector.

Waste water

Section 5.1.3 conveys that the amount of waste water handled by the black box each day is about 1,800 tons. For the proposed three systems, the amount of waste water discharged every day is about 5,400 tons. The weight of sediment in the discharged waters for the proposed three multiple systems is approximately 100 tons per day (see Section 5.1.3). This gives sediment to water concentration ratio of less than 2% (w/w), as compared to the initial intake ratio of 20% (w/w). It has been described in the Section 5.1.3 that the collected sediments are diluted with wastewater to aid the resettlement of suspended sediments and to minimise the scale of plumes after being discharged to water.

The sediments and wastewater are discharged at about 100 – 200 m above the seafloor of 5,000 m water depth (in-situ discharge). Fewer organisms are expected at such a deep water level beyond the depth of the oxygen-minimum layer. Although any discharge into the local marine environment may pose harmful effects, the choice of having in-situ discharge with the black box is expected to reduce any associated impacts.

Sewage

The MARPOL provides guidelines about the prevention of pollution on the marine environment. On 2nd November 1973, the MARPOL convention was adopted by the International Maritime Organization (IMO). Apart from the regulations on routine operations pollution, the convention also includes regulations to prevent and minimise pollution from accidental pollution of the ships (www.imo.org).

Annex IV of the MARPOL convention contains a set of requirements to control sewage pollution on the sea. It is forbidden for a ship to discharge sewage into the sea unless the ship has an approved sewage treatment plan, or the sewage is disinfected using an approved system, at a distance more than three nm from the nearest shore. Sewage that is not disinfected has to be disposed at a distance more than twelve nm from the nearest shore (www.imo.org). Although pollution from sewage discharge seems to be a minor issue in comparison to sediment plumes and wastewater discharge, the above regulations will be closely adhered to during the normal operation and transportation periods.

6.3.2 Air Pollution

Annex VI of the MARPOL convention provides guidelines regarding prevention of air pollution from ships. Since 2011, IMO have adopted the technical and operational energy efficiency provisions to significantly reduce the amount of greenhouse gas emissions from ships. The provisions will be implemented from 1 January 2013.

Air emissions from nodule recovery are expected to contain sulphur dioxide, carbon monoxide, carbon dioxide and nitrogen oxide. These air emissions are mainly from combustion emissions from the power supply and some machinery of the PSV and ore barges. The convention limits the amount of the above-mentioned emissions and prohibits deliberate emissions of ozone-depleting substances from ships. It also provides more stringent standards for sulphur dioxide, nitrogen oxide and particulate matter in the designated emission control areas. Although there will still be emissions in air, it is expected that the pollution will be reduced by adhering to the rules and regulations set by the convention, such that there is no direct and profound impact on the marine life and environment.

6.3.3 Noise Pollution

Estimating the underwater noise generated by a conceptual design is a highly complex task. It requires a broad knowledge, not only of predicting the acoustics, but also of understanding the flora and fauna that occupy the area and their reaction to this noise. The detailed study is outside the scope of this work, although some key points are here presented and briefly discussed.

Before reading the discussion on noise issues, it is advised to refer to the section on the environment of the deep sea and its inhabitants. It is important to understand that different species have different audibility levels and properties. This is normally not well understood or to be more precise, the data for the species inhabiting these depths is insufficient. The components of marine life to be included in any environmental assessment are fish (audible range 1 Hz – 1 kHz), big marine mammals, which often dive to a depth of 1,000 m to feed (sensitive in 10 KHz – 200 kHz) and other smaller scavengers whose audibility characteristics have not been studied in detail. Ideally, the environmental risk has to be assessed, even when little information is available on the audibility of some of these species.

Historically, the problem of underwater noise and its repercussion on the marine ecosystems has always been neglected. The maritime industry legislation, according to Professor Victor Humphrey at the Institute of Sound and Vibration at the University of Southampton, is a long way behind the aerospace industry for instance. It is only relatively recently, effectively in the last 20 years, that some of the public and expert concern has arisen regarding the environmental impact of underwater noise generated by humans. The concern that arose due to changes in behaviour of whales after the introduction of a particular sonar system by the US navy has played a major role. The signal used by the sonar was discovered to be similar to those emitted by killer whales, thus driving other kinds of whales, falsely perceiving danger, to change their behaviour. This led to concerns from environmental associations and the result was an increased awareness among both the general public and the experts.

In the last few years progress has been made in regulating the noise emission in the maritime environment, although up to date, only sensitive habitats have generated an increased interest and a specific set of regulations. A good example for instance is the arising awareness around north right whales, whose population is threated in the east cost of the USA. Ship strikes are one of the main problems threatening whales in this case. Researchers have proposed that the main problem associated with ship strikes could be the extremely high background noise levels associated with the touristic vessels. This would prevent the whales from distinctively hearing the approaching ships. In marine research, there is evidence for avoidance due to high noise levels. However the authors believe that in this particular case, migration patterns will not be affected. This is due to the relatively localised effect that one of these systems would have on the environment owing to its scale in relation to the entire area of interest.

Referring to Figure 36, the following main sources of noise can be isolated:

- The mother ship;
- The riser;
- The pumps;
- The collector unit;

All of the above elements of the system will contribute differently to the environmental impact on the ecosystems. Before we discuss this topic any further it is necessary to introduce a few basic acoustical concepts and the effect that water will have on them. Before understanding any acoustic problem it is necessary to define the following:

- The type and location of the **source,** which is the point of noise generation;
- The **propagation,** which involves the spreading of noise and the influencing parameters;
- The **receiver** ,which is the final recipient of the noise

All three parameters are influenced in this particular problem by the changing characteristic of the environment due to the water column. Figure 49 shows how some common physical properties vary with water depth and this certainly influences the noise propagation. Effectively, because the sound speed depends on the propagation medium, its propagation pattern changes accordingly.

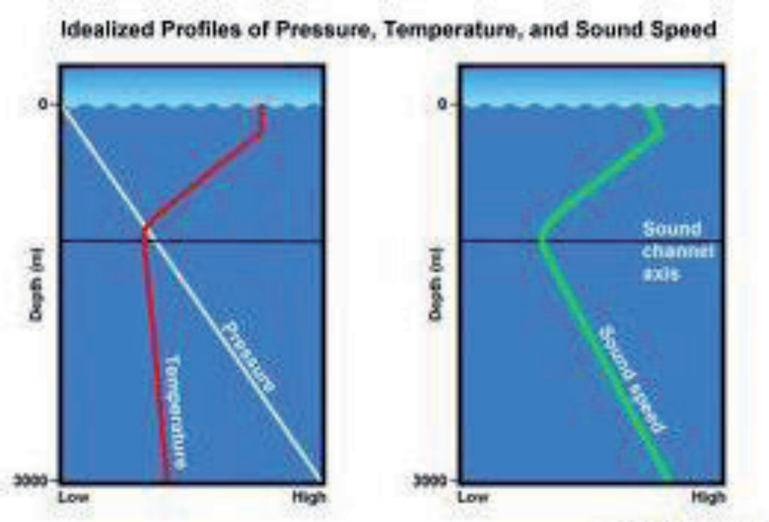


Figure 49: Idealized profiles of pressure, temperature and sound speed (COMET)

This creates a **sound channel** in which the sound can, under some conditions, propagate for thousands of miles. A further important distinction in terms of acoustics is the different behaviour of high and low frequency acoustic waves. A high frequency signal, although containing conspicuous amounts of information, cannot travel too far compared to a low frequency sound, which, although containing very little information, can travel much further away. Because of these two simple principles, the criticality of the noise is not confined to intensity alone, but many more factors play a role in it.

Having examined the reasons, the different components can now be discussed. The mother ship: because it is the only component of the system on the water surface, noise is propagated both in the atmosphere and just below the water level, where the majority of fish live and feed. Marine legislation is fairly behind in terms of regulating the maximum accepted level of noise that a ship can generate.

Despite supplying power for the mining, the noise generated by the vessel in this present case, is not comparable with much larger ships. It is not considered a critical component. In the riser, the major contributor of noise would be the nodules impacting on the inner surface of the riser (especially in the case of a rigid riser). This would be a high frequency source rapidly damped and lost because of its properties. However, a coating of absorbing material can be easily designed in order to minimise any adverse effects.

The collector unit noise and vibrations, which seem to represent the majority of noise for the whole system, can almost be neglected because of the marine environment in which it operates (refer to paragraph on environmental challenges). Furthermore, because it works considerably below the sound channel, most of the sound will actually reflect back into the seabed, and will be absorbed by the soft layer of sediment due to its acoustic damping properties.

Surprisingly the pumps have been identified as the most critical component, not because of the nominal decibel values, which are relatively low, but because of their location in the system. It is unlikely that a single pump can generate the required lifting force. This therefore obligates in favour of a system of pumps. With multiple pumps operating, it is quite likely that one or more of them might fall in or near the sound channel. This could create a problem due to the long spreading of this noise.

Noise emitted from the pumps, particularly the centrifugal pumps, has been demonstrated (Robinson et al. 2011) to have a low frequency component due to the pumping itself, and one high frequency one due to the particles impinging on the inner surface of the pump. As previously stated, the critical component would be the low frequency one due to its long spreading. A relatively easy engineering solution would be to avoid pumps in the sound channel or if this is not possible, to shield the design with an acoustic insulation box filled with high porosity material. A challenge would in that case be designing a high porosity material, which could withstand the pressure of the water.

6.4 Safety Assessment

Regarding labour safety, deep sea mining seems to offer increased worker safety compared to land based mining, as no worker will be directly exposed to the dangers of the mining site. All mining operations will be performed unmanned. Most of the safety assessments are hence focused on the personnel on-board the floating ship.

The International Convention for the Safety of Life at Sea (SOLAS 1974) (www.imo.org) governs all jurisdictions concerning the safety of ship operations. The safety assessment is performed in accordance with the guidelines and regulations provided by SOLAS 1974.

The safety assessment on PSV and shuttle barges require provisions of watertight integrity and bilge pumping to ensure the vessels remain afloat and stable in the event of flooding after damage to the hull. The provision for subdividing or modularising compartments and machinery and electrical equipment aligns with the modularised concept of the proposed engineering system, where a failure of one system does not affect the integrity of the whole. The provision is listed in Chapter II – 1, of the SOLAS regulations: Construction – Subdivision and stability, machinery and electrical installations.

Fire safety provisions including fire protection, detection and extinguishing systems are to be included on board for all floating vessels. Necessary arrangements for the division of the ship have to be made, for instance separating the accommodation block from any combustible machinery and electrical systems. The provision is listed in Chapter II – 2 of the SOLAS regulations: Fire protection, fire detection and fire extinction.

Chapter IX of the SOLAS regulations: Management for the Safe Operation of Ships requires a safety management system to be established by a company assuming responsibility of the whole operations.

The weather forecast in the designated area of operation has a major impact on the mining operation itself. In the event of bad weather, it is required to stop all operations and evacuate all personnel on board to a safer location. Thus, the envisaged solution for the proposed modular engineering system would be to leave the mining system on the seabed and to disconnect the riser system from the PSV while attaching a buoy to the top end of it for recovery purpose. The CCZ area is fortunately an area characterised by relatively calm seas. However, the riser system should be designed to withstand any storm predicted in the area and the vessel-riser connection should be designed in such a way that the riser could be left floating autonomously in case of a storm. The ship would therefore be allowed to easily disconnect to safeguard human life. The collector and the equipment situated several metres under the water level, are expected to be undisturbed by any storm and could be safely left in place.

In the event of a breakdown of the collector units or the riser systems, Remotely Operated Vehicles (ROVs) and/or divers can be deployed for repair work depending on the water depth in which operations are taking place.

7 Business Model

This chapter examines and presents the business model proposed for the nodules operation system. It focuses on the potential customer, value proposition, customer relations and SWOT analysis.

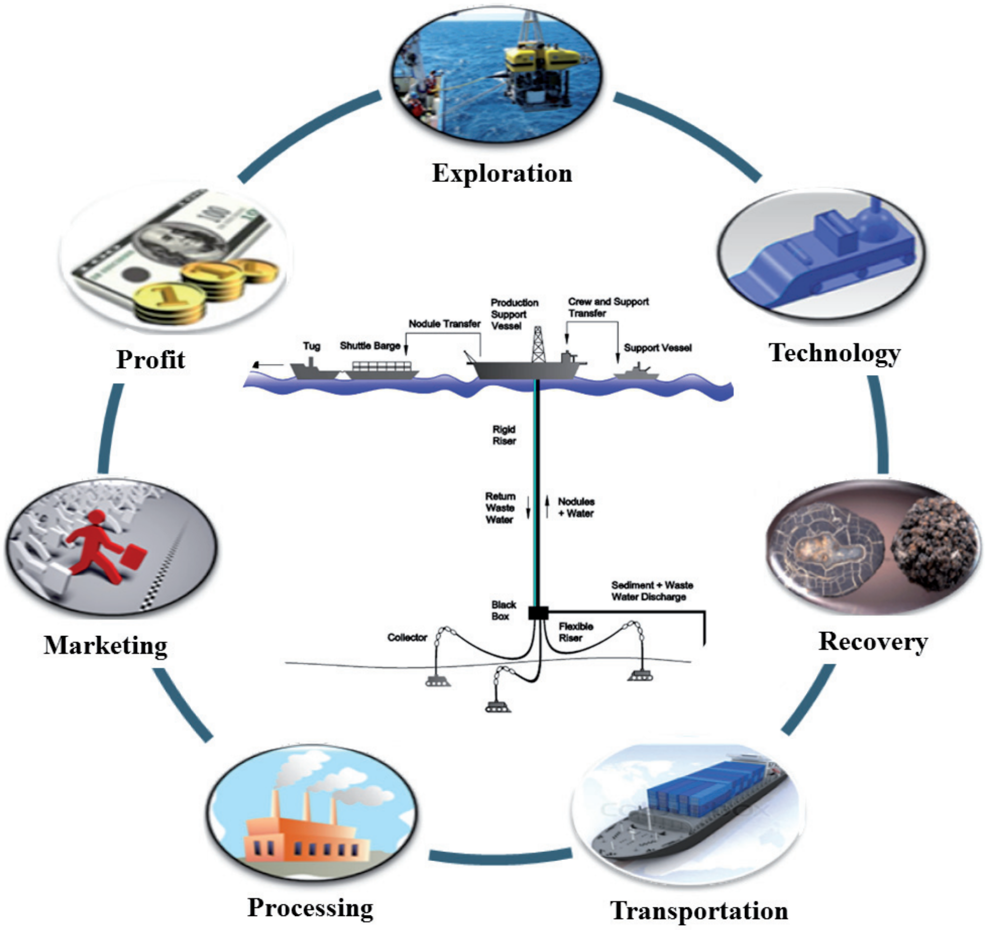


Figure 50: The complete cycle of a commercial manganese nodules recovery

Before addressing the business model, the individual aspects of the whole nodule recovery operation cycle, represented in Figure 50, are briefly described.

Exploration and Resource Assessment: This aspect has been the subject of considerable work by the contractors in the CCZ. In fact, a sufficient amount of exploration/money invested is the necessary requirement to be a nominated pioneer investor and hence to be issued an exploitation license. This feasibility study benefits significantly from past explorations, using the data previously acquired for the design parameters.

Technology Development: The literature review on this aspect has been detailed and thorough. The relative advantages and disadvantages of the various existing systems have been comprehensively examined.

Mineral **Recovery**: This aspect has been afforded considerable attention, particularly relating to the application of the developed technology. The proposed engineering system incorporates various sub-systems to derive an optimum system, both in terms of minimising the environmental disturbance and preserving the economic interest of the potential customers.

Transportation: This aspect serves as an important bridge linking the production site to the market. The various logistical challenges have been thoroughly addressed.

Metallurgical **Processing**: It was beyond the scope of this feasibility study to provide suggestions in regards to the metallurgical processing. However, for economic feasibility assessment, the acid leaching method was chosen for illustrational purpose.

Marketing: Various theories exist on how the marketing must be accomplished. The next section applies them in formulating a business model. In the authors' view, this can be adopted to preserve the economic interest of the community involved in the nodule recovery process.

Profit: Once the net profit is obtained from one complete cycle, the financial resource can be invested in another new complete cycle for further manganese nodules recovery.

7.1 Potential Customers

There are two types of potential customers for manganese nodules recovery: direct and end customers.

The **direct customers** have been identified as all the nine contractors who have been granted exploration licenses in the CCZ by ISA. The nine contractors include a mixture of government or state-owned bodies and private enterprises. They are COMRA of China, DORD of Japan, Government of Korea, IFREMER of France, Interoceanmetal Joint Organization, State Enterprise of the Russian Federation, Federal Institute of Germany, Tonga Offshore Mining Limited, and Nauru Ocean Resources Inc. After the exploration contract expires, the nine contactors would intend to apply for the exploitation license. Thus, a robust and feasible engineering system with technically sound components is essential to make the recovery process of manganese nodules happen.

The **end customers** are represented by the public. They are the end users of the nodules recovery operation, in the form of mobile phones, batteries, electric cars etc. Although considering the public as one of the customers may seem too far-fetched, they actually play an important and dynamic role with the direct customers or the nine contractors in this case.

The **key risk to the direct customers** is strong public objection and anti-mining campaigns. These could arise from inadequate impact assessments and the associated poor mitigation factors put in place on the local marine environment due to the mining activities. Public protest could possibly hamper or even potentially call off the mining operation. The **key risk to the end customers** which leads to public protest is the health implications and social impacts associated with contamination of the marine environment, as well as impacts on the marine flora and fauna.

The above illustrates the dynamic relationship between the two customers. A feasible technical solution alone is not enough. The need for a green solution is clear. It should also incorporate various detailed and transparent risk assessments, such as commercial and investment risks, environmental impact assessments and safety assessments, to help justify the proposal to the nine contractors, as well as appeal to the public. The support of both customers will allow the manganese nodule recovery to commence and operate smoothly.

Here, an environmentally friendly engineering system with a smaller production scale and modularised design concept is proposed as the solution to achieve a potentially full-scale commercial manganese nodules recovery.

7.2 Value Proposition

With the advanced technologies available today, it is argued that there is a sufficiently sound technical system layout for components of any proposed engineering system. Full-scale testing of an integrated engineering system is the only aspect that has not thus far been attempted. Once this gap is filled, manganese nodules recovery can be expected to soon follow.

As aforementioned, the key ongoing consideration and challenge is the impact on the local marine environment. It is identified as a **short term problem** for both the direct and the end customers. The **long-term problem** is the scarcity and uncertainty of land based metal supplies. Hence the idea of deep sea mining exists.

Thus, the **value proposition** for the business model is that the proposed green and technically feasible engineering system is the best manganese nodules recovery solution for minimising the environmental impacts and its footprints. Customers are brought together with the proposed green solution to tackle both short and long term problems.

7.3 Customer Relations

A joint venture customer relation is preferred. This consists of a long-term relation with the nine contractors, and a longer-term relation with the public, given that a mining company has to be responsible to the public as long as the operation is being planned and carried out.

Details on this joint venture customer relation are provided as follows. The proposed customer relation is based on the existing iron ore market, with some modifications. This means that the nodules will be sold as the end product after recovery and an established nodule market can be set up, as is the case for iron ore.

One of the major problems with the seabed mineral recovery plans to date is the volatile metal market. A sudden collapse in the price of metals makes the whole venture economically unfeasible. Thus, a sense of assurance needs to be guaranteed from the nine contractors/governments. This sense of assurance will not only help the industry to see the realisation of the full scale deep-sea recovery, but also assist in promoting and building up confidence for similar projects in different sites in the near future (refer to paragraph 8.1).

One form of assurance for economic sustainability is to keep a set of fixed threshold prices or support prices for the metals of interest. The commercial viability analysis shows that under normal circumstances, the whole mining process is profitable. However, in the case of a sudden collapse in metal prices, a set of minimum support prices has to be fixed by the nine contractors to prevent a mining company from going bankrupt. This will trigger increasing interests in commercial deep-sea mining by eliminating all the unstable market related risks.

In authors' opinion, the engineering system proposed in this study can be realised commercially with the economic help from the nine contractors (in this study COMRA). To preserve the economic interest of COMRA, as well as the mining company, a Memorandum of Understanding has to be signed by both parties. COMRA can set the minimum required annual amount of nodules to be recovered and sold by the mining company. In return, COMRA can provide all the required design data such as nodule abundance, local topography, etc. The mining company will be paid based on the amount of nodules sold, with some provisions for unforeseen risks such as unfavourable weather conditions. This method will boost confidence levels in the industry and keep the mining company on schedule, since the more they recover the more they earn. Moreover, if COMRA is willing to invest on the initial capital cost, there can be a provision for discounted nodule prices from the mining company. Alternatively, the large initial cost can be loaned to the mining company by COMRA, which can then be repaid during the course of the mining activity. This proposed customer relation will mutually benefit both parties.

7.4 Reaching Out to Public – Channel

The motivations for deep-sea mining have been well documented to convey the need for it to the public. The comparison between land-based mining and deep-sea mining has been provided for the same reason. It is the responsibility of every mining company to reach out to the public, to create awareness and to educate about the idea of deep-sea mining, in the form of public forums, workshops, company days etc.

Specific to this feasibility study, more transparent environmental impact assessments need to be provided to convince the public (the end customers) that the associated environmental impacts have been considered and minimised appropriately (for example through innovative concept ideas such as: the black box).

7.5 SWOT Analysis

The Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis is provided as follows.

7.5.1 Strengths

The **strong point** of the feasibility study is reflected in the commitment to reducing the footprint and impacts on the local marine environment by providing a green engineering system as a solution. The **unique** selling proposition of the system proposed in this study would be:

- The black box: innovative idea which helps to reduce the environmental impacts of the system, the overall power consumption and unnecessary amount of clean water (seawater) by recycling waste water used in the system.
- Modularised design concept: multiple small collector units are used instead of single large units to increase production efficiency and redundancy.
- Use of active hydraulic, crawler type collectors: to reduce the amount of sediment plumes generated and minimise the environmental footprint.

This study has aimed to provide a solution to enable deep-sea mining and to address the shortage of land based metal supplies in the long term. This study is also intended to provide a platform for full-scale research for scientists and researchers in any of the commercial recovery operations. It is hoped that is will encourage more interest and research in deep-sea mining, particularly in the area of environmental impacts.

7.5.2 Weaknesses

The main **weakness** of this feasibility study is that the proposed engineering system does not provide a fully integrated solution, from the exploration stage to the metallurgical processing and marketing stage - from raw nodules to refined metals. An integrated solution is preferred to achieve more control, as every stage of nodule recovery closely interact. This main weakness will be addressed further as part of the recommendations for future work.

7.5.3 Opportunities

The market analysis and the motivations for deep-sea mining have identified that the current market condition offers good **opportunities** for realisation of commercial manganese nodules recovery in the near future. As discussed, good investment prospects with IRR > 12% can possibly be achieved.

This feasibility study still has a buffer period of 7–8 years for finalisation of the proposed green engineering system before the first full scale commercial deep-sea mining can take place in the CCZ once the exploration license for the nine contractors expires in around 2020.

However, the realisation of a full-scale operation requires a sense of assurance to be incorporated, as described in the Customer Relations Section. This is to cover the volatility of the metal market. It is possible that the full operation needs to be put on hold for another twenty years from now if the market conditions, seven years from now, are not favourable.

A further opportunity comes from the waste after on-shore metallurgical processing. Initially, it is believed that dumping the waste on land after processing will create a new challenge of waste disposal. For the production scale of this feasibility study, about 107,300 tons of tailings have to be disposed of annually. Fortunately, these tailings could possibly be made useable in the near future. Wiltshire et al. (2001) studied the environmental implications of using the tailings in specialty agriculture, and concluded that their utilisation as fertilisers in agriculture has enormous potential. This challenge-turned-opportunity definitely contributes to the attractiveness of the idea of manganese nodule recovery.

7.5.4 Threats

One of the biggest **challenges** for the proposed engineering system is the integration of all the components together. Even though individual components of the mining system have been tested separately, the question of scaling and integrating them together remain unanswered. This explains why the proposed green engineering system is of a smaller production scale and intended to provide a platform for more studies. The proposed system can be treated as a full-scale experiment.

An obvious **threat** for manganese nodule recovery is when any or all of the four major metals found in manganese nodules (Cu, Ni, Mn and Co) are no longer of commercial interest. This could be due to the introduction of new technologies, which uses different metals. Consequently, the proposed engineering system will no longer be of commercial interest to industries. This system applies to every existing profitable activity and changes of such big magnitudes cannot be predicted. However, it could still be used for research purpose provided funding could be granted by government bodies or private enterprises.

8 Conclusion and Future Work

This final chapter firstly deals with drawing the conclusion and secondly presenting a recommendation for future work.

8.1 Conclusion

The mining of minerals from the deep seabed still remains in its infancy. However, in the authors' view, unprecedented pressure on terrestrial natural resources will eventually lead to a significant expansion of human mineral recovery activities to the deep sea. Moreover, with the advancement of technology and a greater understanding and appreciation for the marine environment, the recovery of manganese nodules in the seabed has become ever more feasible. This type of seabed resource is in the spotlight for researchers given that its location on the seabed requires no digging or mining. This study has shared many insights about deep-sea manganese nodule recovery. An insufficient green solution and environmental impact study still remain the biggest obstructions as far as starting a commercial recovery operation is concerned.

This feasibility study aims at reducing environmental impacts and footprint by introducing the innovative idea of the Black Box. The Black Box allows in-situ waste discharge, thus containing the effects of sediment plumes generated to a more localised and lower water depth, and reducing the radius of influence, as compared to the conventional waste discharge from the mother ship, or at a shallower water depth. The Black Box also offers utilisation of wastewater, by recycling the wastewater pre-processed on the mother ship to perform nodule – sediment separation, thus reducing the unnecessary amount of clean water (or seawater) used. This novel idea is not only more environmentally friendly but also more cost effective as it saves 5% of the total power consumption (under conservative assumption).

Many innovative ideas and improvements from the conventional designs are incorporated into the proposed green engineering system. One example is the concept of a modularised system, which increases the level of redundancy. Instead of a big and heavy collector unit, multiple smaller and lighter units are deployed, such that failure of one component does not affect the integrity of the whole system. Another example is the improvement in the forward shape of the collector unit, which is intended to contain sediment plumes created during collection activities. Also, a long and narrow (slender) collector is chosen rather than a short and wide (bluff) one to allow for a better sediment plume re-settlement. All of these ideas and improvements are included with an aim to deliver a green recovery solution, which interacts with the local marine environment in the least destructive way.

A smaller production scale of 0.5 M dry tons of nodules has been chosen as the target production scale. The intention is to avoid oversupplying refined metals to the volatile metal market and breaking the metal prices, and to reduce the initial capital cost. Another reason arises from the business model that such a small production scale can also be considered as a full-scale experiment, providing a platform for research and development. This idea could encourage more interest and research into deep-sea mining, particularly in regards to the environmental impacts.

Various risk assessments have been performed on the proposed green engineering system, such as commercial viability, logistics, environmental impacts and safety. Commercial analysis has crudely approximated that the proposed system yields a viable return with an impressive IRR of 14%, even for such a small production scale. The environmental impact assessment on the system yields significantly smaller sediment plumes generated to nodules ratio, largely due to the choice of a hydraulic water-jet and smaller collector units. Also, the sediments are diluted in the Black Box from the initial slurry concentration of 20% to less than 2%, to minimise the scale of plumes generated from in-situ discharge. A safety assessment has been put in place to ensure that health and safety of personnel is taken care of, as well as the operational safety procedure.

A comprehensive business model has been presented following the risk assessment. All of the nine contractors in the CCZ and the public are the potential customers to the proposed green engineering system. Valuable lessons gained from the Solwara 1 experience have helped to identify the key risks to both customers, which resulted principally from an insufficient and less transparent environmental impact assessment. To generate awareness about the environmental impacts and to be publically transparent, the proposed green engineering system can be used for both commercial and experimental purpose in parallel. This demonstrates the value proposition of the system, which brings together the two customers (nine contractors and the public) to tackle both environmental impacts (short term) and the need to address deep-sea mining (long term) problems.

A unique compromise on the customer relations with the nine contractors has been proposed. The concept of a base price for the nodules could ensure continuous interest and commercial viability for the nodule recovery process. This will also maintain a sustainable operation and create room for sufficient technological development. Despite the fact that COMRA and their contracted area have been chosen for the case study, the proposed engineering system and the associated business model are applicable at any location in the CCZ (and if possible, with suitable modifications, in the Indian Ocean Basin).

8.2 Recommendation for Future Work

This study provides a feasible and green solution for the recovery of manganese nodules from the seabed. However, this research is not meant to be exhaustive and the authors are conscious of the gaps that need to be filled. Due to time constraints, there are some aspects that need to be addressed more fully in the future:

- Thorough development of the proposed green engineering system, including the innovative idea of the black box and the collector design
- Integrated solution for the whole engineering system, from exploration to metallurgical processing, to address every mining stage in detail.
- Studies on the effect of scaling experimental test results into full scale, and integrating the whole mining components. This still remains unanswered.
- More recommendations to preserve the commercial interest of deep sea mining.
- Development of computational and experimental models to simulate the impacts and disturbance of seabed mining on the environment.
- Establishment of a computational ecosystem model of the pioneer exploitation area.

References

Amos, A. F. and Roels, O. A. (1977) 'Environmental aspects of manganese nodule mining', *Marine Policy,* 1(2), 156-163.

Andrews, B. V., Flipse, J. E. and Brown, F. C. (1983) *The economic viability of a four-metal pioneer deep ocean mining venture,* Texas A & M University, Sea Grant College Program.

Antrim, C. L. (2005) 'What was old is new again: economic potential of deep ocean minerals the second time around', in *Oceans 2005 Conference*, Washington, IEEE, 1311-1318.

Brockett, T. (1999) 'Nodule collector subsystem', *Workshop on Proposed Technologies for Deep Seabed Mining of Polymetallic Nodules: International Seabed Authority Meeting*, 67-93.

Brooks, M. R. and Cullinane, K. (2006) *Devolution, Port Governance and Port Performance,* JAI Press.

Charles, C., Herrouin, G., Mauviel, F. and Bernard, J. (1990) 'Views on Future Nodule Technologies Based on IFREMER-GEMONOD Studies', *Materials and Society,* 14(3/4), 299-326.

Chung, J. S. (2002) *Deep Seabed Mining Environment: Preliminary Engineering and Environmental Assessment*, International Society of Offshore & Polar Engineers.

Chung, J. S. and Tsurusaki, K. (1994) 'Advances in deep-ocean mining systems research', in *Proc 4th International Offshore and Polar Eng Conference, ISOPE*, 18-31.

COOP-COAST (2010) 'World Trade Routes', [online], available: http://co-opcoast.blogspot.co.uk/2010/10/world-trade-routes.html [accessed 22 August 2012].

Cullinane, K., Fei, W. T. and Cullinane, S. (2004) 'Container terminal development in mainland China and its impact on the competitiveness of the port of Hong Kong', *Transport Reviews,* 24(1), 33-56.

Erry, B., Johnston, P. and Santillo, D. (2002) *Seabed Mining: A Technical Review*, Greenpeace Research Laboratories Technical Note 24/2000.

Fukushima, T. (1995) 'Overview 'Japan Deep-Sea Impact Experiment = JET'', in *Proceedings of the ISOPE - Ocean Mitting Symposium (1995)*, Tsukuba, Japan, November 21-22,1995, Tlte lnternatiottal Socicty Offshore and Polar Etigincers,

Glasby, G. P. (2002) 'Deep seabed mining: past failures and future prospects', *Marine Georesources & Geotechnology,* 20(2), 161-176.

Glover, A. G. and Smith, C. R. (2003) 'The deep-sea floor ecosystem: Current status and prospects of anthropogenic change by the year 2025', *Environmental Conservation,* 30(3), 219-241.

Groves, S. (2011) 'Law of Sea Treaty could cost U.S. trillions', [online], available: http://www.heritage.org/research/commentary/2011/07/law-of-sea-treaty-could-cost-us-trillions [accessed 25 July 2012].

Herrouin, G. (1991) 'French study indicates profit potential for industrial manganese nodule venture', *Trans. Soc. Min., Metallur. Expl,* 288, 1893-1899.

Hoagland, P. (1993) 'Manganese nodule price trends: Dim prospects for the commercialization of deep seabed mining', *Resources Policy,* 19(4), 287-298.

Hong, S., Kim, H. W., Choi, J. S., Yeu, T. K., Park, S. J., Yoon, S. M. and Lee, C. H. (2010) 'Development of a self-propelled miner and shallow water test', *Mineral of the Ocean,* 5, 97.

ISA (2001) 'Standardization of Environmental Data and Information – Development of Guidelines', *Proceedings of the International Seabed Authority's Workshop held in Kingston, Jamaica 25-29 June 2001* [online], available: www.isa.org.jm/files/documents/EN/Pubs/2001-Standards.pdf [accessed 23 August 2012].

ISA (2008a) 'Background Document', *Workshop on Polymetallic Nodule Mining Technology - Current Status and Challenge ahead* [online], available: http://www.isa.org.jm/files/documents/EN/Workshops/Feb2008/Backgrd.pdf [accessed 23 August 2012].

ISA (2008b) 'ISA Technical Study No. 3: Biodiversity, Species ranges, and Gene Flow in the Abyssal Pacific Nodule Province: Predicting and Managing the Impacts of Deep Seabed Mining', *ISA Technical Study Series* [online], available: [accessed 22 August 2012].

ISA (2010) 'ISA Technical Study No. 2: A Geological Model of Polymetallic Nodule Deposits in the Clarion-Clipperton Fracture Zone', *ISA Technical Study Series* [online], available: www.isa.org.jm/files/documents/EN/Pubs/GeoMod-web.pdf [accessed 22 August 2012].

ISA (2011) 'Draft Environmental Management Plan for the Clarion-Clipperton Zone.', [online], available: http://www.isa.org.jm/files/documents/EN/17Sess/LTC/ISBA-17LTC-WP1.pdf [accessed 22 August 2012].

Jamasmie, C. (2012) 'Nautilus Dispute with Papua New Guinea to Delay or Even Cancel Underwater Mining Dreams', [online], available: http://www.mining.com/nautilus-dispute-with-papua-new-guinea-to-delay-or-even-cancel-underwater-mining-dreams [accessed 1 August, 2012].

Jankowski, P. and Heymann, E. (2010) *Offshore Production System Definition and Cost Study*, Nautilus Minerals.

Khadge, N. and Valsangkar, A. (2008) 'Geotechnical characteristics of siliceous sediments from the Central Indian Basin', *Current Science,* 94, 1570-1573p.

Li, J. C. (2007) 'China's rising demand for minerals and emerging global norms and practices in the mining industry', *Minerals & Energy-Raw Materials Report,* 22(3-4), 105-126.

Li, L. and Jue, Z. (2005) 'Research of China's pilot-miner in the mining system of Poly-metallic nodule', in *Proceedings of The Sixth ISOPE Ocean Mining Symposium*, Changsha, Hunan, China,

Liu, F. (1999) 'Environmentally friendly deep seabed mining system', *Workshop on Proposed Technologies for Deep Seabed Mining of Polymetallic Nodules: International Seabed Authority Meeting*, 187-212.

MAN (2010) 'Bulkers - Propulsion Trends in Bulk Carriers', [online], available: http://www.mandieselturbo.com/files/news/filesof5479/5510-0007-02ppr_low.pdf [accessed 22 August 2012].

Martino, S. and Parson, L. M. (2012) 'A comparison between manganese nodules and cobalt crust economics in a scenario of mutual exclusivity', *Marine Policy,* 36(3), 790-800.

Melcher, P. R. (1986) *Untersuchungen über das Befahren des Tiefseebodens mit aktiven Manganknollenkollektoren*, Ph.D. Thesis, University of Siegen.

Mero, J. L. (1965) *The Mineral Resources of the Sea,* Elsevier.

Mero, J. L. (1977) 'Economic aspects of nodule mining', *Elsevier Oceanography Series,* 15, 327-355.

Morales-Nin, B. and Ramos, S. (2009) 'Target objectives in Spanish Marine Science within the European context (2003-2007)', *Scientia Marina* 73, 199-204.

Morgan, C. L., Odunton, N. A. and Jones, A. T. (1999) 'Synthesis of environmental impacts of deep seabed mining', *Marine Georesources and Geotechnology,* 17(4), 307-356.

Mukherjee, A., Raichur, A. M., Natarajan, K. and JAYANT, M. M. (2004) 'Recent developments in processing ocean manganese nodules - a critic review', *Mineral Processing and Extractive Metallurgy Review,* 25(2), 91-127.

Rehorn, I. (1994) *Entwicklung eines Tiefseeraupenfahrzeugs und Untersuchung seiner inneren Fahrwiderstände,* Shaker.

Robinson, S. P., Theobald, P. D., Hayman, G., Wang, L. S., Lepper, P. A., Humphrey, V. F. and Mumford, S. (2011) 'Measurement of Underwater Noise Arising from Marine Aggregate Dredging Operations', [online], available: http://www.cefas.defra.gov.uk/media/462859/mepf%20p108%20final%20report.pdf [accessed 23 August 2012].

Rona, P. A. (2000) 'Metallogenesis of maritime mineral deposits', *Workshop on Mineral Resources of the International Seabed Area: International Seabed Authority Meeting*.

Rosenbaum, H. (2011) *Out of Our Depth: Mining the Ocean Floor in Papua New Guinea*.

Schwarz, I. W. (1999) 'Deep sea mining - lift subsystem', *Workshop on Proposed Technologies for Deep Seabed Mining*.

Sharma, R., Nagendernath, B., Valsangkar, A. B., Parthiban, G., Sivakolundu, K. M. and Walker, G. (2000) 'Benthic Disturbance and Impact Experiments in the Central Indian Ocean Basin', *Marine Georesources & Geotechnology,* 18(3), 209-221.

Smith, C. R. (2007) *Rational and Recommendations for the Establishment of Preservation Reference Areas for Nodule Mining in the Clarion-Clipperton Zone*, Kingston, Jamaica: University of Hawaii at Manoa, Hawaii, United States of America.

Soreide, F., Lund, T. and Markussen, J. (2001) *Deep Ocean Mining Reconsidered a Study of the Manganese Nodule Deposits in Cook Island*.

T.Radziejewska, K.Szamałek and R.Kotliński (2003) 'Marine Environment in the IOM Area (Clarion-Clipperton Region, Subtropical Pacific): Current Knowledge and Future Needs', *Proceedings of The Fifth Ocean Mining Symposium, Tsukuba, Japan*.

Terzaghi, K. (1943) *Theoretical Soil Mechanics,* John Wiley and Sons, New York.

Thiel, H. (1991) 'From MESEDA to DISCOL: a new approach to deep-sea mining risk assessments', *Marine Mining,* 10(4), 369-386.

Thiel, H. (1992) 'Deep-sea environmental disturbance and recovery potential', *Internationale Revue der gesamten Hydrobiologie und Hydrographie,* 77(2), 331-339.

TRAM (1991) *R&D of Manganese Nodule mining systems*, Japan.

Trueblood, D. D., Ozturgut, E., Pilipchuk, M. and Gloumov, I. F. (1997) 'The ecological impacts of the joint U.S.-Russian benthic impact experiment', *Proceedings of the Second ISOPE Ocean Mining Symposium: Exploration and Survey, Environment, Mining Systems and Technology, and Processing.*, 139-145.

UNCTAD (2011) 'Review of Maritime Transport (Series)', [online], available: http://unctad.org/en/Pages/Publications/Review-of-Maritime-Transport-(Series).aspx [accessed

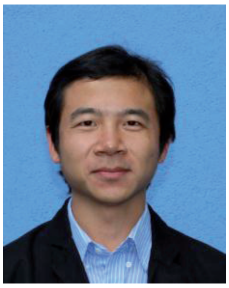
USNO. (1969) *The Sea: A Plan for National Action. Report of the Commission on Marine Science, Engineering and Resources.*, Washington, D. C: Government Printing Office.

Wiltshire, J., Moore, K. and Lay, T. (2001) 'Environmental management of tailings from deep-sea mining through soil engineering', in *Proceedings of ISOPE-Ocean Mining Symposium*, Sczcecin, Poland, International Society for Offshore and Polar Engineers, 82-87.

Wood, M. C. (2007) 'The International Seabed Authority: fifth to twelfth sessions (1999 – 2006)' in *Max Planck Yearbook of United Nations Law*, 47-98.

Yamazaki, T. (2008) *Model mining units of the 20th century and the economies, ISA Workshop on Polymetallic Nodule Mining Technology - Current Status and Challenges Ahead,* Chennai, India.

Baivau Agarwal is currently working as a Senior Engineer (Ship Design) in Bharati Shipyard Limited (BSL), one of the largest Shipbuilding and Ship Design Company in India. After obtaining a Masters Degree in Naval Architecture from the Indian Institute of Technology, Kharagpur, presently he is involved in Tank Testing, CFD analysis and other Naval Architecture related calculations for his company.



Pan Hu is a Ph.D. candidate at the University of Western Australia (UWA). After pursuing a master degree in geotechnical engineering at Dalian University of Technology (DUT), he is enrolled in the Centre for Offshore Foundation Systems (COFS). His research interest lies in Spudcan penetration into multi-layer soils.

Marco Placidi is a Ph.D. candidate at the University of Southampton, working across the Fluid Structure Interaction and the Aerodynamics and Flight Mechanics groups. He received his master from La Sapienza, Università di Roma. His research interest lies within turbulent flows. He is currently working on wall-bounded turbulent flows over rough walls.

Harrif Santo has joined Centre for Offshore Research and Engineering (CORE) in National University of Singapore (NUS) as a Research Engineer and a part time Ph.D. student in Civil Engineering since August 2010. He is currently working on the effects of current blockage on offshore structures under the joint supervision of Prof. Y. S. Choo, Prof. P. H. Taylor and Dr. W. Bai. He is a regular academic visitor to the University of Oxford.

Jenny Jin Zhou is currently pursuing her Ph.D. study at Nanyang Technological University (NTU) in Singapore. She is now working to improve the Life Cycle Assessment (LCA) model, including three aspects: increasing the feasibility of LCA model; improving the reliability of local and regional studies; and building a sustainability evaluation framework to support decision-making.

Feasibility Study on Manganese Nodule Recovery in the Clarion-Clipperton Zone

ISBN 978-0-85432-950-2

9 780854 329502 >