Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Per Henrik Ramberg

Configuration of a Deep Sea Mining Vessel Specialized for the Mining of Seafloor Massive Sulfides

Master's thesis in Marine Technology
Supervisor: Bjørn Egil Asbjørnslett
June 2023

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MASTER THESIS IN MARINE TECHNOLOGY

SPRING 2023

For stud.techn.

Per Henrik Ramberg

Topic:
Configuration of a deep sea mining vessel specialized for the mining of seafloor massive sulfides

Background
The need for rare earth elements for green technologies has never been more present than it is today. The minerals are needed to be able to develop technology that is more environmentally friendly than the ones we use today. These minerals mostly come from onshore mining and some recycling, but to fulfill the needs of the future, this is not sufficient. A solution is to utilize the vast occurrences of rare earth elements found on the seabed. There are three types of deep sea mining that are of interest. This is the mining of polymetallic nodules, cobalt-rich ferromanganese crust, and seafloor massive sulfides. The difference is the depth where they are found, the kind of minerals they contain, and how they are formed. The latter is important because it dictates the solution for how the minerals shall be mined.

The Norwegian continental shelf is a promising area to conduct deep sea mining. A part of the mid-Atlantic ridge, called the Mohn's Ridge, is located here. This is an area with substantial amounts of sulfide chimneys and seafloor massive sulfides. Mining in these areas can provide a vast amount of rare earth elements needed for technology development. Additionally, Norway has a long shipbuilding history as well as vast experience in offshore operations from the oil and gas industry. Combined, these factors make Norway an ideal location for deep sea mining.

There are some projects and vessels within the field of deep sea mining today, but they have yet to be proven economically sustainable. Most of them have been converted from offshore drilling vessels to deep sea mining vessels.

Objective
The objective of this thesis is to utilize well-proven engineering design theory to lay the foundation for vessel configuration of a specialized deep sea mining vessel that is built for mining seafloor massive sulfides. The vessel needs to be able to conduct mining operations at a depth of up to 3000 meters and retrieve both solid pieces of sulfides, as well as a slurry containing copper, lead, zinc, gold, and silver. It is estimated that there are approximately 600 million tonnes of seafloor massive sulfides globally. The mining of seafloor massive sulfides requires specialized equipment for seabed mining, vertical transportation, and onboard handling of the minerals. Mining-specific equipment has a significant effect on the vessel's configuration. All these elements need to be considered in the final configuration.

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Tasks
The candidate is recommended to cover the following parts in the project thesis:

a. Review state of art within the topic. That means to document what others have done and published previously.
b. Document the system in which the problem is located.
c. Document the problem in a generic way.
d. Document relevant approaches and methods for addressing and solving the problem, and choosing an approach/method for one's own work.
e. Apply the relevant approaches and methods for the thesis topic.
f. Discuss strengths and improvement potential in one's approach and work – with respect to conclusions.
g. Suggestions for further work.

General
In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work.
Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.
The candidate should utilize the existing possibilities for obtaining relevant literature.
The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.
The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.
The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.
The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Supervision:
Main supervisor: Bjørn Egil Asbjørnslett

Deadline: 11.06.2023

Abstract

The deep sea mining industry may be an important contribution to the development of green technologies due to the vast occurrences of minerals. A deep sea mining vessel will make a contribution to the establishment of this industry. This master's thesis provides a low-level of detailed basis for a deep sea mining vessel specialized for seafloor massive sulfide mining. The vessel is based on a theoretical foundation by well-known engineering design theory and approach. An extensive literature study presents different aspects of the deep sea mining industry, mining equipment research, and theoretical approaches to vessel configuration. A breakdown of the mining systems shows a substantial amount of sub-function needed to successfully retrieve seafloor massive sulfides from the seabed. Equipment needed for the task is evaluated, selected, and modularized with regard to the mining operation. Additionally, a set of design structure matrices describe the dependencies between needed components. Finally, a configuration of a specialized seafloor massive sulfide deep sea mining vessel is illustrated with all presented modules.

Sammendrag

Gruvedrift på havbunnen har muligheten til å være en viktig bidragsyter til utviklingen av grønne teknologier på grunn av forekomsten av store mengder mineraler. Et fartøy spesiallaget for gruvedrift på havbunnen vil være et stort bidrag til oppstarten på denne industrien. Denne masteroppgaven presenterer en lite detaljert base for et dyphavs gruvefartøy spesiallaget for gruvedrift av undersjøiske sulfidforekomster. Fartøyet er basert på et teoretisk grunnlag med kjente ingeniørdesignteori og -tilnærminger. En omfattende litteraturstudie presenterer forskjellige aspekter av gruvedrift på havbunnen, undersøkelser av gruvedriftsutstyr, samt teoretiske tilnærminger til fartøyskonfigurasjon. En dekomponering av gruvedriftssystemene viser en omfattende mengde delfunksjoner som er nødvendige for å hente undersjøiske sulfidforekomster fra havbunnen. Utstyret som trengs for å gjennomføre dette er evaluert, valgt og modulert med tanke på gruvedrift på havbunnen. I tillegg til dette vil flere design struktur matriser beskrive de forskjellige avhengighetene mellom valgte komponenter. Til slutt er et spesiallaget fartøy for gruvedrift av undersjøiske sulfidforekomster illustrert med alle tilhørende moduler.

Preface

This master's thesis is written as the final part of the Master of Science degree in marine systems design in the spring of 2023 at the Norwegian University of Science and Technology, NTNU. The entirety of this thesis is the author's work. Parts of this thesis are based on the preliminary project thesis written in the fall of 2022 by the author.

At times, the work has been challenging. Especially the limited amount of information on the thesis subject has been arduous. On this part, Ph.D. Astrid V. Solheim has been of great help.

I want to use this opportunity to extend my gratitude to my supervisor Professor Bjørn Egil Asbjørnslett for his support throughout the semester. He has contributed with guidance and knowledge, which this paper could not be written without. Additionally, I would like to thank my fellow students Jacob Maurud and Felix Dietrichson for meaningful discussions and a good working environment.

Trondheim, June 8^{th}, 2023

Per Henrik Ramberg

Table of Contents

List of Figures

List of Tables

Abbreviations

AHC	Active Heave-compensated Crane
AUV	Autonomous Unmanned Vehicle
BOP	Blow Out Preventer
Cb	Block coefficient
DP	Dynamic Positioning
DSM	Design Structure Matrix
DSMin	Deep Sea Mining
ECDIS	Electronic Chart Display and Information System
Hs	Significant Wave height
HWC	Heavy Work Class
IMO	International Maritime Organization
ISA	International Seabed Authority
kW	kiloWatt
LARS	Launch and Recover System
LCOM	Levelized Cost of Mining
LCSV	Large Construction Service Vessel
LOA	Length Over All
LPP	Length Between Perpendiculars
m	meter
MDM	Multidomain Matrix
MDO	Marine Diesel Oil
MV	Motor Vessel
MW	Mega Watt
OCV	Offshore Construction Vessel
OEV	Ocean Engineering Ventures
OSV	Offshore Service Vessel
PBSA	Pahl and Beitz's Systematic Approach
PC	Pipe Handling Crane
POB	People on Board
RALS	Riser and Lifting System
RIPS	ROV Integrated Pumping Solution
ROV	Remotely Operated Vehicle
RPM	Revolutions per Minute
RRE	Rare Earth Elements
SMS	Seafloor Massive Sulfides
SSLP	Seabed Slurry Lift Pump
STD	Submarine Tailing Disposal
SWL	Safe Work Load
t	Ton
TRL	Technology Readiness Level
UUV	Underwater Unmanned Vehicle
VTS	Vertical Transport System
WC	Working Crane

1 Introduction

Background
The world is in a situation where green technologies and environmentally friendly development are crucial for the existence of the ecosystems as we know them. A considerable part of this technology development is based on rare earth elements (REE) and minerals [1]. Until now, the only sources we have been able to mine have been on shore. These mines will eventually run out and there is not enough raw material on shore to sustain tomorrow's development. This is why we need to look for new places and ways of mining. The natural way forward is to utilize the opportunity of deep sea mining (DSMin). Considerable amounts of REE have been discovered on the seabed in numerous locations. According to estimates, there are approximately 600 million tonnes of seafloor massive sulfides (SMS) which contain 30 million tonnes of copper and zinc globally. All of these are found in the immediate vicinity of oceanic plate boundaries [2]. To be able to mine these resources we need to develop specialized deep sea mining vessels. These vessels have to be both economical and environmentally sustainable.

The interest in deep sea mining is not new. The first ever discovery of manganese nodules was in the 1870s during the Challenger expedition, but commercial interest did not appear before the 1960s [3]. The first idea to utilize the resources on the seabed through deep sea mining was raised by John L. Mero with his paper *Minerals on the Ocean Floor* [4] which later became the book *The Mineral Resources of the Sea* [5]. Following this, several successful tests were conducted, but none of these led to any commercial mining. The projects were abandoned and there was little to no development in the field until recent times [6].

With the rise of interest in deep sea mining, environmental concerns began to increase. There were several attempts to create international regulations, both for the environmental and legal sides. This effort finally succeeded in the conference called *Third United Nations Conference on the Law of the Sea.* More than 150 nations participated in these negotiations that lasted for nine years, from 1973 to 1982. This resulted in the United Nations Convention on the Law of the Sea [7]. It is important to know that this is not only an agreement of regulations for deep sea mining, but *a comprehensive regime of law and order in the world's oceans and seas establishing rules governing all uses of the oceans and their resources* [8]. Later on, a new body within the organization was created. This is called the International Seabed Authority (ISA) and has a special focus on regulations concerning deep sea mining. This is all within the International Maritime Organization (IMO).

Norway is in a position that allows them to be pioneers in the field of deep sea mining. In 2021, the Norwegian government started an impact assessment of mining on the Norwegian continental shelf [9]. The area of interest is the size of Germany and is located around Jan Mayen and north towards Svalbard [10]. The most promising area is called Mohn's Ridge, and more specifically Loki's Castle. It is located at the Mid-Atlantic ridge with an average depth of 2500 meters [11]. There is an "excess" of high-temperature venting along slow and ultra-slow spreading ridges and these

areas may have the strongest mineral resource potential for the global ridge crest [12]. Mohn's Ridge is an ultra-slow spreading ridge.
Additionally, Norway has a long history of shipbuilding and a lot of experience in deep ocean operations from the oil and gas industry. All of this combined gives Norway an opportunity to be world-leading in the field of deep sea mining.

There has been an attempt to build a deep sea mining vessel previously. In 2018 the MV Nautilus New Era was supposed to be delivered to Marine Asset Corporation with a charter contract to Nautilus Minerals for 5 years. This was a deep sea mining production support vessel. The vessel was the first of its kind. It was supposed to be stationed outside Papua New Guinea for the Solwara 1 project. This is however not what happened. In late 2018, Ocean Energy Ventures (OEV) together with Quippo Oil and Gas acquired the newly built vessel. The reason was that Nautilus Minerals had put themselves in severe debt and could not afford the vessel [13].

The MV Hidden Gem is the most modern DSMin vessel to date. It was converted from a drilling vessel in 2020 and 2021. It is owned by the company Allseas in partnership with The Metals Company. This 228-meter-long vessel is the first in the world to be classified as a sub-sea mining vessel under the American Bureau of Shipping [14]. The vessel is able to deploy a 4,5 km raiser to transport polymetallic nodules from the ocean floor to the surface. In addition, it is equipped with a custom-engineered collector vehicle for the responsible recovery of polymetallic nodules. The collector is controlled and powered by a 5000-meter umbilical from the vessel and deployed over the side by means of a launch and recovery system (LARS) [15]. The collector is operated from a control cabin onboard the vessel and moves in parallel motion with the vessel's dynamic positioning system. The MV Hidden Gem achieved a milestone in October 2022 by successfully extracting polymetallic nodules from the seafloor in the Clarion-Clipperton Zone. This is the first time such a feat had been accomplished since 1970. [16]. The collector was driven 147 meters along the seabed during a 60-minute pilot collection run. The result was that 14 tonnes of nodules were collected and brought onboard the vessel through a 4,3 km riser system with compressed air. The nodules were stored in the MV Hidden Gems cargo hold. This operation proved that a riser is a solution to the vertical transport of polymetallic nodules.

Objective

The available resources on the ocean floor are crucial for our development of tomorrow's environmentally friendly technology. The minerals mined from the seabed contain valuable metals such as lithium, copper, nickel, and rare earth elements [1]. These metals are essential components in batteries, cars, cell phones, and more. To be able to mine these resources, we need specialized deep sea mining (DSMin) vessels. As of today, there is a few vessels that are able to do this job and none of them has been specially built (from scratch) singlehandedly for this purpose. All of the vessels have been converted vessels, mainly from drilling ships.

This thesis starts with a literature study of relevant papers linked to deep sea mining and engineering design theory. This will consist of articles focused on the main dimensions of a deep sea mining vessel, the development of equipment used for deep sea mining, the environmental impact of deep sea mining, the possibilities of extraction of RRE in different locations, and theoretical approaches to vessel configuration. A literature study will increase knowledge and give a starting point for the master's thesis to come.

The main purpose of this paper is to utilize methods for deep sea mining vessel configuration. The methods have been developed for vessel design, but they have yet to be utilized in the field of deep sea mining. To be able to justify the equipment placement and interaction between equipment it is important to use proven theory. One of these decision tools is Design Structure Matrices (DSM). The DSM method will give a visual representation of the interaction between all the equipment that is planned to go on the vessel.

Furthermore, the thesis will utilize the knowledge gained through literature studies to develop a base for a DSMin vessel. This will include a selection of equipment needed for SMS mining. This basis is going to have a foundation in a system breakdown. The final product will be a low-detailed illustration of a possible vessel configuration.

As mentioned, there are no specially built (from scratch) vessels today for deep sea mining. In addition, there are next-to-non developed concepts in the area. This is what this thesis is going to investigate and lay fundamentals for. On the basis of the main dimensions stated in the paper *Technology Transfer in Novel Ship Design: A Deep Seabed Mining Study* written by Solheim et al. [17], this thesis is going to explore the possibilities of fulfilling this gap when it comes to vessel configuration for a DSM vessel. The main focus is to thoroughly dive into the connection between needs, function, and form of the vessel. Meaning that first, the needs of a DSM vessel are mapped. When this is done, the specific requirements of each need have to be combined with the functions of the rest of the vessel. To do this, modularisation and design structure matrix is utilized. The combination of all these modules will result in a layout and description of the vessel form.

A specialized DSM vessel is an important step toward making the deep sea mining industry environmentally and economically sustainable. The possibilities that arise with an efficient and up-to-date vessel will help the industry grow and prove it selves as an invaluable part of the development that is tomorrow's green energy. To achieve this, the vessel needs to have a well-based foundation and all decisions must be backed up through well-proven methods. This master's thesis aims to provide a functioning and well-founded description of a deep sea mining vessel.

Structure
The remainder of this paper is organized as follows: Section 2 describes the literature studies which includes the state-of-the-art within deep sea mining as well as engineering design theory. Section 3 describes a variety of possible deep sea mining-related equipment. Section 4 is a description of the mining system. The results of the vessel configuration are shown in Section 5. Finally, a discussion, conclusion, and further work are given in Section 6, Section 7, and Section 8.

2 Literature Studies

In Section 2, a wide range of papers are reviewed and described. In addition to this, there are several sources that have provided information for this paper. These are shown in the bibliography. This section is divided into two main sub-sections. The first is *General literature studies* which focuses on general knowledge of the DSMin industry and current projects. The second, *Theoretical literature studies*, is more theoretical and describes different approaches and methodologies within engineering design. All sources are reviewed with regard to how they can contribute to this thesis. A description of the possible contribution of the papers is shown at the bottom of each sub-section.

Parts of this section are from the preliminary studies for this master's thesis written by Ramberg, *Preliminary Work for Vessel Optimization within Deep Sea Mining* [18].

2.1 General literature studies

General literature studies include articles that present solutions to different aspects of DSMin, describe DSMin projects, and in general the DSMin industry. The goal for this part of the literature review is to gain a general knowledge of the industry and to know what the state-of-the-art publications conclude on.

Seafloor Massive Sulfides

Seafloor massive sulfides have been of commercial interest since the first exploration and feasibility studies in the marine environment were conducted in the 1980s on the East Pacific Rise [19]. Despite this, the cost of extraction, falling mineral prices, and technological barriers appeared to halt potential SMS mining in the deep sea before it became a commercial reality [6]. The reason for the interest in SMS deposits is that they contain vast amounts of copper, zinc, lead, silver, and gold which are needed for developing tomorrow's green technology. In addition to their economic value, seafloor massive sulfides are also of great scientific interest, as they support unique ecosystems that are home to a wide variety of marine life.

SMS deposits are found on the seabed. These consist of hard substratum with high base metal and sulfide content. These sites are commonly found at hydrothermal vent sites located on deep sea ridges around the world [20]. An example of such a deposit is the area called Loki's Castle. This is located on the Mohn's ridge in the Atlantic Ocean, shown in Figure 1.

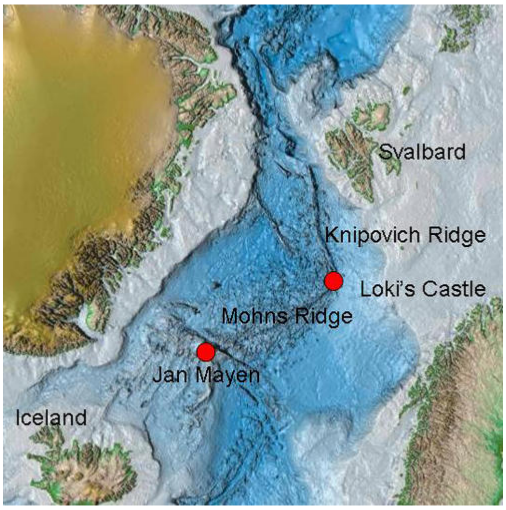


Figure 1: Location of Loki's Castle [21]

Among the three main types of mineral deposits on the seabed, polymetallic nodules, seafloor massive sulfides, and ferromanganese crust, the SMS is the one that contains the highest concentration of copper with grades ranging from 0.8wt% to 13.4wt% [22]. Copper is important because it is a good conductor of electricity and is used in a lot of electronics. The SMS deposits get formed on and below the seabed. This is due to the interaction between cold seawater and the magma in deeper regions of the seafloor. The formation of SMS is shown in Figure 2 and goes as follows: (1) Through fault and cracks, the seawater penetrates down to several kilometers into the seafloor, (2) seawater approaches the magma and is heated. The elements from the surrounding rocks are leached by the heated water, (3) the low-density seawater, now enriched with minerals, rises towards the seafloor through permeable areas in the crust. As it reaches the cooler temperatures at the surface, the minerals precipitate and accumulate in the mineralized zones of the stockwork and the sulfide mound, (4) the seawater erupts as plumes from chimney-like structures and (5) the sediments in the plumes get colder and continues to enrich the sediments around the hydrothermal site. This process takes millions of years to reach an amount that is desirable to mine [22].

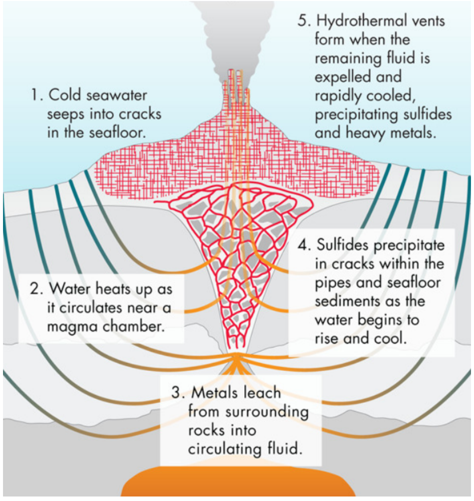


Figure 2: Formation of volcanogenic seafloor massive sulfide deposits [23]

Environmental Impact Statement Solwara 1 Project

The Solwara 1 paper [24] is a description of the Solwara 1 project and its possible environmental impact. This is a paper that Nautilus Minerals have ordered to map the feasibility of deep sea mining on the floor of the Bismark Sea, New Ireland Province, Papua New Guinea. The main focus is the environmental impact, but it is not the only aspect of the paper. A description of the Solwara 1 project as well as a (relatively) detailed description of the planned approach is written in this paper. This description contains the different phases of the project, the area to be mined, the tools which are going to be utilized, the mining support vessel, and the solutions for bringing the mined material to the surface and to shore. An economic perspective and timeline are briefly mentioned as well.

The main focus is as mentioned the environmental impact. It has been conducted several exploration trips and studies in the area. The area is filled with sulfide chimneys. Previously there has been little to no knowledge about the marine life in these areas. This has now changed. Marine life has been found, both dead and alive, in the area. These findings make the environmental aspect of mining even more complicated. There are also complications regarding the dewatering discharge. This has been investigated for this particular project. The findings say that if the dewatering discharge is dumped close to the seabed where originates from, both vertically and horizontally, this will have little impact on marine life.

The Solwara 1 paper will not play a significant role in my paper. There are two main reasons for this. The first is that the paper is written in 2008 and a lot of the material described is outdated. Another reason is that this paper focuses area on the environmental impact of deep sea mining. This is not the focus area of this thesis.

Technology Transfer in Novel Ship Design: A Deep Seabed Mining Study

The goal of this paper, written by Solheim et al. [17], is to utilize methods developed for the oil and gas industry to set the main dimensions and other important parameters for a deep sea mining vessel. First, there is a mission description from the case which includes where the operation is planned, the distance to shore, and the water depth. The next step is to set three possible cases. They are separated by how many tonnes needed to be produced per day. After this, important performance expectations are set, and significant wave heights in the relevant area were studied. The next step is to inspect the bulk carrier segment of the market to find possible vessels to be used in the transportation of ore to shore in all three cases. Cost factors and equipment needed to be determined as well. When all this was done, the paper presents the results. The results are divided into three different cases. There are two main results in this paper. The first is the main dimensions for a deep sea mining vessel. The second one is the comparison between the new build cost of the vessel and the levelized cost of mining (LCOM).

Case three, the largest vessel, is the most favorable solution from the paper. A general description of the finding is shown below together with the specific data shown in Table 1 and Table 2.

The basis in this case is an offshore construction vessel (OCV). The operational region has been specified to the Norwegian Sea with a desired dynamic positioning (DP) capacity of Hs = 4.85 meters. The block coefficient (C_b) is set manually to obtain a rounded hull which allows for more storage. A diesel-electric propulsion system is chosen. The engine room setup contains two engine rooms and two switchboards. Mining-specific equipment for the vessel is a crushing/dewatering plant, pipe/riser storage, self-offloading system, and collector system.

Technical data related to the ship systems and mission-related equipment are shown in Table 1.

Ship Systems	**Technical Data**
Hull	Cb = 0.8
Engine Room	50MW
Accommodations	150 POB
Station-Keeping	DP 3, 6x5,000 kW thrusters
Deck Area	Riser joint storage 20x30m workshops Safehouse
Mission Equipment	
Seabed Collectors	3 collectors + 2 spare collectors
Launch and Recovery	System & 3xA-frames á 210t, 260t and 310t
Crushing and Dewatering	
Ship-to-Ship ore Transfer	2x self-unloaders
Ore Storage	
Riser Assembly	2x AHC offshore cranes á 350t 14m w/ 3000 wire
Riser Deployment	8x8 m Moonpool Derrick
Riser Storage	Pipe racks
ROV	2x work ROVs (hangar and work deck) Overside system with 3000m reach
Other Data	
MDO density	0.9 t/m^3
Contingency Factor	1.3
Fuel Capacity	820 t
Ore density	3.5 m^3

Table 1: Data for ship systems and mission equipment [17]

Further, the results in *Technology Transfer in Novel Ship Design: A Deep Seabed Mining Study* [17] are divided into three cases. These cases are *Small vessel, Medium vessel* and *Large vessel.* Only the results from *Large vessel* will be presented as this is the case that is going to be the base for further work. The reason this case was chosen is that the Levelized Cost of Mining is a lot more sustainable for the *Large vessel* case than for the other two others. This is shown in Figure 3. The parameters for the DSM vessel are shown in Table 2

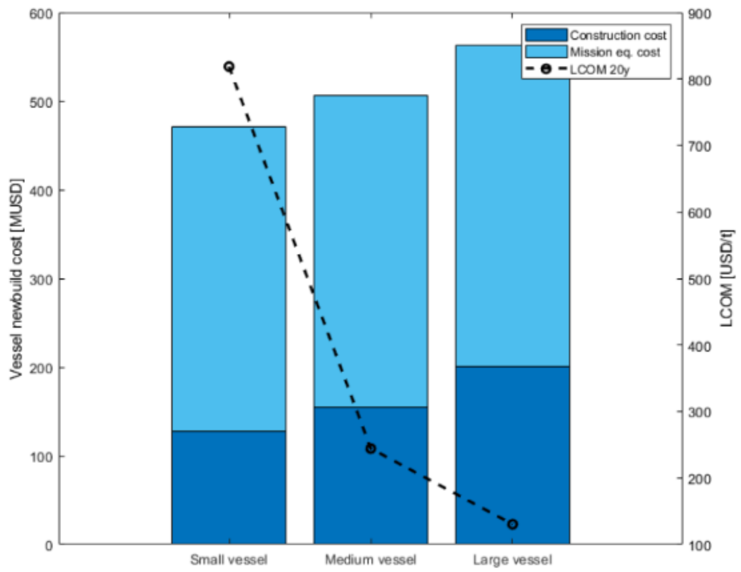


Figure 3: LCOM for all three cases [17]

Parameter	**Large Vessel**
Length over all (LOA)	225 m
Length between perpendiculars (LPP)	215 m
Beam	40 m
Depth	20 m
Max draft	15
Cb at maxt draft	0.81
Design draft	14
Free deck area	5.395 m^2
Power installed	47.231 kW
Design deadweight	69.669 t
Max deadweight	78.392 t
Max deadweight w/ moonpool and topside	80.665 t
Length/beam rato	5.63
Length/draft ratio	15.0-16.0
Beam/draft ratio	2.7-2.9
Deck load - initial	69.199 t
Deck load - final	34.348 t
Steel weight	14.627 t
Lightweight	24.378 t

Table 2: Main parameters for a large DSMin vessel [17]

The paper has three conclusions: Firstly, the results show that a larger vessel has favorable stability and capacities, allowing a higher production rate and contrasted strong effect on the levelized cost of mining. The next result is that this paper has shown that when examples of reference basis vessels are short or non-existing, it is very important to identify the most relevant reference vessel segment and explore supporting documentation for a novel ship design concept coming from that segment. Finally, the resulting strategy – to keep the special equipment on the mining vessel and keep it producing – had a direct effect on the engineering tactics and marine systems design configuration.

This paper will be an important resource in the following thesis. The main dimensions for a deep sea mining vessel are not something that can be easily found by looking at other existing vessels, nor is it easy to establish them. This data found in *Technology Transfer in Novel Ship Design: A Deep Seabed Mining Stud*, as well as the equipment described, will be useful for this thesis.

A Novel Mining Approach for Seafloor Massive Sulfide Deposits

The paper written by Spagnoli et al. [25] is exploring the possibility of vertical mining of seafloor massive sulfides. This is a method that has been used successfully previously, but only in shallow waters or for onshore applications. The main goal is to develop an industrial, reliable, and environmentally friendly vertical continuous mining machine feeding a slurry lifting system adapted to harsh subsea conditions. The machine is independent of the riser system. A vertical "plunging" method is foreseen. This will create a rectangular well in the seabed to access the SMS. It is yet to be decided how the machine will move horizontally to create numerous wells. The paper described different design challenges, especially related to the hyperbaric conditions the machine will be exposed to. Further, it is shown how much energy is needed for deep sea mining at 2000 meters depth and an expected mining rate.

This paper may play a role in my project. This is because the mining tool developed in this paper may be relevant equipment for the deep sea mining vessel. Further research needs to be conducted before the final decision can be made. This is because the interaction between different equipment onboard has to be mapped.
The calculations from this paper will not be used in further work.

Preliminary Design of a Trench Cutter System for Deep-Sea Mining Applications Under Hyperbaric Conditions

This paper, written by Spagnoli et al. [26], investigates the effect of hyperbaric cutting in terms of energy, and a preliminary cutting tool designed to be able to work under hyperbaric conditions. The paper is closely connected to the other paper written by Spagnoli *A novel Mining Approach for Seafloor Massive Sulfide Deposits* [25]. Both of them focus on a vertical cutting method and the development of a machine useful for deep-water applications. The description of how this deep water mining machine will work is: *As the cutter penetrates, soil, rock, and bentonite are conveyed toward the openings of the suction box, from where they are pumped by a centrifugal pump through the slurry pipe incorporated in the cutter's frame, via the mast head into the slurry conveying system to the desanding plant.* Similar machines have been built and used previously. The difference between the "old" machines and the ones being developed is their working environment. Previously they have been working on shore or in shallow waters, meaning that this is a continuation of existing technology combined with innovation. The paper calculates the forces working on the mining machine. This is done to know how much stress the machine needs to endure as well as to know what force it needs to execute. The result is that it is feasible to use this machine at water depths up to 2000 meters and the estimated energy needed is 2.9 times higher than on shore. This is calculated for a worst-case scenario.

As for the other paper written by Spagnoli [25], this might play a role in my project. This is because the machine may be relevant equipment to implement on the DSMin vessel. The calculations carried out in this paper will not be used in further work.

Well drilling

This sub-section is based on the oil and energy company Shell's description of deep sea drilling [27]. It will also describe possible solutions for utilizing known well drilling technology in deep sea mining.

An offshore well aims to be drilled directly above the deposit that contains the desired hydrocarbons. When a drilling vessel is used, it relies on its DP system to maintain its position. When the position is fixed, the drilling can begin. It starts by lowering a drill bit down to the seabed. This is called "spudding in" a well. The drill bit is located inside a pipe casing when it starts drilling. This is done to ensure that the surrounding soft sediments do not cave in. The casing is jetted into the soft sediment with the help of water or drilling fluid. This process is done while the drill head is right above the seafloor, acting like a base. The drilling head will then be drilling within the pipe casing. When the drilling head reaches the end of the casing, it will continue to drill down in the solids below. At this point, sediments and water will be pumped down through the drilling bit. This is done to cool down the drilling bit and act as a lubricate. In addition, it will bring the cuttings and sediments from the bottom of the hole up to the seabed through the hole and the casing. Another reason for choosing this solution is that it equalizes the pressure between the outside and the inside of the casing and hole and keeps fluids from flowing into the well. At a specific depth, dependent on the surrounding conditions, a new casing pipe will be run down into the well through the old, larger case pipe. When the new casing is in place, concrete will be pumped down the pipes and flow up around the outside of the casing. This will permanently secure the pipes. Mud is used to push the cement down through the pipe. The mud and the cement are separated with a plug. This process is repeated until the desired depth is reached. Each time a new casing is installed, it has a smaller diameter than the last one, thus a smaller drill head. Before the hydrocarbons are reached, a blow-out preventer (BOP) is installed. The BOP will be the connection between the well and the riser that is attached to the production facility. In addition, the BOP acts as a protection so the trapped hydrocarbons do not leak into the ocean or are pushed uncontrolled through the riser.

Using Drilling Technology in Deep Sea Mining

Using known technology from the oil and gas industry in deep sea mining is a way of utilizing proven methods. An example is the interaction between the drill head and the riser system. There are differences in both size and purpose, but the basic principles are the same. When drilling a well using mud as a lubricant, the mud is pumped up to the vessel for cleansing and recycling. For DSMin, it is the valuable ore that needs to be transported through a riser to the vessel. In both situations, the drill head will grind up the soil/ore and the riser will transport it to the surface. In addition, the mud will counteract the outside pressure so the system does not collapse.

Another example is the drilling technique, especially directional drilling. Directional drilling is a technique developed in the oil and gas industry to be able to drill into hard-to-reach oil deposits. This technique makes it possible to drill in most directions, not only straight down. The advantage of utilizing directional drilling is that need of moving the vessel will be limited. Moving the vessel requires the drilling equipment to be hoisted up and thus a stop in the drilling operation. Such a maneuver is costly. If directional drilling is utilized instead, the DSMin vessel is able to stay in the same position for a longer period of time. To do this will make the most of the limited weather windows that are the reality in the North Sea. However, there are challenges related to this as well. In the oil and gas industry, a small drill head is used for drilling. This makes directional drilling possible. This is not the case for DSMin. A larger drilling head is likely to be utilized. How to implement the directional drilling technology with this equipment is not yet known.

Preliminary Powerplant Concepts of a DSM production Support vessel

This paper, written by Roelofsen [28], has the main goal of presenting possible powerplant concepts for a deep sea mining vessel. First, the paper starts by doing research on the weather conditions in the Clarion-Clipperton Zone as well as determining how many tonnes of polymetallic nodules are to be mined. The next step is to look at the equipment which will be used. It is decided to use a nodule collector with a with of 16 meters, a length of 20 meters, and a total weight of 120 tonnes in air. For the process of bringing the mined material to the surface, a riser system is chosen. Both the possibility of utilizing a hydraulic system and an airlift system are being examined. Another important piece of equipment is the dewatering system. Dewatering is done to be able to store the nodules in a dry state. This will significantly reduce the required storage space and reduce the stability concern. The offloading system is also to be considered. This can be done as wet or dry offloading. Both possibilities are investigated.

The next step in the paper is to determine design requirements. These are all based on previous decisions and assumptions made earlier in the paper. The design requirements is considering vertical transport system (VTS), vessel size, emissions, DP system, and sea states. Further, the paper splits the vessel into blocks/modules. These modules consist of accommodation, collector, vertical transport(riser storage, hydraulic transport, airlift transport, return pipe assembly tower, energy dynamics and jumper hose & ROV), dewatering, nodule storage, internal transport, offloading and onboard cranes. The next chapter has focused on vessel design. This chapter takes a closer look at the main dimensions, stability, and resistance of the hull. The different powerplant options for both hydraulic and airlift VTS are considered. These chapters describe the different demands of power from the different solutions as well as different ways of achieving the required output.

This paper covers a lot of the elements that are important for a deep sea mining vessel, but its main focus is the power requirements and configuration. This is important, but the main focus of this thesis is the configuration of mining-specific equipment. It means that the knowledge gained is valuable, but the paper itself may not be a main source in further work.

Deep sea mining: Towards conceptual design for underwater transportation

This paper, written by Astrid Solheim and Maxime Lesage [29], has a goal to describe and design a system that has the definition "to transport ore from the deposit at seabed to the quayside". The paper presents the first steps toward conceptual design for the underwater transportation of minerals from the seabed to shore. The methodology in the paper is based on a conceptual design using a systematic approach. The systematic approach is described in the book *Engineering design: A systematic approach* [30]. The methodology is essential for this paper and to put it briefly it goes like this: abstraction to find essential problems, establishing function structures, searching for working principles, combining working principles into working structures, selecting suitable combinations, firming up into solution variants evaluating against technical and economic criteria and finally we reach the principle solution.

There are several possible methods described in this paper. The key similarity is that the transportation is done underwater, instead of on the surface with bulk ships. An example of this, which is presented in the paper is to utilize a large fleet of underwater unmanned vehicles (UUV). They will pick up the payload and transport it from the mining site, either internally or externally, directly to the quayside. Another solution is to utilize barges with payload. This concept is designed to work in potential ice-covered waters. In short, a barge is filled with payload, attached to an autonomous underwater vehicle (AUV), and pulled underwater. While the barge is underwater, the AUV will pull it under the ice and to the quayside. Here, the barge will resurface.

The results show that the systems have one overall function, FR0 - Transportation system, and this system is divided into three subsystems, FR1 - Collecting system, FR2 - Underwater vehicle, and FR3 - Unloading system. Further, the paper describes these subsystems in detail. The paper has no final solution or design, but it describes the process and may, later on, be used to describe and design a fully functional system.

This paper will be a resource in my further work. The main reason for this is not necessarily because of the concepts described, but because of the approach used. The use of the book *Engineering Design: A systematic approach* [30] is a good example of how this thesis can utilize the same source. This is a well-known method that is intended to use be used to back up decisions and give them credibility.

Finding the generic function structure of a deep-sea mining system

This paper, written by Maxime Lesage and Stein Ove Erikstad [31], presents a method within a systematic approach to design that consists of (1) reviewing various existing concepts (2) establishing a function structure for these concepts and, (3) synthesizing a generic function structure by merging the produced function structures. The paper uses an approach referred to as PBSA (Pahl and Beitz's Systematic Approach). In short, the method starts by identifying the essential problems of the system being designed. The next step is establishing function structures and decomposing the initial problem into sub-problems that are less complex. Then, possible solutions are created and mapped. This is done for each sub-system. These systems are combined into working structures. The working structures are evaluated in order to identify the principle solution. In the next step, embodiment design uses these working structures to fully describe the system.

The next part of the paper describes the theory behind how one would break down a system into sub-systems on different levels (Level 0, level 1, and so on). The theory also states that the three main inputs/outputs that a system receives or produces are energy, a signal, or material. For a DSMin system, the main type of function is to transform the state of the material. In addition, there is a distinction between main functions and auxiliary functions. A main function is a sub-function that directly contributes to the overall function. An auxiliary function contributes indirectly because it is necessary for the support of one or more main functions.

Further, the decomposition of several systems is presented. The systems presented are concepts that have been either tested or concepts that have yet to be realized.

The conclusion presented is that the recognized method PBSA is well-suited for a systematic review and analysis of existing concepts within deep sea mining. The resulting function structure can be considered generic for any deep-sea mining system and is composed of four sub-functions: 1) the extraction of minerals from a subsea deposit, 2) the vertical transportation of the minerals from the seabed to the surface, 3) the horizontal transportation of the minerals from the deposit's location to a shore location (port) and 4) the interface between the vertical and horizontal transportation.

This paper will be used in further work in this master's thesis. The method presented, and used, is considered a respected way of breaking down and describing a system. This is one of the goals for this thesis as well, thus it will be a good resource for further work.

A conceptual design framework for deep-sea mining

The paper *A conceptual design framework for deep-sea mining* by Lesage et al. [32] aims to fulfill the gap in the literature for deep sea mining design framework. It is utilizing the book *Design Engineering* by Pahl et al. [30]. The design process from Design Engineering divides the process into four phases. These are: (1) the task clarification where the needs of stakeholders are reformulated into a design problem (i.e. requirements of the product), (2) the conceptual design where the complex design problem is decomposed to identify the basic principles of the solution, (3) the embodiment design where the basic principles are organized into a layout satisfying some technical and economic constraints and (4) the detailed design phase where the desired solution is finalized to a level of detail required for production. The paper goes on to describe a generic function structure, the same as in *Finding the generic function structure of a deep-sea mining system* [31] and a description of Loki's Castle - the base case for Norwegian SMS DSMin. The next step is to describe the theory behind the suggested approach. This is a brief description, or summary, of the key elements from the Pahl and Beitz book *Design Engineering.* One of the main takeaways from this chapter is how to establish a working structure by using a morphological approach. In short, it describes how different subsystems are related and "identifies and investigates the total set of possible relationships or configurations". The strength of the systematic approach is that it will obtain the widest possible solution field, i.e. the probability of missing an exceptionally good solution is minimized. The downside is that the vast number of solutions will increase the workload. The validation of the solution is described next.

The next chapter describes the methodology. It starts by producing design catalogs for the function structure and shows a generic template. The next step is mapping the space of overall solution variants. Evaluating the overall solution variants and selecting principle solutions comes as the following steps. When this is done, a summary is made.

From the generic function, four sub-functions are identified for the DSMin system. These four are (1) extracting minerals from a subsea deposit, (2) vertical transportation, (3) horizontal transportation, and (4) interfacing vertical and horizontal transportation. Further, the paper describes different solutions for each of the subsystems in detail. After this, an example using the BAUER Maschinen's design is used for further explanation of the approach.

The paper will be a valuable resource for further work. The use of Pahl and Beitz's book *Design engineering* is directly transferable to this thesis. In addition, the suggested approach that is described and exemplified is well-suited for the upcoming work.

Summary

The field of deep sea mining is not explored in great depth. The sources described in Section 2 are of varying relevance for this thesis. The most important paper is *Technology Transfer in Novel Ship Design: A Deep Seabed Mining Study* [17]. The descriptions of the main dimensions and equipment will be used in the majority of the work to come.

The engineering design approach described in Lesage et al. in [31] and [32] is useful for the goal of this thesis. The well-known basis they are built on helps to form a reliable background for both their papers and the resulting work in this thesis. Some of the approaches might be slightly modified for better use in the *Result* section.

Other papers, like the two written by Spagnoli [25] and [26] have limited relevance. They describe a trench cutting system in various detail. Calculations are a great part of these papers, but that will not be in focus for this thesis. The cutting system it selves is an interesting solution that will be implemented in the further work of evaluating relevant mining equipment.

The papers described in this section have all provided information within the field of deep sea mining. As mentioned, they will be used to various extend in further work with this master's thesis. Even if some of the papers are not going to be cited in the following text, the information is valuable and makes the overall understanding of deep sea mining easier to comprehend.

2.2 Theoretical literature studies

The theoretical literature studies presents a theoretical background of methodology and design theory that will be utilized to achieve the overall task of DSMin vessel configuration, as described in Section 1. These sources are described more thoroughly than the general literature studies. This is because these approaches will be used in the process of deep sea mining vessel configuration.

Engineering Design: A Systematic Approach

Engineering design theory is a field in constant development. There is no one way to do it, but there are some recognized methods within the field. Several methods, papers, and books have been written on the subject, but the one that may be the most known is *Engineering Design: A Systematic Approach* by G. Pahl and W. Beitz [30]. The book provides a detailed overview of the principles and practices of engineering design, offering insights and strategies for navigating each stage of the design process.

The goal of this book is to provide a comprehensive and structured approach to the engineering design process. The book presents a systematic approach to engineering design that can be applied to a wide range of engineering projects. The entire design process is covered in the book, from understanding the problem and defining design requirements to generating and evaluating design concepts, to prototyping and testing, and finally manufacturing and implementation. It emphasizes the importance of considering multiple design alternatives and evaluating them systematically, using tools such as decision matrices and trade-off analysis. The book also covers important aspects of design, such as sustainability, ethics, and design for manufacturability. It provides practical guidance and examples throughout, as well as case studies that demonstrate how the design process can be applied in real-world situations. The entire book is not presented in this thesis. The focus area is the design process approach.

There are four main steps for the design process presented in the book: (1) Planning and task clarification, (2) conceptual design, (3) embodiment design, and (4) detail design. The first phase typically starts by receiving, or developing, a main goal or a task description. The task description contains "general" statements of the desired goal. This is often regarding functionality and performance as well as deadlines and cost limits. These descriptions are vague and need a lot of processing to become a platform one can continue working with. When this is done, one can start with the next phase - conceptual design. The goal for phase two is to produce a principal solution. The principal solution will be the starting point for the embodiment design phase. The conceptual design phase starts by establishing a function structure. A function structure is a graphical representation of the functions of a product or system, as well as the relationships between those functions. It is used to identify and define the essential functions that the product or system must accomplish, as well as the interdependencies between these functions. Then, alternative working principles will be explored. These principles are for realizing each sub-function of the function structure. The physical effect necessary to accomplish a function is expressed through the working principle, which is further characterized by its physical embodiment, including its geometric and material properties. As an example, "the transportation of goods" can be the function that is desired to be realized. The working principle may be "by ship", "by train" or other solutions that will lead to the function being realized. There are three types of methods described in *Engineering Design: A systematic approach* for the exploration of working principles: conventional methods, intuitive methods, and discursive methods. The latter recommends a stepwise procedure that systematically will progress towards one or more solutions. One of the discursive methods that are recommended is a *design catalog*. A design catalog uses classifying criteria to organize information when gathering information on known and proven solutions to a design problem [33]. Classifying criteria, as suggested by Pahl and Beitz, can be the physical effects of working principles, working geometry, motion, and basic material properties. There are three main types of design catalogs: object catalogs, solution catalogs, and operation catalogs. A design catalog will provide a systematic approach to a design problem. More specifically, it provides: (1) more efficient, problem-oriented access to a large amount of available information, (2) presents the most comprehensive range of possible solutions, (3) allows for the possibility of extension when more knowledge becomes available, and (4) providing data for both conventional design procedures and computer-aided methods or knowledge-based systems. An example of a design catalog is shown in Table 3.

Classifying criteria	1	2	3
1	1.1	1.2	1.3
2	2.1	2.2	2.3
3	3.1	3.2	3.3
4	4.1	4.2	4.3

Table 3: Generic example of a two-dimensional design catalog

The next step is to present concept proposals, the overall solutions. For this, the working principles must be combined following the function structure that has already been established in the early stages of the conceptual design phase. The systematic combination that needs to be established to achieve this has one main challenge - to guarantee the compatibility of the working principles being combined in regard to their inputs and outputs. A method that is used to solve this is morphological matrices. This is a method that takes all possible solutions into account, no matter how unlikely they might sound. Morphological matrices are utilized to implement the morphological technique in a design challenge after creating a functional structure and compiling a catalog of alternative solutions (working principles) for each function in the functional structure. The matrix will illustrate the combinations of variant solutions, thus leading to a valid overall solution. For the solution to be valid, it is required that the compatibility of inputs and outputs, between its constituting working principles, is respected. A generic example of a morphological matrix is shown in Table 4.

Solutions (Horizontal) Sub-functions (Vertical)	1	2	...	j	...	n
FR_1	S_{11}	S_{12}	...	S_{1j}	...	S_{1n}
FR_2	S_{21}	S_{22}	...	S_{2j}	X	X
. . .	. . .	. . .	. . .	. . .	. . .	. . .
FR_i	S_{i1}	S_{i2}	...	S_{ij}	X	X
. . .	. . .	. . .	. . .	. . .	. . .	. . .
FR_m	S_{m1}	S_{m2}	X	X	X	X

Table 4: Example of a generic morphological matrix for a function structure with m sub-functions

The final step is to evaluate the concept proposals. This has the possibility of being a challenge for the designer. This is due to the vast amount of possible solutions. On the other hand, with a big pool of possible solutions, the possibility of missing out on a good solution will be minimized. In *Engineering Design: A systematic approach*, a two-step approach is suggested for this task. First, the unsuitable solutions are eliminated and then the remaining solutions are sorted using preference criteria. For the latter, four criteria are established: coherence with the project objectives and with each other, meeting the requirements outlined in the project specifications, feasibility with regard to performance and any other predetermined limitations, and falling within acceptable budgetary constraints. Within these criteria, there might be other selection criteria that might become essential as well. Safety, technology choice, collaboration partners, ergonomics, or technology readiness level (TRL) are some examples.

This sub-section is based on the book *Engineering Design: A systematic approach* written by Pahl et al. [30]. Additionally, the two papers *Finding the generic function structure of a deep-sea mining system* [31] and *A conceptual design framework for deep-sea mining* [32], both written by Maxime Lesage, have been of great value for this chapter.

Modularity

Modularity is the division of a larger system into smaller parts or components [34]. These modules will be (relatively) self-sufficient. I.e. that the machines or components that interact with each other are going to be in the same module. They may have similar power requirements, be located near each other, or work together to achieve the same sub-task within an operation. For an offshore service vessel (OSV), these modules can be divided into topside, tween deck, ROV hangar, machinery, helideck, bridge, hotel, and propulsion. This is just an example from Ulstein [35]. All these modules can be divided into smaller modules if this is favorable.

There are three main types of modularity [34]: (1)Slot modularity - the interface is specific to the module type, (2) Bus modularity - interface standardized across module types, and (3) Sectional modularity - there is no platform, but rather one or a few common interfaces.

The modules that are to be utilized in a deep sea mining vessel will be a combination of well-known modules and entirely new modules. For instance, when looking at the power requirements for a DSMin vessel one would make this its own module for the propulsion. This will most likely be similar to a drilling ship. But when the power requirements for the mining operation are taken into account, there is an entirely new situation. There is a lot of equipment that requires additional power. The installation of the raisers, the operation of the mining machines, and the dewatering system are just a few examples. To be able to provide a sufficient amount of power to these operations, one would need to keep both the interactions of power requirements and the synergy between equipment in mind.

There are both pros and cons of modularization. Product variety and customization are one of the advantages. This gives the possibility to use different modules and combine them to fit your project in the best possible way. The alternative is to order an "off-the-shelf vessel" with little to no possibility of customization. Production efficiency may be both an advantage and a disadvantage. It will become a more efficient way of producing a vessel when modularization is utilized compared to if everything is customized down to the smallest details. Doing this will increase the building time and cost. On the other side, building with modules will be less efficient than an "off-the-self vessel". But as previously mentioned, one would lose a lot of opportunities for making the vessel specific for your project when deciding on the latter. The reduced lead time is an advantage as well. Lead time is the amount of time that passes from the start of a process until its conclusion [36]. When production is done in modules, the process of manufacturing is standardized, hence demanding less time for planning, production, and delivery. Risk reduction is also an argument for modularization. When a product is standardized, the risk of manufacturing errors, delays, and other complications will be severely reduced. Outsourcing the production and making the production international or global is also possible when a product is modularized.

Even with all the advantages that modularization brings, there are still some disadvantages. The main one is the less optimized physical architecture. It is difficult to make the modules fit together in a 100% optimized way when everything is made by standardized sizes and weights. For a vessel, this might lead to complications in deck space, weight distribution, or utilization of space below deck. Further, if the placement of modules is not optimized, the performance and interactions between them may not be optimized either.

Utilizing modularity when building a vessel is not only favorable in the planning and building phase but also in its operational phase. Modular interfaces reduce the propagation of changes due to subsystem changes [34]. This means that even if there are some functional requirements that change in one subsystem, this will not affect other systems as much as if the interaction between them were not separated.
Modularity in the operating phase will also enable modifications later on. These might be due to new technologies, changes in the market, or new regulations in the industry. The components within the modules will be (relatively) easy to change. The same will be possible if a system were to fail. Service is also made easier, both with regard to doing it offshore and with remote maintenance monitoring by the supplier.

Product Platforms and Modularisation in Shipbuilding

The purpose of this document, written by Stein Ove Erikstad [37], is to give an overview of modularization as a part of the course Design Methods at NTNU. Modularisation and modularity are also described in Section 2.2. Modularization is related to product platforms in terms of being the building blocks from which the product platform is built. By adding, removing, or scaling modules, the product platform can be targeted toward specific markets or customer requirements. The paper describes different concepts related to modularization. One of them is product architecture. This is described as *the abstract skeleton in which the concrete mod-*

ules can be placed according to given rules. The SFI system can be considered a generic product architecture for a ship. Further on, the paper describes the advantages and drawbacks of modularization. The main advantages are product variety and customization, production efficiency, reduced lead time, product development and design, reduced risk, outsourcing, and globalization of the supply chain. The main drawbacks are less optimized physical architecture, increased weight, and size, less optimized performance, excessive capability, and risk of product similarity. The different types of modularization are also elaborated. The three types are slot modularity - where the interface is specific to the module type, bus modularity - where the interface is standardized across several module types and sectional modularity - where the is no "platform" module to which the other modules attach. The last chapter of the paper describes modularization in the marine industry. The combination of short lead time, rapid configuration, and customization is highlighted as a potential benefit within the ship tendering process. Further, the difference between a module-oriented, product platform and a traditional approach is explained. This is put in context with the tendering process. The last part of this chapter has descriptions of how modularization is utilized in different phases of vessel development and operation with reel life examples.

This paper is useful for my thesis. Modularization is a key concept when designing a DSMin vessel. The theoretical understanding of the concept, as well as the examples provided, are going to help with the forthcoming challenges of the thesis.

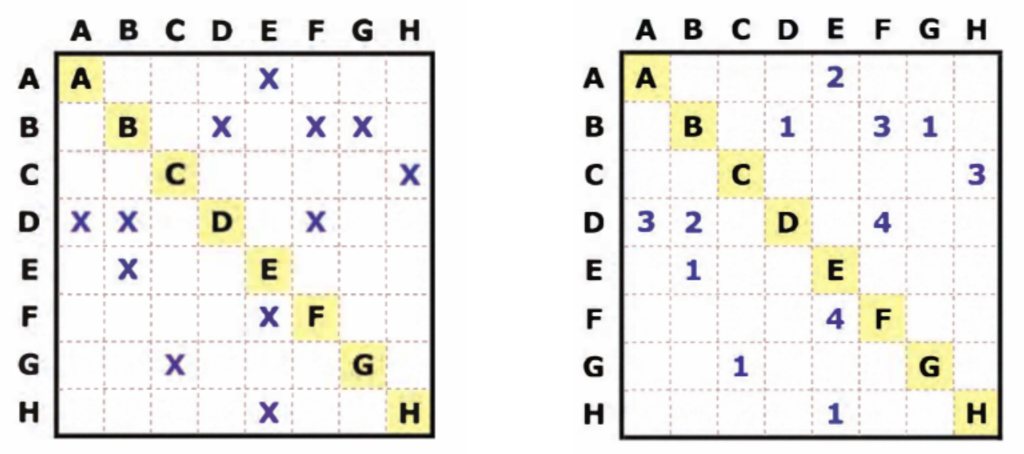
Design Structure Matrix

The design structure matrix (DSM) is a network modeling tool used to represent the elements comprising a system and their interaction, thereby highlighting the system's architecture (or design structure) [38]. The DSM method is used in a lot of areas, but is particularly useful for complex engineering problems. The DSM is always represented by a square $N \times N$ matrix. DSMs are typically used to identify dependencies, constraints, and other factors that can affect the design and performance of a system. The main advantage of the DSM method, compared to other network modeling methods, is the geographical nature of the matrix display format. The matrix provides a highly compact, easily scalable, and intuitively readable representation of a system [38].

The DSM is as mentioned a compact display of a systems architecture. To make the matrix as compact as possible, the full names of the system elements are often written on the left side of the rows, rather than in the cells within the matrix. Another common way of implementing the matrix is to think of each diagonal cell to have inputs entering from its left and right side while the output of the matrix leaving from above and below. It is important to know that this is a norm, not a rule when designing or interpreting a DSM.

There are several ways of both constructing a DSM and categorizing them. The most high-level way of dividing them is to separate between binary DSM and numerical

DSM. A binary DSM simply indicates the presence or absence of an interaction between two elements in the matrix. The numerical DSM is an extension of the binary DSM. The difference is that instead of simply showing that there is an interaction, the numerical DSM gives an indication of numbers, importance, impact, and/or strength of interaction. This can be visualized using numerical values, symbols, shadings, or coloring. An example of a binary DSM is shown in Figure 4a and a numeric DSM is shown in Figure 4b.



(a) Example of binary DSM [38]

(b) Example of numerical DSM [38]

Figure 4: Binary and numerical design structure matrices [38]

Advantages of the DSM method

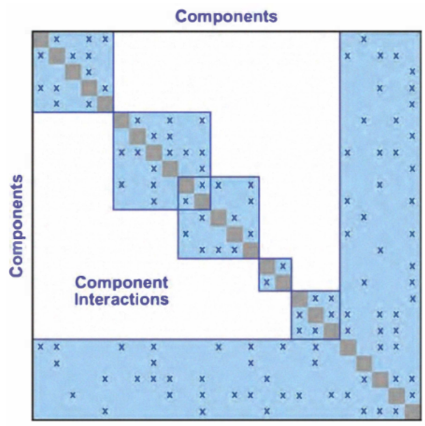
There are a lot of different tools that may be useful in systems design. The chosen method in this paper is the DSM, but this is only one important available tool. In many cases, it is not a question of finding or choosing a single best method, tool, or representation for architectural modeling; rather, a combination of representations is the most powerful [39]. However, the DSM method provides a lot of advantages and it is chosen for this task because of these. These advantages are described in the book *Design Structure Matrix Methods and Applications* [38].

The first advantage is conciseness because the DSM is a compact and structured representation of the elements that make up a system. Compared to many other networking models, the DSM will describe a large, complex system in a relatively small space. Further, the next advantage mentioned is visualization. The DSM is a visual method that highlights relationship patterns within a system. It is also easy to distinguish between different types and intensities of interactions. In addition, the DSM visualizes the system on a global level, making global optimal solutions and decisions easier to make and back up. The third reason for using a DSM is intuitive understanding. DSM is an easy tool to understand when introduced to the basics. It simplifies the basic structures of a complex and comprehensive system in an easy-to-read manner when properly displayed. Even in a cursory review, hierarchy, and complexity become apparent. Analysis of the system is the next highlighted advantage. The matrix-based nature of the DSM allows for the application of various powerful analyses in graph theory and matrix mathematics, as well as specialized DSM analysis methods. Through DSM analysis, designers can uncover important patterns and effects, such as indirect links, change propagation, process iterations, convergence, modularity, and others. This can help to identify potential problems or vulnerabilities in the design and can inform design decisions to optimize the system's performance. The final element is flexibility. The DSM method is highly flexible. The creator of the DSM is not locked to strict rules and can freely choose to implement or modify elements in the DSM to make it more relevant for a specific use. Colors, numerical values, graphics, or additional data are just some examples of addable items.

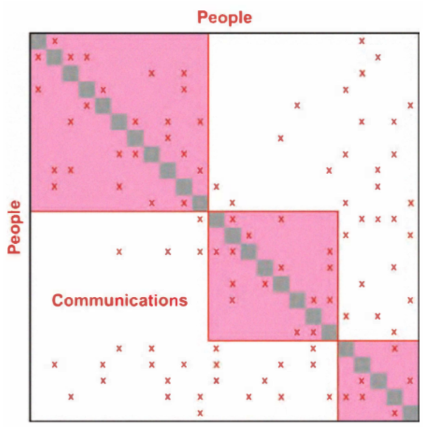
Types of DSM

There are several different types of DSM, each of which is used to represent and analyze different aspects of a system or design. The four common types of DSM models include:

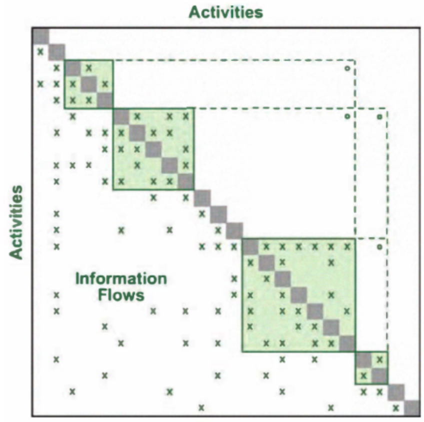
(1) Product Architecture DSM - This type of DSM is used to represent the relationships between different components or subsystems within a product or system. It is used to identify potential areas of risk or inefficiency in the product's design, and to take action to improve it. An example is shown in Figure 5a. (2) Organization Architecture DSM - This type of DSM is used to represent the relationships between different departments, teams, or other organizational units within a company or organization. It is used to identify potential inefficiencies or conflicts in the organization's structure and to take action to improve it. An example is shown in Figure 5b. (3) Process architecture DSM - A process architecture DSM is used to represent the relationships between different processes or activities in a system. This type of DSM is typically used to identify feedback interactions, change propagation, process iterations, and other factors that can impact the performance of the system. An example is shown in Figure 5c. And (4) Multidomain DSM - A multidomain design structure matrix (MDM) is used to represent multiple DSMs in one single matrix. This type of matrix is typically used to identify patterns and effects that can impact the overall performance and functionality of the system and can inform design decisions to optimize the product's performance. An example is shown in Figure 5d.



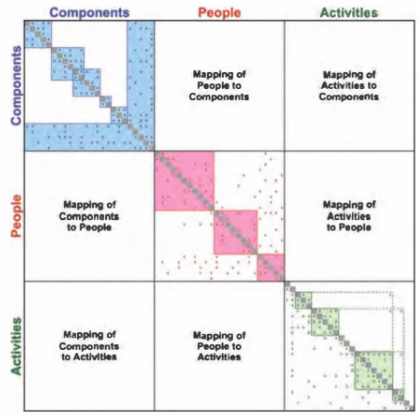
(a) Product Architecture DSM [38]



(b) Organization Architecture DSM [38]



(c) Process Architecture DSM [38]



(d) Multidomain MDM [38]

Figure 5: The four primary types of DSM models [38]

Overall, there are many different types of DSM models, each of which is used to represent and analyze different aspects of a system or design. These models are valuable tools for identifying patterns and effects that can impact the performance of a system and can help designers to make informed decisions to optimize the system's performance.

The DSM approach

To make a DSM, there are five universal steps that need to be followed. This five-step approach is as follows:

1. **Decompose** - Break down the system into smaller subsystems or elements.
2. **Identify** - Document the relations between the system's subsystems or elements.
3. **Analyze** - Arrange the elements or subsystems and their relations in such that understandable patterns and their implications in the system are understood.
4. **Display** - Create the visual representation in a DSM model. The features of particular importance or special interest should be highlighted.

5. **Improve** - The DSM created is not a finished product until the project is done. It is ongoing work that needs to be improved when new knowledge is gained, new requirements or limitations are identified, new technology is available, or similar events occur.

3 Vessel Equipment Design Catalog

Section 3 is a design catalog for equipment that is to go onboard the deep sea mining vessel. This section consists of both proven and well-tested equipment, as well as new technology. The main focus is the seafloor massive sulfide mining equipment and the systems related to the mining. Additionally, some auxiliary functions that are special for deep sea mining vessels and other offshore construction vessels will be presented. For several equipment categories, there is more than one option to choose from. The selected solutions will be presented in Section 5.

The design catalog in this section is modified from the one described in Section 2.2. The physical representation is not utilized. This is because a list is more suited for the amount of information needed in the decision-making. Additionally, the design catalog below contains both proven and new solutions. As the deep sea mining industry is in its starting phase, this can not be avoided. All four advantages are still considered relevant for this version of a design catalog.

The section is divided into four sub-sections. The first will present the mining equipment, the second one will show equipment in the use of vertical transport, the third sub-section contains equipment for the handling of slurry and payload onboard, and finally, the fourth sub-section focuses on the process of unloading the vessel.

3.1 Mining equipment

In this thesis, mining equipment is defined as specialized machinery, tools, and systems responsible for the extraction of mineral resources from the ocean floor. This is equipment that is directly in contact with the seafloor massive sulfides at the seabed. Its main function is to make valuable minerals available for transport to the vessel. It is not specified what state the minerals shall be in, i.e. in solids, partially crushed, or in a slurry.

Working ROV

Heavy work class ROV - Millennium Plus
This Heavy Work Class (HWC) ROV from Oceaneering is side entry and cage deployed. The dual manipulator power supply of 220 hp is equipped with a fly-by-wire

station keeping system [40]. This means that it uses a computer to process the signals sent from the ROV pilot to the ROV. There is no direct mechanical connection between the pilots' movements and the ROV movements, but a computer that in turn determines how to move the control surfaces to best achieve what the pilot wants [41]. The depth rating for the Millennium Plus is 3000 meters as standard, but it is available with a depth rating of 4000 meters. Its dimensions are (LxWxH) 3.3 x 1.7 x 1.9 meters. This gives a total volume of 10.7 m^3. The total weight (in air) of the ROV is 4000 kg. The ROV has a maximum vertical thrust of 950 kg.

Heavy work class ROV - Millennium Plus with RIPS IT3
This ROV is based on the Millennium Plus ROV mentioned above. The difference is that this one has isolated tooling. The ROV Integrated Pumping Solution (RIPS) IT3 solution delivers an isolated tooling circuit capable of pressure up to 3000 psi [42]. This means that the tools (arms) are separated from the main body, and control systems, of the ROV, making the operations possible without directly manipulating or affecting the vehicle's stability. Because of the RIPS system, there are some slight changes in the characteristics of the ROV. The weight is 4535 kg (in air) and the dimensions are (LxWxH) 3.3 x 1.6 x 2.1 meters. The depth rating is the same.

Both of the ROVs suggested by Oceaneerings have several options for a LARS system. These options are overboarding, A-frame with or without docking head, heavy-weather overboarding system, cursor, winch, or heavy lift winch.

Heavy duty construction class ROV Quantum

The Quantum ROV made by SMD is their largest and most powerful ROV [43]. It is a heavy-duty ROV made for complex construction duties. It has an extra focus on in-current performance and extensive free tool and instrument space as well as it is optimized to work in deep water environments with tasks that require intensive power. This means that the ROV is suitable to carry large amounts of payload. Its depth rating is up to 4000 meters and it has a weight (in air) of 5000 kg. The dimensions of the Quantum ROV are (LxWxH) 3.7 x 2.0 x 2.0 meters. These dimensions add up to a total volume of 14.8 m^3. The vertical thrust for this ROV is 900 kg. The typical LARS system for the Quantum ROV is a 12 Te telescopic A-frame with a 3500 meter winch.

SMD delivers all their ROVs with a full control system, meaning control cabin and power supplies.

Mining machines

Auxiliary Cutter
When conducting deep sea mining operations one will face a lot of uneven submarine topography that will make the mineral deposits difficult to reach. The auxiliary cutters' main job is to carve out flat working surfaces, called benches, from an

uneven seabed [44]. The 250-tonne machine is able to work on slopes up to 20 degrees. It operates by deploying stabilizers and then sweeping the seabed with its cutting head. This will crush the soil until the desired shape has been made. When this part of the job is done, the auxiliary cutter will be utilized to grind up ore as well. An example is shown in Figure 6.

Figure 6: Auxiliary cutter built by Soil Machine Dynamics, owned by Nautilus Minerals [44]

Bulk Cutter

When the auxiliary cutter has flattened the seabed (made benches), the bulk cutter is able to work. The bulk cutters' job is to cut and crush rock and ore. It has a massive cutting drum in the front which is specially made to cut into the seabed in hyperbaric conditions. The bulk cutter can be compared to a bulldozer [44]. An example is shown in Figure 7.

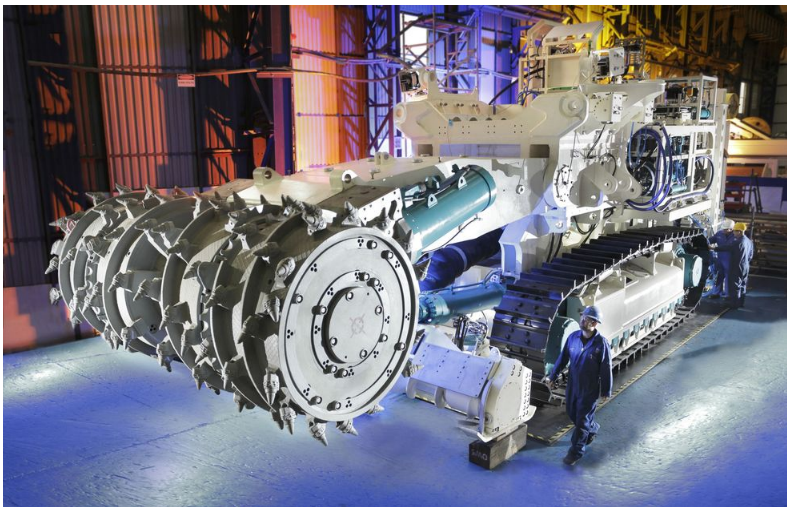


Figure 7: Bulk cutter built by Soil Machine Dynamics, owned by Nautilus Minerals [44]

Collecting Machine
When the previously mentioned machines have done their job, the collector machine will begin to operate. The collector machine is used to suck up the crushed ore. It is fitted with a large boom with a crown cutter on the end. This technology is similar to the one used in dredging operations. The crown cutter agitates the crushed ore on the seabed so it is stirred up with the seawater. The next step is to suck the slurry up and into the dredge pumps within the machine. From there it is pumped to the surface through risers.

Figure 8: Collecting machine built by Soil Machine Dynamics, owned by Nautilus Minerals [44]

Vertical trench cutting systems
In the paper *Preliminary Design of a Trench Cutter System for Deep-Sea Mining Applications Under Hyperbaric Conditions* [26] Spagnoli et al. have designed a trench cutting system for deep water applications. The paper is described thoroughly in Section 2.1. The concept is to have a vertical mining system that drills into the seabed and reaches the mineral-rich ore below. The trench cutter it selves has a drill head and a main body. Within the body, all the hydraulic and electrical instruments are installed. In addition, there are pumps and gearboxes for the cutting head. A trench cutting system like this has an estimated required cutting power of 480 kW at 2000 meters depth. The drill head itself has a diameter of 2 meters, and there are two of them mounted side by side. Dimensions for the entire machine are (LxWxH) 4.0 x 3.6 x 13.2 meters. The total weight of the system is estimated to be between 140 to 155 tonnes. It is estimated that this system will be able to reach a production of 120 tonnes per hour. It is not specified in the paper how the mined material be transported to the surface, but a riser that is connected to the trench cutter is a possible solution. An illustration is shown in Figure 9.

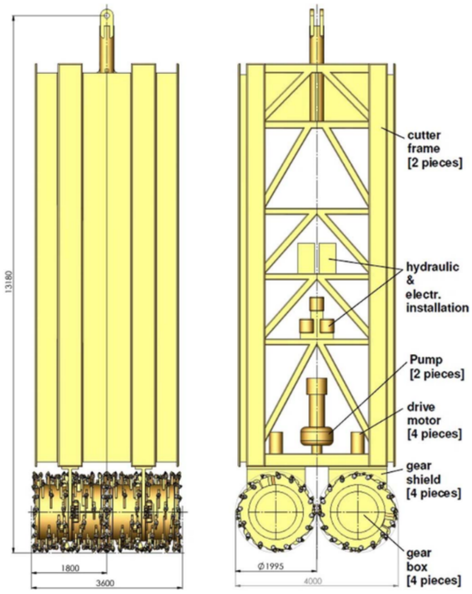


Figure 9: Illustration of the double trench cutter for deep sea applications (measurements are in millimeters) [26]

Another vertical trench cutting system is developed by BAUER Machinen GmbH [45]. Their concept is called "Vertical Approach". There are a lot of similarities between the two concepts, but the main difference is that while the concept developed by Spagnoli is always dependent on the wire from the vessel crane, the BAUER Machinen GmbH concept will be able to sit on the seabed by it selves. It has three (assumed to be) self-leveling legs that allow it to be deployed on the seabed and then begin drilling from the established base. Both concepts rely on the vessel crane to move horizontally. The BAUER Machinen GmbH is shown in Figure 10.

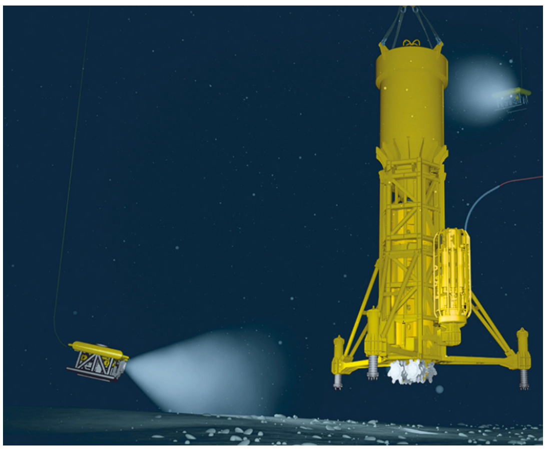


Figure 10: The trench cutting system "Vertical Approach" from BAUER Machinen GmbH [45]

3.2 Vertical transport

The vertical transport system's objective is to transport ore from the seabed to the vessel. This includes both slurry and solid pieces of sulfide chimneys, as well as equipment. There is a distinction between lifting capacities that only can be used for vertical transport and lifting capacities that can be used on board as well. The latter is described in Section 3.3.

Seafloor mining risers
The riser and lifting system (RALS) designed by GMC is a system that is specialized for deep sea mining [46]. It will lift crushed ore in the form of a slurry from the seabed to the DSMin vessel. A subsea slurry lift pump (SSLP) will be utilized. The SSLP is attached at the base of the riser and pumps the slurry to the surface through the gravity-tensioned riser. The riser is deployed to the seabed by using a derrick on deck. The DSMin vessel will need a moonpool for this operation. GMCs lightweight mining riser system has a snaplay connection solution that enables the system to be rapidly deployed. There are no special vessels or top drive equipment needed for the installation. Utilization of the cranes and derrick already onboard will minimize the storage area required when using GMCs riser system. At the end of the riser, there is a flexible hose. The hose is the connection between the riser and the mining equipment. A flexible hose allows the mining equipment to move freely without the movement of the vessel having an impact on it. The riser is available om diameters from 8" to 60" (20.3 cm - 152.4 cm) and is made of X65 grade ultra-high strength carbon steel. Joint lengths are between 12-24 meters and it can be deployed in water depths up to 4000 meters.

Subsea basket
For the recovery of SMS chimneys that have been retrieved by an ROV, a subsea basket is a possible way of bringing them to the surface. These baskets are standard in the offshore installation industry today and well-suited for the safe transport of material and equipment from subsea locations. The baskets are designed to operate in tough subsea environments. Cranes onboard the DSMin vessel will be utilized for the vertical transport and ROVs will be at the seabed to fill them with payload. A 40ft subsea basket has the outer dimensions (LxWxH) 13 x 2.4 x 1.5 meters, meaning a volume of 46.8 m^3 [47]. It is designed to be stacked for saving deck space. The tare weight is 4.5 tonnes and the basket has a payload capacity of 20 tonnes. An example is shown in Figure 11.

Figure 11: Subsea basket from Norwegian Offshore Rental [47]

Subsea slurry lift system
After the ore has been crushed by the trench cutter, it needs to be transported to

the surface. This is done through a riser with a slurry lift system. FSubsea has a centrifugal pump called the Mudrise that is suitable for deep sea mining operations [48]. One single pump is able to generate 250 meters of differential pressure. This means that several pumps are needed to be able to mine at desired depths. According to FSubsea, this is no problem as the pumps are designed for up to 3000 meters depth. The capacity of one single unit is up to 600 m^3/hr. The pumps can be mounted in any direction. This is advantageous because it will likely be mounted on or within the trench cutter. It can have either a hydraulic or electric drive. The power requirement for the pump is 400 kW. An illustration of the centrifugal pump is shown in Figure 12.

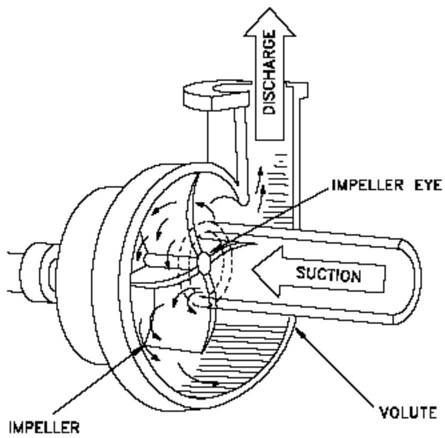


Figure 12: Illustration of a centrifugal pump used as a seabed slurry lift system. Illustration: Engineerings Edge [49]

A-frame

The A-frames are box-shaped crane structures, designed in an A-shape and mounted on the deck. The capacity range for an A-frame from NOV is 10-350 tonnes [50]. They are equipped with ram cylinders that allow for lifting between inward and outward positions. They are capable of performing lifts from the deck of the vessel over the stern or over the side. Depending on the application, a suitable winch package is installed with the A-frame. Along with the A-frame, a winch and active heave compensator (AHC) system are mounted. An example is shown in Figure 13.

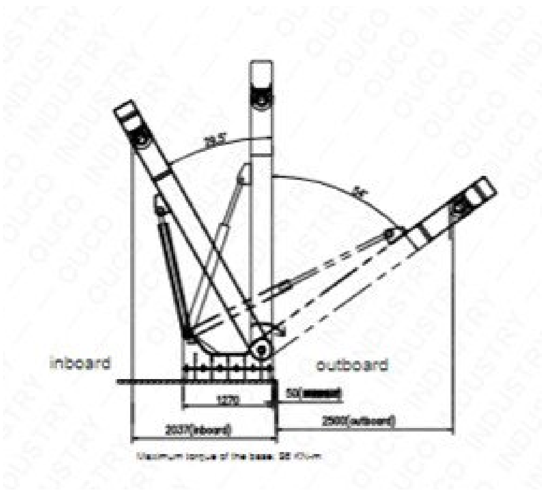


Figure 13: A-frame crane. Illustration: OUCO [51]

ROV launch and recovery system
A launch and recovery system (LARS) for an ROV is essential for a DSMin vessel. The LT series ROV LARS from West Marine is capable to launch and recover a working class ROV down to 3600 meters [52]. It is equipped with an armored umbilical cable suitable for harsh environments. The system is an A-frame construction with a 3g dynamic amplification factor, i.e. it has a safety factor of 3 to comprehend the possible increased loads that may occur in harsh environments. It is designed for operation up to a sea state of 4.5 meters significant wave height. The safe working load (SWL) is 11 tonnes and the power requirement is 152 kW. The ROV LARS is shown in Figure 14.

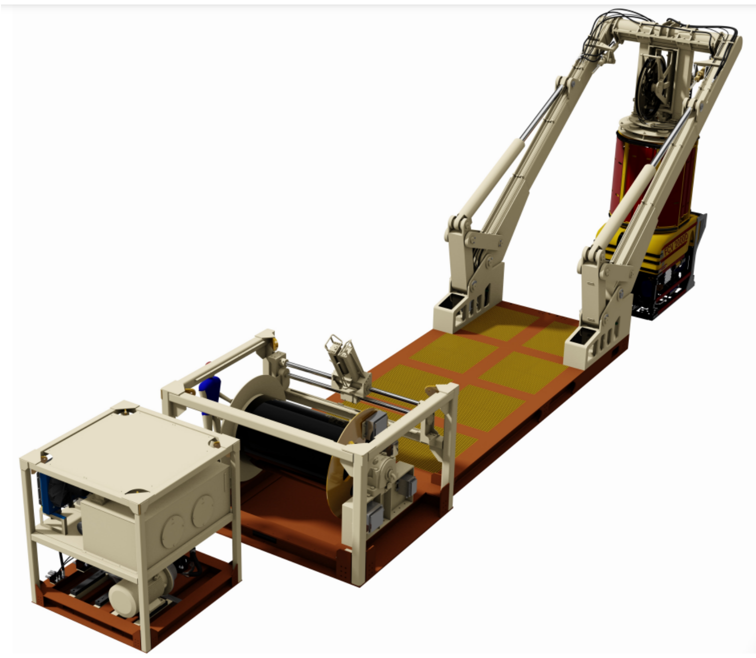


Figure 14: LT Series ROV LARS from West Marine [52]

3.3 Onboard handling

The onboard handling systems consist of the equipment that either processes the slurry as it comes onboard or is used for handling equipment on the vessel. This is equipment that is used in the day-to-day operation. Some of the cranes can, and will, be used for both onboard work and for vertical transportation from the seabed. The reason they are in this category is their location on board.

Dewatering systems

Fine material screw washer
A fine material screw washer is able to wash, dewater and classify solids in one machine. This particular model from McLanahan is made for mining companies [53]. A typical screw washer is a low-capital cost and low-electric power user machine. The screw washer is fed with the slurry from the seabed and directed to the feed box for regulation of the flow of fluid. Heavy materials sink to the bottom of the box. The finer materials will be carried by the up-current of water to the surface and overflow the weirs. The heavy material that has settled to the bottom is conveyed up a slope towards the discharge end. In this process, the material is rolling and tumbling. This releases fine particles and lightweight fractions into suspension. In addition, superficial clay will be scrubbed from the mineral surface. When the discharge end is approaching, the water begins to separate from the material. A channel in the washer tube is located on the opposite side of the conveying and allows water to drain from the solids and overflow the weirs. When using a screw washer it is important to maintain a steady and controlled flow of slurry. If the flow is greater than the capacity, it will overflow and one may lose some of the desired materials. The dimensions for the screw are (Diameter x L) 1118mm x 10.1 m. The system has a capacity of 317 Tonnes per hour. The screw will have a maximum RPM of 17 and the required power will be 2 x 18.5 kW. A fine material screw washer is shown in Figure 15.

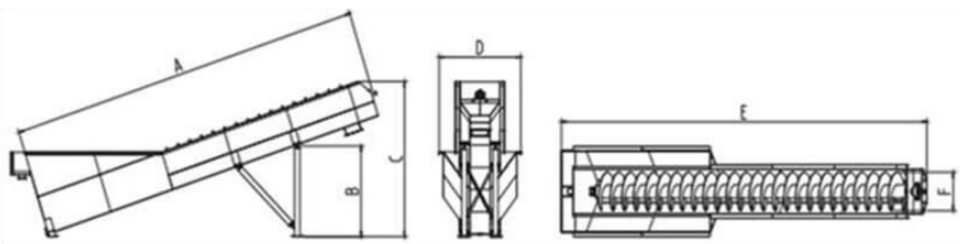


Figure 15: Fine material screw washer. Illustration: Constmach [54]

Hydrocyclone
A hydrocyclone has the same goal as the fine material screw washer, to separate the material and remove the water from the slurry. The feed inlet of the hydrocyclone receives slurry at a specified pressure and volume. The slurry follows the rotation of the upper cylinder and is subjected to centrifugal forces that push coarser material

towards the outer wall, where it moves downwards and accelerates further in the conical sections. The coarser fractions exit through the bottom spigot or apex of the hydrocyclone, while the finer fractions remain in the inner core and are removed upwards with the fluid by an air core. The air core is formed at the spigot/apex where air enters the hydrocyclone, and the vortex finder provides a means for the air to exit the body. As the air flows through the vortex finder, the fluids and finer fractions are dragged along for material classification. The air core is essential for the proper functioning of the cyclone, and if excessive solids discharge, also known as roping, prevents the formation of the air core, the slurry classification will be inefficient. The size of the apex/spigot is determined based on the anticipated range of solids, and significant process changes may necessitate resizing. To increase the capacity, it is possible to install several hydrocyclones in parallel [55]. A hydrocyclone is shown in Figure 16

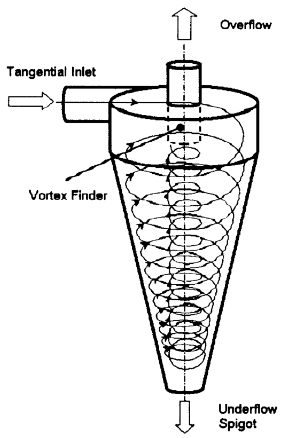


Figure 16: Hydrocyclone Illustration: M. Dalmani [56]

Slurry disposal system

An important part of the mining process is to get rid of waste material that is produced together with valuable minerals. For this, a slurry disposal system is needed. There are several possible solutions to this. The four main methods are submarine tailing disposal, tailing dam disposal, backfill disposal, and tailings reuse disposal [57]. The submarine tailing disposal (STD) method has been well tested and utilized since 1938 [58]. This method has mainly been used close to the surface, but now it is considered a way of disposal for DSMin operations as well. To make sure the unwanted sediments do as little damage as possible, the disposal occurs at a depth below 1100 meters [59]. This is done with a pipe system, preferably connected to the riser. This is to avoid entanglement in the two systems.

Derrick

A derrick is a drilling tower and riser installation contraption that has a pumping system and a turntable. It is installed on the DSMin vessel above a moonpool and used to deploy a riser. A drilling derrick consists of a steel lattice tower that supports the crown block and provides temporary storage facilities for riser pipe stands [60]. From the drilling vessel "Ocean Rig Olympia", which is to be used for deep sea mining by DEME and Transocean, one can find that it has a derrick onboard for the riser deployment [61]. The derrick is made by NOV and has dimensions (HxWxL) 61 x 18.3 x 24.4 meters. This gives the footprint of the derrick - 446.5 m^2. The derrick from Ocean Rig Olympia is shown in Figure 17.

Figure 17: Derrick from Ocean Rig Olympia [61]

Moonpool

A moonpool on a DSMin vessel will be used for the deployment of a riser system and will be where the mined ore will reach the surface. It will also be where the slurry disposal system pipes enter the water. It will be located roughly amidships, below the derrick. A moonpool is used because it allows the riser or pipes to be run vertically through the hull and not over the side. In addition, a moonpool will reduce the movement in the sea when the equipment is launched, called sloshing. The moonpool on "Ocean Rig Olympia" is 24.6 meters long and 12.48 meters wide [61]. This results in a footprint of 307 m^2.

Cranes

Trident crane

The Trident crane series from NOV is a subsea construction crane with a capacity range of 70-400 tonnes [50]. This crane is designed to use fiber rope, but it is still able to operate with steel wire or a hybrid solution. When a fiber rope is utilized, one eliminates the loss of capacity for subsea lifts due to wire corrosion issues. In addition, one does not need to grease the fiber rope, thus making it more environmentally friendly than steel wire. A fiber rope has the possibility to be continuously monitored, hence the status of the rope will always be known. The Trident crane is an AHC which is important for deep sea operations. The Trident crane will mainly be used for the deployment of a mining system or other seafloor mining equipment. This will be the crane with the biggest capacity onboard.

If the trench cutting system mentioned in Figure 3.1 is used for dimensioning the crane, one would get that the TRI250 crane is suitable. The TRI250 crane has a capacity of 250 tonnes at 18 meters. This is well over the maximum expected specific weight (155 tonnes) for the mining system. The range capacity is 7-36 meters. The weight of the TRI250 is 575 tonnes. The crane is shown in Figure 18.

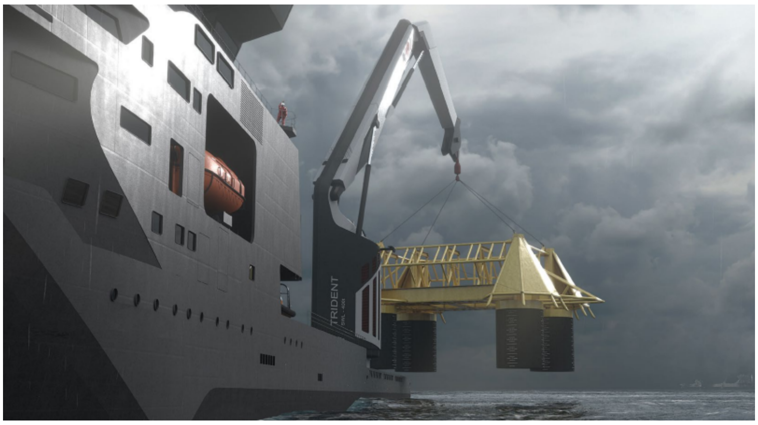


Figure 18: Illustration of the NOV Trident crane [50]

Pipe handling crane

A pipe handling crane (PC) is a combined knuckle- and telescope crane. The crane is specially built for the handling of drilling pipes and risers[50]. In the case of a DSM vessel, it would be used for handling the riser pipe sections and working closely with the derrick. The PC has the possibility to be equipped with a gripper, magnet, or screen yokes. This ensures that there is no need for personnel to be in proximity to the lifting operations. A pipe handling crane from NOV is shown in Figure 19.

Figure 19: Pipe handling crane from NOV [50]

Working crane

A working crane (WC) is a smaller crane used for onboard operations, assisting quayside handling of equipment and the hoisting of equipment to the seabed. The OCK-S crane from NOV is suitable for this job [50]. The crane is an AHC crane with a knuckle boom. It has a capacity of 50 tonnes with up to 10 meters of extension of the boom. When the crane is working at its maximum working radius of 21 meters, the capacity is 10 tonnes. It is delivered with a wire length of 3000 meters. The working crane is shown in Figure 20.

Figure 20: OCK-S working crane from NOV [50]

Helideck
A helideck is important for offshore operations of this scale. This is where the helicopter will land, mainly with either personnel or supplies for the vessel. The helideck is typically installed in the front of the vessel, above the bridge. The helideck that is to be installed must be capable of handling large transport helicopters. A typical helicopter used for this purpose in the Norwegian offshore industry is the Sikorsky S-92 [62]. It has a capacity of 19 passengers, a total length of 17.1 meters, and a maximum total weight of 12 020 kg [63]. As can be seen on the Ocean Rig Olympia, a drilling vessel converted to a DSMin vessel, the helideck has no problem with these requirements. It has a helideck that measures 27.2 m x 27.2 m. Its maximum load capacity is 21 tonnes [61].

3.4 Vessel unloading

Section 3.4 presents the systems that will make both ship-to-ship transfer and unloading at a quay possible. Additionally, the cargo hold is in this section due to its close connection to the conveyor system and unloading.

Ship-to-ship transfer

All the mined ore needs to be transported to a processing facility on shore. This can be done with bulk ships or barges that sail from the mining location to a predetermined destination. For the ore to get off the DSMin vessel and onto the bulk ship or barge, a ship-to-ship transfer is needed.

Dry Ship-to-ship transfer
A gravity-fed self-unloading system is a system that consists of numerous conveyor belts and hatches, as well as a discharge boom [64]. The payload in the cargo holds

will be released from hatches located at the bottom of the cargo holds. Beneath there is a conveyor belt that transfers the payload to the elevating system and lifts it above deck. From here, the payload reaches the discharge boom conveyor. The boom can move to both port and starboard side of the vessel for unloading. The boom from CSL has a maximum length of 76 meters and can discharge up to 10 000 tonnes per hour (depending on the density of the payload). An illustration of the system is shown in Figure 21.

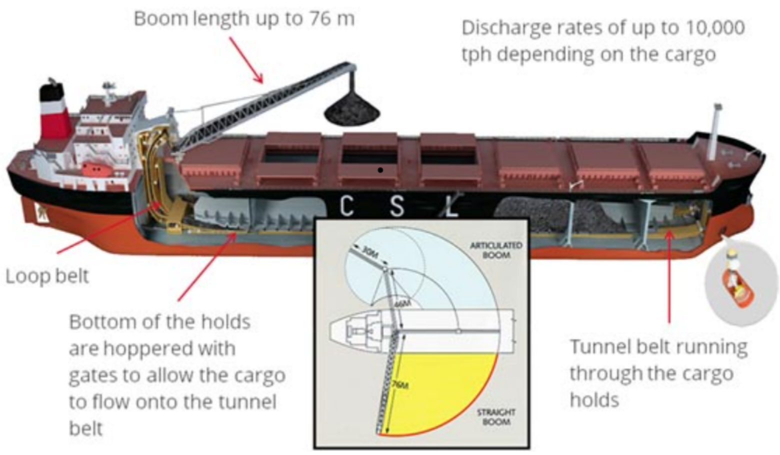


Figure 21: Illustration of a gravity-fed self-unloader from CSL [64]

Wet ship-to-ship transfer

Another possibility for ship-to-ship transfer is to do it with the payload in a wet state. This means that the payload which has been through a dewatering process needs to get water added again. This is done by adding seawater to the payload so it can be pumped in hoses from the DSMin vessel to the receiving ship. A wet ship-to-ship transfer is primarily applied to petroleum products, liquid bulk chemicals, and liquefied gas [65]. If wet ship-to-ship transfers are going to be used, one needs another dewatering facility on the bulk ship. That is not standard practice on these kinds of vessels today so they would need to be retrofitted. Another challenge is that the water in the slurry needs to be handled. It can not be dumped straight from the side of the bulk ship. A solution to this is to utilize the slurry disposal system on the DSMin vessel. A secondary pipe would be needed for this transfer.

Cargo hold

A cargo hold for SMS needs to be designed with regard to the density of the payload it will contain. The density is estimated to be 3.5 t/m^3 [17]. Due to the high density, the center of mass for a fully loaded vessel will be very low. The result of the low center of mass is an initial stability that is favorable. However, this will at the same time cause a very short period of rolling and high accelerations. Inertial forces will be affecting the ship structure, outfitting, cargo, and crew. A solution to this is to raise the center of gravity with an elevated double bottom [66]. A solution to this is shown in Figure 22

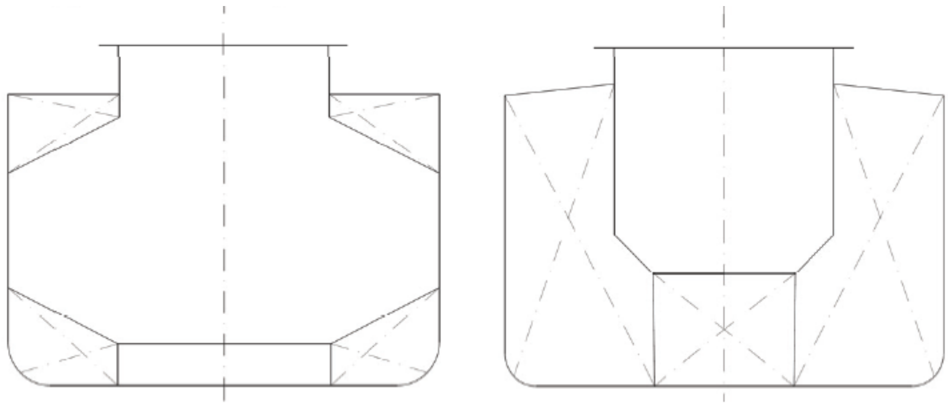


Figure 22: Heavy payload cargo hold (right) compared to regular bulk cargo carrier (left) [66]

4 System Description

The main goal of this paper is to describe a complete DSMin vessel and its equipment with a low level of detailing. The focus is mining-specific equipment. The interactions and dependencies between these components will be thoroughly explained through well-known methods within the field of vessel design and configuration.

The DSMin vessels hull is based on the results from the paper *Technology transfer in novel ship design: a deep sea mining study* written by Solheim et al. [17]. The results from the paper describe the technical specifications and can be found in Section 2.1. The vessel has a LoA of 225 meters, a beam of 40 meters, and a maximum draft of 15 meters. The power installed on the vessel is 47 231 kW and will be used for propulsion, DP systems, power supply for mining systems, and power supply for accommodations. The free deck area is 5 395 m^2. This area will be used for storage when the vessel is in transit as well as an outside working area during operation. This is for maintenance, temporary storage, and other minor day-to-day tasks. The DSMin vessel will be transporting the mining equipment from shore to the desired mining site itself, removing the need for a support vessel. For the riser assembly and launch, the derrick, in collaboration with the pipe handling crane, is used. The deployments are done through a moonpool. For the deployment of the mining equipment, the Trident crane is used. When the machine is located at the seabed, it will be connected to the riser system with a flexible hose. The flexible hose allows the mining system to move more independently than if it was connected directly to a rigid riser. When all the equipment is deployed, it will start mining and pump a slurry through the riser system up to the vessel on the surface with the help of the seabed slurry lift system. On the vessel, the slurry will get to the dewatering system to remove unwanted water, sand, and other sediments. Simultaneously, the ROV will be deployed and collect the SMS chimneys. The chimneys will be put in the subsea basket and hoisted back up to the vessel. The wastewater from the slurry is transported from the dewatering plant to the slurry disposal system and disposed back into the water column through the disposal pipes in the moonpool.

From the dewatering system, the dry payload will be stored in the vessel's cargo holds. When the cargo holds are full, the payload will be transported to a bulk ship or a barge. This ship-to-ship transfer will require conveyor belts and a boom that will transport the payload from the DSMin vessel's cargo hold to the bulk ship or barge. The system is visualized in a low-detailed illustration shown in Figure 23.

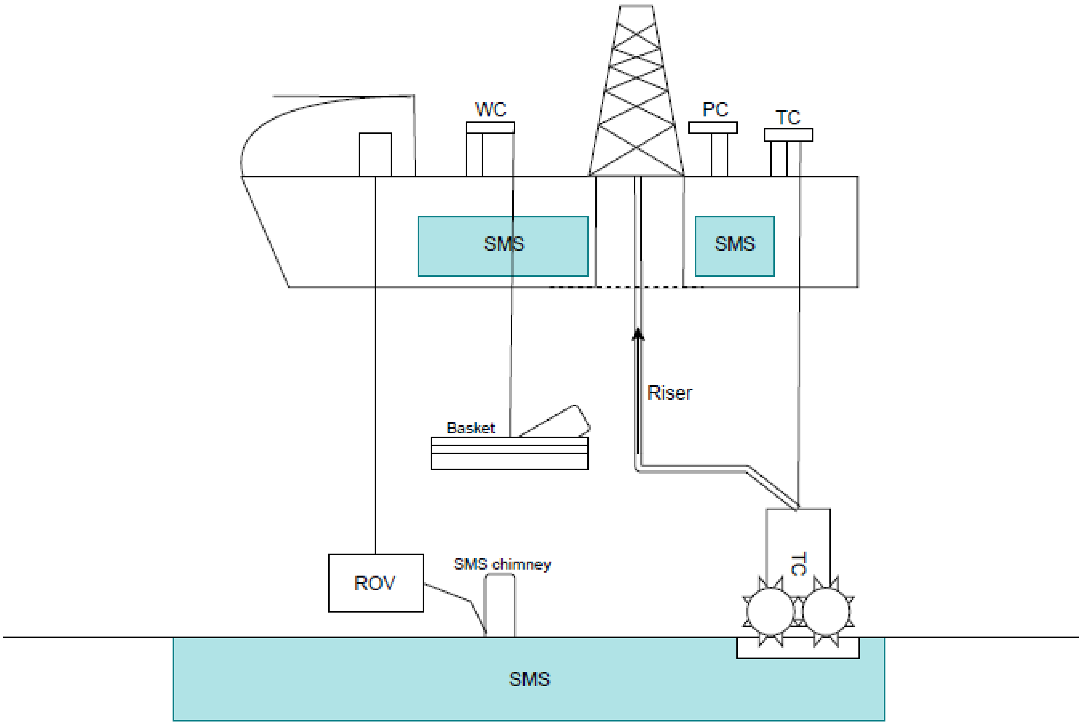


Figure 23: Illustration of the deep sea mining system

4.1 System decomposition

For a thorough presentation of a complex system, a system decomposition is needed. From *Engineering Design: A Systematic Approach* [30], one can see that all systems and sub-systems needs an input and an output described as flow. These flows are separated into three different types: energy flow, material flow, and signal flow. A general illustration of a system decomposition is shown in Figure 24.

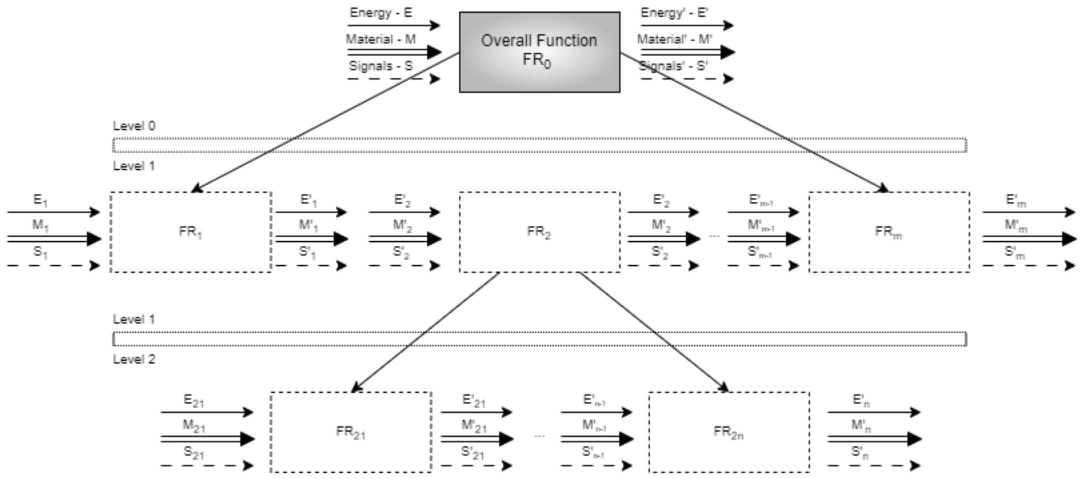


Figure 24: General illustration of a system decomposition

In Figure 25, a low-detailed decomposition is shown. This is based on the categories of equipment from Section 3. It shows how the different components contribute to the overall function, and in what order. The decomposition is not a final product but serves as a starting point. It will be elaborated and more detailed in Section 5.

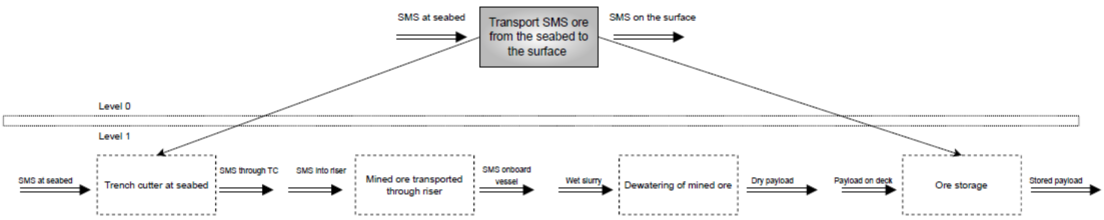


Figure 25: System decomposition of a deep sea mining vessel

4.2 Value Chain

For a new type of industry and operation like deep sea mining to succeed, it is important to know the relevant value chain. A value chain is defined as: *a series of consecutive steps that go into the creation of a finished product, from its initial design to its arrival at a customer's door* [67]. The value chain identifies each step that is needed for a successful result. The main criterion is that the step needs to add value to the finished product. It includes everything from sourcing, manufacturing, and marketing. The goal when doing a value chain analysis is to increase production efficiency. This means delivering maximum value for the least possible cost.

The value chain framework can be used by deep sea mining companies to identify areas where they can lower costs or add value to differentiate themselves from competitors. This is especially important as the industry is in its start-up face. A detailed value chain analysis is key to making the operations economically sustainable. For example, companies may focus on developing the most efficient extraction methods or improving the quality of the minerals they extract. They may also invest in marketing and sales to promote the benefits of deep sea mining to customers.

Another important outcome of a value chain analysis is that policymakers (i.e. International Seabed Authority - ISA) and governments can identify areas where they can support the development of the deep sea mining industry. This is an important part of getting this industry up and running. For example, governments may invest in research and development to improve the efficiency and safety of extraction methods or provide incentives for companies to develop new mining technologies. As of now, the development is mainly done by the mining companies themselves. Some arrangements have been done between companies and governments. One example is the cooperation between the DSMin company Allseas and the island states of Tonga, Kiribati, and Nauru [68]. The countries have the right to mine in the Clarion Cliperton Zone and Allseas has partnered up with them for their mining rights. The island states will receive economic benefits and in return, Allseas has the right to utilize the seabed resources.

For deep sea mining, the value chain can be divided into development, exploration, extraction, transportation, and marketing/sales. The early stages will be the development phase. This is where the feasibility of the project is investigated. A positive result is essential for the rest of the project. In this phase, one will only have rough estimates and assumptions that will be further developed in the value chain. The next step is exploration. This is where areas of interest are identified. These will be areas on the seabed where deep sea mining is considered possible and the occurrence of minerals is sufficient. This involves using geophysical surveys to locate potential mining sites and assess the quality and quantity of the resources. When this is done, the extraction of minerals is next. This includes the processing onboard the vessel after the minerals have been extracted. In this case, the extraction will be done with the use of a seabed mining system and a riser system. Onboard it will be processed in a dewatering plant. This is described in Section 5. When the minerals are processed, they will need to be transported to shore and to customers. This is the next phase. The transportation will start with a ship-to-ship transfer from the DSMin vessel to a bulk ship or similar. The bulk ship sails to shore where it is unloaded at a processing plant. When the SMS is processed it will be sold to customers located all over the world. The transportation to these locations is dependent on distance and the specific material to be transported. The last phase in the value chain is marketing and sales. There is no need to extract valuable metals if there is no one to buy them. For deep sea mining, this is a substantial challenge that needs to be solved for the industry to survive. Several companies, for example, BMW, Google, and Volvo have said that they will exclude seafloor minerals from their supply chain [69].

For a supply chain to be complete, all the phases mentioned above need to be analyzed. For this thesis, however, this task would be too comprehensive. There will be a focus on the extraction phase of the operation. In Section 5, the operation and equipment that will give value to the deep sea mining operation are decided and described in detail. They are all a part of the value chain and will in some form add value to the project. It can be economic value, value in the form of research, or value in the form of social acceptance of a controversial industry. The latter can be achieved with good solutions for slurry handling and low-impact mining solutions.

5 Results

Section 5 utilizes the theory from Section 2 and content from Section 3 and Section 4 to form the basis of a DSMin vessel configuration. The chapter is organized as follows: First, the function structure, on a basis from the system decomposition, with all its sub-functions is established. Then the working principles are needed. These two sections will together prove that the suggested way of conducting the mining is plausible. When this is established, the specialized vessel equipment selection is done. The equipment chosen is believed to be best suitable to accomplish the goal described in the main function. While the selection is ongoing, the function structure and working principle are updated. When the needed equipment is chosen, the modularization is done. This is done with regard to need, function, and form. The next step is to make the design structure matrix. The matrix combines all components and the modules as well as described their dependencies. The DSM is then evaluated against the requirements for a successful DSM. Finally, when all dependencies are shown in the DSM, a visualization of a DSMin vessel is shown. The approach is presented in the flowchart below, Figure 26.

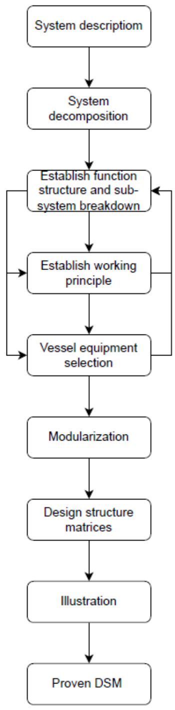


Figure 26: Flowchart for the approach used in Section 5

5.1 Function Structure

To create a function structure there are several steps that need to be conducted. First of all, the main function of the vessel needs to be established. This would be the main purpose of the vessel. In this case, it is *transport SMS ore from the seabed to the surface*. The next step is to decompose the main function into sub-functions. These sub-functions are the tasks or operations that need to be done to be able to achieve the main function. Those will be described next. After this, the sub-functions need to be sorted. This is done by arranging them in a hierarchical system. The higher-level sub-functions will be the more general systems and the lower level contains details within the higher-level sub-functions. A generic illustration of a system breakdown for a function structure is shown in Figure 24. The detailed decomposition is listed in tables instead of in a figure. This is to improve readability. A decomposition is shown in Section 5.2.

When the decomposition is done, the next step is to identify inputs and outputs for each function. Inputs are the requirements or conditions necessary to perform the function, while outputs are the results of the function. Finally, one needs to verify the function structure. To do this ensures that all sub-functions are necessary to achieve the main function as well as each system has clear inputs and outputs.

5.2 Function structure for a deep sea mining vessel

Main function

The main function of a deep sea mining vessel is to *transport SMS ore from the seabed to the surface*. This will be level 0 in the system decomposition.

Sub-functions

Table 5 shows the least detailed decomposition of a deep sea mining vessel. These sub-functions are a general description of the processes and functions that need to be fulfilled for a successful deep sea mining operation. All sub-functions are divided with regard to what part of the mining operation it contributes to. Although the sub-functions are separated, there are dependencies between some of them. The DSM shows this in Section 5.8.

Sub-function (Level 1)	**Description**
Deep sea mining equipment	All the equipment in direct use for the mining operation.
Ore transportation equipment	The equipment in use for either vertical or horizontal transportation of ore.
Dewatering	The equipment responsible for the dewatering and separation of materials.
Ore storage	Cargo hold to store all mined material
Equipment storage	Storage of equipment under sailing and for operations
Lifting equipment	Includes all types of lifting equipment for mining and general use
ROV	All systems connected with ROV operations
Propulsion	All propulsion systems needed for sailing and DP
Navigation	Navigation equipment on the bridge and steering systems
Hull	Hull design and main dimensions for the vessel
Accommodations	Living quarters for crew including galley, leisure room, and other facilities
Electrical system	Includes generators, wiring, and switchboard room

Table 5: Table of all sub-function required for a deep sea mining vessel

Hierarchy

All sub-functions from Table 5 have been further elaborated. In Table 6, the components marked as *Level 1* are the same as in Table 5. *Level 2* in the table describes which equipment or systems that *Level 1* needs to fulfill its sub-task. Further, the *Level 3* section of the table has the same purpose.

Level 1	**Level 2**	**Level 3**
Deep sea mining equipment	Trench cutter	
Ore transportation equipment	Vertical transportation Horizontal transportation	Riser system ROV w/crane ROV on seabed Ship-to-ship transfer Conveyor belt
Dewatering equipment	Hydrocyclone	
Ore storage	Cargo hold	
Equipment storage	Sailing Operation	Trench cutter Riser Subsea basket Workshop Spares
Lifting equipment	Mining operation General Use	Trench cutter Subsea basket ROV
ROV	Control room ROV hangar ROV LARS	
Propulsion	Main propulsion DP systems	
Navigation	Bridge systems Steering systems	
Hull	Main dimensions	
Accommodations	Auxiliary power Living quarters Galley Leisure rooms	
Electrical systems	Generators Wiring Switchboard	

Table 6: Hierarchy of sub-function for a DSM vessel

Inputs and outputs for each sub-function

Inputs and outputs for all sub-functions categorized as Level 1 are shown in Table 7. The *Level 1* sub-functions are considered as a general description of the task or components needed onboard. The inputs and outputs for each sub-function explain what is needed for the sub-function to work as intended and what the outcome is. I.e. what the sub-function requires to successfully contribute to the overall function and what that contribution is.

Sub-function Level 1	**Input**	**Output**
Deep sea mining equipment	Unsullied ore	Crushed ore
Ore Transportation equipment	Ore at location A	Ore at location B
Dewatering equipment	Untreated ore	Valuable payload
Ore storage	Cargo hold capacity	Safe cargo handling
Equipment storage	Storage space	Bring needed equipment
Lifting equipment	Lifting capacity	Handling of heavy equipment
ROV	Monitoring and lifting capacity	Safe operation and mining capacity
Propulsion	Fuel	Thrust
Navigation	Position	Course
Hull	Outline specifications	Stability
Accommodations	Living conditions	Safe living
Electrical systems	Fuel	Electricity

Table 7: Inputs and outputs for all Level 1 sub-functions

Inputs and outputs for all sub-functions categorized as Level 2.

Sub-function Level 2	**Input**	**Output**
Trench cutter	Energy	Crushed ore
Vertical transportation	Energy	Payload on the surface
Horizontal transportation	Energy	Movement of payload
Hydrocyclone	Slurry	Payload and unwanted material
Cargo hold	Storage space	Payload storage
Equipment storage while sailing	Storage space	Bring needed equipment
Equipment storage while operating	Storage space	Workspace and storage
Lifting equipment for mining operations	Energy	Lifting capacity
Lifting equipment for general use	Energy	Lifting capacity
ROV control room	Personnel	Control of ROV
ROV hangar	Storage space	Safe storage
ROV LARS	Energy	Launch and recovery of ROV
Main propulsion	Fuel	Thrust
DP system	Computer signals	Steady Position
Bridge systems	Position	Course
Steering systems	Heading	Rudder movement
Main dimensions	Design requirements	Stability
Auxiliary power	Fuel	Electricity
Living quarters	Crew requirements	Satisfied crew
Galley	Raw materials	Meals
Leisure rooms	Crew requirements	Satisfied crew
Generators	Fuel	Electricity
Wiring	Electricity at point A	Electricity at point B
Switchboard	Electricity	Control of electricity flow

Table 8: Inputs and outputs for all Level 2 sub-function

Inputs and outputs for all sub-functions categorized as Level 3.

Sub-function Level 3	**Input**	**Output**
Riser System	Payload at seabed	Payload at the surface
ROV w/crane	Payload at seabed	Payload at the surface
ROV on seabed	Payload at point A	Payload at point B
Ship-to-ship transfer	Payload at DSM vessel	Payload at transport vessel
Conveyor belt	Payload at point A on vessel	Payload at point B on vessel
Trench cutter (storage)	Storage space	Bring needed equipment
Riser (storage)	Storage space	Bring needed equipment
Subsea basket (storage)	Storage space	Bring needed equipment
Workshop	Available working area	Fixed equipment
Lifting of trench cutter	Lifting capacity	Mining operations
Lifting subsea basket	Lifting capacity	Payload at the surface
ROV LARS	Energy	Launch and recovery of ROV

Table 9: Inputs and outputs for all Level 3 sub-functions

5.3 Use of a riser system

The solution that is presented above has a riser system as one of its components. This is a solution that has never been used for deep sea mining of seafloor massive sulfides before. The method has been developed for use within the oil and gas industry but is a suggested solution for the vertical transport of mined ore from the seabed [17]. A detailed description of the riser is found in Section 3.2. Even with no prior use for SMS, it has been used for deep sea mining. It started when the MV Hidden Gem in the summer of 2022 successfully commissioned a riser and jumper hose [70]. This was a successful launch of a riser that through a flexible jumper hose was connected to a nodule collector at depths of 745 meters. This first test confirmed that the MV Hidden Gem was capable to deploy such equipment and that it was ready for the next step, trying to mine from the seabed. On the 12th of October 2022, this became a reality. The MV Hidden Gem deployed a collector vehicle in the Clarion Clipperton Zone. The vehicle was connected to the vessel through a 4.3-kilometer-long riser system and began the collection of polymetallic nodules [71]. In the 60-minute-long test, the collector vehicle drove 147 meters along a pre-determined route. It managed to collect 14 tonnes of polymetallic nodules. The nodules were lifted to the surface using compressed air. The journey from the seabed to the surface took 12 minutes. The wastewater was returned to the midwater column. At which depth is not specified. While this operation was ongoing, there was a dedicated monitoring vessel at sight. It had experts and independent scientists onboard. Their task was to monitor all possible impacts the mining operation might have on the environment.

It is proven that a riser system is suitable for the mining of polymetallic nodules. The main difference between using the riser for oil and gas and deep sea mining is the absence of continuous flow. The MV Hidden Gem proved that this is a manageable problem. It is not yet known if this is the case for SMS mining as well. The difference in the properties of the polymetallic nodules and the SMS, shape and toughness, might cause challenges. Although, a riser system is chosen due to its prior proven achievements.

5.4 Use of an ROV

In the areas where seafloor massive sulfides are found, there will be sulfide chimneys. These chimneys are made out of the same materials as the SMS found below. This means that these are just as valuable as the ore to be extracted beneath. When the chimneys grow too high, they will collapse and lay on the seabed [20]. To be able to mine these chimneys as well, an ROV will be used to retrieve the pieces of the collapsed structure. A heavy work class ROV will be able to pick up pieces of the chimneys and put them in a subsea basket. The basket will be lifted to the surface using one of the onboard cranes. These kinds of ROVs are made for the retrieval of objects and have proven to be able to recover offshore infrastructures such as subsea manifolds and blowout preventers [72]. This makes the ROV suitable for the retrieval of sulfide chimneys.

5.5 Working principle for a deep sea mining vessel

In the book *Engineering Design: A systematic approach* [30], the next step for concept development would be to determine the working principles. This is further described in Section 2.2. However, to not repeat the work done by Lesage et. al in the paper *A conceptual design framework for deep-sea mining* [32] these results will be presented and used for further work as an argument for the choices done with regard to equipment and solutions. There will be some differences and adjustments but these will be converged into an overall solution principle.

Section 5.3 in the paper *A conceptual design framework for deep-sea mining* [32] shows a solution principle for a hypothetical Norwegian case. These solution has been chosen among the 3774 possible combinations. The result is shown in Figure 27.

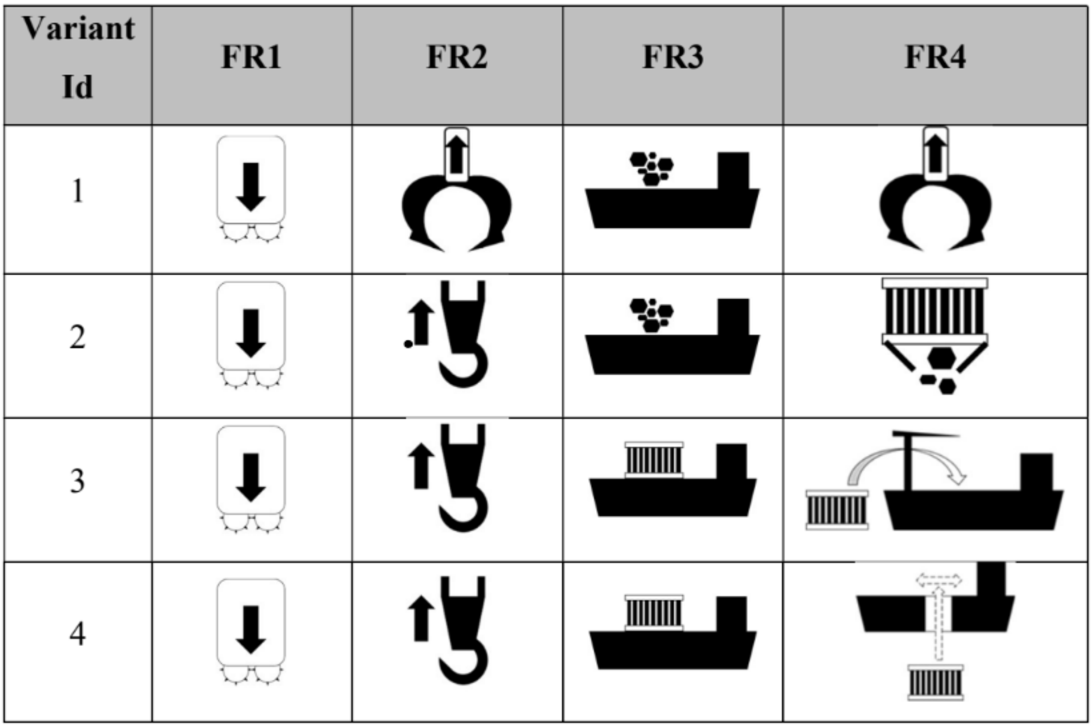


Figure 27: Solution principle for the hypothetical Norwegian case [32]

In Figure 27 there are four different solutions principles marked ID one through four in the columns. In the rows, there are functional requirements - FR. The solution principle marked *ID 3* is the closest to the solution presented in this thesis. The four steps are first to use a vertical trench cutter (FR1) and then use a crane to get the mined ore to the surface (FR2). This is done with the use of a container or basket (FR3). A crane is utilized to get the payload on board the vessel (FR4). The difference is that the ore mined with a trench cutter will be transported to the surface with a riser instead of by a crane. The crane will however be used to transport a subsea basket with the chimneys that have been broken off and collected by an ROV. This means that all the functional requirements will be used but in a slightly different arrangement, and with some additions.

When looking at the results from *A conceptual design framework for deep-sea mining* [32], the riser system described in Section 5.3 and the ROV from Section 5.4, the suggested system is considered as a feasible solution on how to conduct deep sea mining of seafloor massive sulfides.

5.6 Vessel equipment selection

A variety of operational-specific equipment is described in Section 3. In the following sub-section the chosen equipment, and the reasoning for the choice, are listed. It is important to note that the choice of equipment is based on proven methods, a literature review, and the author's qualified opinion.

The ROV of choice is the ROV Quantum. This is due to its focus on in-current performance. In the area where Loki's castle is located, there is a lot of movement in the water, especially close to the seabed. This is due to the volcanic activity that creates the SMS. These conditions require an ROV with the ability to withstand this forces. The Quantum is slightly larger in size and weight than the two other options. This is not considered a problem since the LARS will be installed with regard to the dimensions. Additionally, the difference in size is relatively small compared to the vessel's capabilities.

The chosen solution for a mining machine is the vertical trench cutting system described by Spagnoli et al. in *Preliminary Design of a Trench Cutter System for Deep-Sea Mining Applications Under Hyperbaric Conditions* [26]. This trench cutter is chosen because this is the vertical drilling solution with the most amount of research. A trench cutting system is chosen instead of the seafloor production tools from Nautilus due to the possibility of making less of an impact on the environment on the seabed. The solution from Nautilus will grind down huge areas as one sees from onshore mining. The trench cutter will be deployed directly above the desired minerals and only grind up the valuable ore and the soil in direct proximity. The overall impact is believed to be less invasive with the trench cutter. Another advantage of the trench cutter is the need for only one machine. An operation that requires three seafloor production tools is more susceptible to a system breakdown. Since all machines are dependent on each other, a breakdown in one of them will lead to a stop in the entire operation. Precision is a factor in the choice as well. While the bulldozer-like machines will crush everything in its path, the trench cutter is more likely to only mine the desired minerals. On the other hand, there is a challenge with the trench cutting system. As of now, it is designed for a maximum depth of 2000 meters. However, the design principle is considered favorable to the others. Since the trench cutter is in its early phase of development, the depth challenges can be solved.

Within the section for vertical transport systems, there are two solutions presented. Both of them are considered suitable solutions. The seafloor mining riser is proven to be functional for the mining of polymetallic nodules, as described in Section 5.3. Its intended purpose for SMS mining is somewhat similar, but it is not tested for this purpose yet. Nevertheless, the riser solution is considered the most feasible for this DSMin vessel.
A subsea basket are a part of the vertical transportation solution as well. The solution with a basket and an ROV is not mentioned directly in scientific papers, but it is a combination of known solutions. Using ROVs is standard in the offshore industry. Subsea baskets are a well-known tool for deep-water operations as well. In the paper *A conceptual design framework for deep-sea mining* by Lesage et al. [32], the solution with a container used for vertical transportation of unrefined ore is mentioned as a feasible solution. The combination of the proven methods, ROV operations and subsea basket usage, and the container solution are considered a realistic configuration for the retrieval of SMS chimneys.

A dewatering system is essential for the stability of the vessel, as well as the utilization of cargo space. A hydrocyclone has the ability to fulfill this task in an efficient manner. This is the solution used on the MV Hidden Gem for polymetallic nodules [73]. The solution has not yet been used for seafloor massive sulfides but has been proven viable in similar situations.

The slurry disposal system is set to be a submarine tailing disposal system. An equipment specification for this solution consists of a centrifugal pump and a piping system. The method is identical to the one used in onshore mines and is considered proven and suitable. A pump pumps the unwanted slurry from the dewatering plant through the disposal pipe and into the ocean [74].

A solution with a rigid riser requires a derrick for the riser assembly and deployment. A derrick is proven to be a suitable solution for the task both in the oil and gas industry, as well as on the *MV Hidden Gem* [71]. The derrick on *Ocean Rig Olympia* is chosen because this vessel is the newest conversion from a drilling vessel to a DSMin vessel to date.
The moonpool on *Ocean Rig Olympia* is made to interact with the derrick and will be kept with the same dimensions.

Numerous cranes are needed for an offshore vessel to operate, especially one carrying out subsea operations. DSMin requires a lot of the same capabilities as a large construction service vessel (LCSV). A main similarity is the crane capacities. The main crane is the Trident crane from NOV. The choice of the Trident crane is due to its large capabilities as well as the innovative fiber rope solution which contributes to a slightly more environmentally friendly vessel. The manufacturer NOV is a reason for the choice as well. The Trident crane concept is new, but NOV has an extensive amount of experience within the oil and gas industry as a supplier of cranes and other offshore equipment. They are considered a trusted vendor.
When working with a riser, a pipe handling crane is essential. The chosen crane is installed on the working deck area, close to the derrick. It will provide the derrick with parts of the riser from the riser storage.
The last crane onboard is the working crane. This smaller crane is intended for daily use on deck and for the retrieval of SMS chimneys in the subsea basket. The 50-tonne capacity together with the maneuverability is considered sufficient for the work to be done in the working area.

It is essential for an ROV operation to have a LARS. The LARS from West Marine meets the depth requirements in the area of Loki's castle. In addition, the strengthened umbilical and its ability to work with a high Hs is important when working in such challenging conditions as in the North Sea. With a high SWL, this LARS will be able to work with an ROV that carries a payload, i.e. SMS chimney.

FSubsea delivers a seabed slurry pump that is designed for DSMin. There is a limited supply of specialized pumps on the market for DSMin purposes. The centrifugal pump is believed to have the capacities needed for SMS mining.

The main purpose of the helideck is to provide a landing facility for helicopters during a crew change. Having facilities for this allows the vessel to be located at the mining site for a longer period of time. The chosen helideck is already proven to be efficient on *Ocean Rig Olympia*. The weight capacity is also sufficient for a standard crew transfer helicopter used in Norway.

To keep the DSMin vessel's operational time to a maximum, it is important to have a system that is able to unload payload at sea. Dry ship-to-ship transfer is considered the best solution for this. The main advantage compared to wet ship-to-ship transfer is that the need for a second dewatering is not present in dry ship-to-ship transfer. This saves a lot of equipment and makes the transfer operation less complicated. The ship-to-ship transfer system consisting of hatches, conveyor belts, and a boom is a system that has been installed, tried, and proven effective on numerous bulk vessels [75]. This is also the case for the system presented by CSL.

A cargo hold specifically designed for the high-density SMS is important for the DSMin vessel's stability. A solution as shown in Figure 22 fulfills this demand. The suggested cargo hold design will reduce the capacity of the hold. It is accepted due to bulk vessels or barges that will receive the payload on a regular basis, reducing the required cargo hold volume. Additionally, the space left open on the sides and beneath the cargo hold will be used for the storage of crane wires and similar equipment.

5.7 Modularization

Modularity theory is described in Section 2.2. For a new and unique vessel like the DSMin vessel, it is favorable to utilize this method. This is because of the uncertainty with regard to what kind of equipment is needed and being able to do modifications or upgrade equipment in the future. To be more exact, slot modularity will be the preferred approach on the DSM vessel. This is due to the uniqueness of the vessel. The different modules will share a unique interface with the base element [76]. In this case, the base element is the DSM vessel.

The modules will be divided mainly with regard to which part of the mining operation it contributes to or which support function it has. The modules will be topside, mining operation, ROV, payload storage, machinery, accommodations, bridge, payload handling, and tween deck.

Topside

The topside is located behind the superstructure, towards the aft of the vessel. This is where all of the work that is done on deck is carried out. The main components in this module are the derrick, the cranes, the outside work area, and equipment storage. The moonpool is located below the derrick, but it is in the module called "tween deck". All the components in this module are located in close proximity to each other. The pipe handling crane will be used to feed the derrick with pipes for the riser. These pipes are stored in the riser storage rack. The storage rack is located next to the derrick. Aft from this, the outside work area and equipment storage is located. These two are not defined as specific areas, but they may vary from one mining project to another. They are considered two different sub-systems because of the different uses they have.

Mining operation

The mining operation module contains the equipment that is directly involved in the mining. These components are the trench cutter, the seabed slurry lift system, the riser, and the subsea basket. The ROV is directly connected as well, but this is considered a module of its own. The trench cutter is directly connected to the seabed slurry lift pump. The SSLP is mounted on top of the trench cutter. All the material that the cutting heads grind will be transported through the SSLP and into the riser system. As this process focuses on the minerals in the seabed, the subsea basket (and ROV) has a focus on the seabed. The subsea basket will be used for the transport of the loose mineral-rich chimneys to the surface. The working crane will be used in this part of the process.

ROV

The ROV module consists of the ROV, the ROV hangar, the LARS, and the pilots' control room. This is typically placed on the ship side within the superstructure. There will be a watertight hangar door on the ship side that will stay closed for transit. When it is time to launch the ROV, it opens completely. Within the hangar, the LARS is located. It will extend over the side of the vessel and lower the ROV into the water column. The LARS connects to the ROV with a wire for vertical transportation as well as through an umbilical for controlling the ROV. The controls are located in the pilots' control room within the ROV hangar. The ROV hangar is utilized for the repair, maintenance, and storage of the ROV.

Payload storage

A cargo storage system is critical for maintaining the mining operation over time. The main component is the cargo hold, but it includes the hatches as well. The hatches are located at the bottom of the cargo hold, giving the payload access to the conveyor system below. The payload storage module is closely connected to the payload handling module.

Machinery

The machinery includes propulsion power, auxiliary power, and the DP system. In total, there will be 47 231 kW installed on the vessel. A vast majority of the power will be used for station-keeping. The vessel will have DP 3 that requires 6-off 5 000 kW thrusters. All the power supplies are located in the machine room, at the aft of the vessel. There is an extensive amount of equipment within this room. This includes, but is not limited to, main and auxiliary engines, gearboxes, lubrication systems, engine control room, and switchboards. For simplicity, all these components are considered as a part of either propulsion power, auxiliary power, or the DP system.

Accommodations

The accommodations are located in the superstructure of the vessel. Cabins, mess, galley, recreation room, washroom, and similar are located here. The collective term for all these functions is called living quarters. This is mainly where the crew will spend their time when they are off duty. This area is crucial for the crew's well-being. All of the components within this module are located in close proximity to each other.

Bridge

The bridge is where the captain and the officers overseas the ship's navigation, communication, and safety. This module includes radar, electronic chart display and information system (ECDIS), steering console, engine control, communication instruments, and safety equipment. In addition, the helideck is located above the bridge. Therefore, this is a part of this module. There are a lot of dependencies in this module. Several systems on the bridge are connected to each other and one can not use one without the other. The exceptions are the safety equipment and helideck. The safety equipment is dependent on the other systems to be utilized in an efficient and safe manner, but not the other way around. In addition, there will be quite extensive redundancy for the components in this module, at least two of everything (not helideck).

Payload handling

Payload handling refers to the conveyor system for unloading, the boom, and the dewatering of the payload. All these functions are important for maximizing the utilization of mined ore. The dewatering plant's goal is to only remove the unwanted water sand from the slurry, leaving valuable minerals. For the conveyor system and boom, the goal is safe, reliable, and fast unloading at sea. The conveyor system beneath the cargo holds is directly connected to the unloading boom through various small conveyor belts. These move both horizontally and vertically. The last part of this module, the dewatering system, is located in close proximity to the conveyor belts that lead down to the cargo hold.

Tween deck

The tween deck is located beneath the main deck from the middle of the vessel and towards the aft. The tween deck consists of tanks (water, MDO, lube, etc.), storage, and the moonpool. This module is closely connected to the payload storage module with regard to localization. All the tanks that contain liquids are separated with cofferdams. The storage refers to the general storage of equipment and general consumption material, not payload storage. The moonpool is located in the middle of the vessel, directly below the derrick. It starts at the main deck and continues all the way through the vessel.

5.8 Design structure matrix

The general background and description of a DSM are described in Section 2.2. For the making of a specific matrix, one starts with the system boundaries. This is done to limit the scope of the system to be described. The system boundaries are limited to the DSMin vessel, the riser system, and the mining equipment located on the seabed. This means that the horizontal transportation from the DSMin vessel to shore, the possibility for support vessels, and the onshore processing are not within the system boundaries to be described in the resulting matrix. When the system boundaries are set, the individual components need to be identified. For such a complex vessel as a DSMin vessel, there is a vast amount of systems and components. The focus of the DSM is not all the minor sub-systems, but the major components. In addition, the standard components of a vessel, such as details within the living quarter and details in the engine room, are not elaborated. All components are described in detail in Section 5.7. The chosen components are critical for the mining operations and what defines this vessel as a deep sea mining vessel. To be able to identify the equipment needed, a system decomposition was done. The decomposition is shown in Table 5 and further described in Section 5.2. The decomposition is broken down into levels where each level gets more detailed. This is done to get a detailed insight into the tasks and functions that each system or component fulfills. In this case, the systems are broken down with regard to which part of the mining operation it contributes to and their placement onboard. Further, the inputs and outputs of each system and sub-system are defined. Doing this helps with the understanding of the system structure and later on the modularization.

The DSM shows the level of interaction between the components. This is called a numerical DSM and is an extension of the binary DSM [38]. Different levels are represented with a numerical value of one through five. One is a low level of interaction and five is a high level of interaction.

The final product for the DSM is a visualization of the DSMin vessel systems and their interactions. It is done to simplify the analysis and design of the vessel and to enable a better understanding of the interactions between the various components of the system in an intuitive way. In Figure 28, the DSM for the DSMin vessel is shown.

Components	NR.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Derrick	1	1		5	3	3	3			5									5																1			5	5
Trident Crane	2		2				4	5			2	1							5	3																			
Pipe Handling Crane	3	5		3			5			5									5																			3	5
Working Crane	4	3			4	5	5				5	2							5																				
Outside Work Area	5	3			5	5	5	3		4	4																												4
Equipment Storage	6	3	4	5	5	5	6	5		5	5																								4				5
Trench Cutter	7		5			3	5	7	5	5						2			5	5															2				
Seabed Slurry Lift System	8							5	8	5						3			5																4				
Riser	9	5		5		4	5	5	5	9										5															4			5	4
Subsea Basket	10		2		4	5	5				10	5																											
ROV	11		1		2						5	11	5	5	5				5	4																			
ROV Hangar	12											5	12	5	5																								
Launch and Recovery system	13											5	5	13	5				5	5																			
Pilots Control Room	14											5	5	5	14				5																				
Cargo Hold	15							2	3							15	5																4		4				
Cargo Hatches	16															5	16		5														5						
Propulsion Power	17																	17		5									5							5			
Auxiliary Power	18	5	5	5	5			5	5			5		5	5		5		18		5	5	5	5	5	5	5			5			5	5	5	5		5	5
Dynamic Positioning	19		3					5		5		4		5				5		19						5	5					2							
Cabins	20																		5		20	4	4	4	4														
Mess	21																		5		4	21	5	4	4														
Galley	22																		5		4	5	22	4	4														
Recreation Room	23																		5		4	4	4	23	4														
Washroom	24																		5		4	4	4	4	24														
Radar	25																		5	5						25	3	3	3	3									
ECDIS	26																		5	5						3	26	3	3										
Steering Console	27																									3	3	27	5										
Engine Control	28																	5								3	3	5	28										
Communication Instruments	29																		5							3				29	5								
Safety Equipment	30																													5	30								
Helideck	31																			2												31							
Conveyor System	32															4	5		5														32	5	5				
Boom	33																		5														5	33	5				
Dewatering	34	1					4	2	4	4						4			5														5	5	34				5
Tanks	35																	5	5																	35			
Storage	36																																				36		
Moonpool	37	5		3						5									5																			37	5
Slurry Disposal System	38	5		5		4	5			4									5																5			5	38

Figure 28: Design Structure Matrix for a Deep Sea Mining Vessel

On the left side of Figure 28 all components from Section 5.7 is listed and given an identification number. The same number is shown horizontally on the top of the matrix and represents the same component as on the left side. The gray squares shown diagonally presents the same identification number to make the matrix easier to read. In this diagonal, there is no dependency. This is because no component is considered dependent on itself. In the off-diagonal however, there are numerical values that represent the amount of dependency between the components. These values range from one to five. One represents the lowest level of interaction. An example of this is the interaction between the trident crane and the ROV. This interaction is solely redundant and will not occur under normal circumstances. On the other end of the scale, five is the highest level of interaction. For instance, all interactions the auxiliary power have is considered as five. This is because this component powers all the components it interacts with. In addition, the modules are represented as green squares in the matrix. All components within the same square are a part of the same module. There are a lot of different types of interactions between the components. All of these are described in detail in Appendix D. All

DSMs are shown in a larger format in Appendix A, B, and C.

5.9 Process DSM and location-oriented DSM

The DSMs showed in Figure 29 and Figure 30 has the same system boundaries as Figure 28. The difference between the matrices is that Figure 29 is focused on the dependencies between components with regard to what part of the mining operation the components contribute to. This means that the location does not have anything to say with regard to dependencies. This is known as process architecture DSM which is defined as *A mapping of the network of interactions among the activities in the process* [38]. The numerical values in the process architecture DSM illustrate to what degree the components work together in their given task. The majority has strong dependencies, 5, because the DSMin vessel is specially designed for one particular task, deep sea mining. The lower level of interaction for some components, like the trench cutter and the dewatering system, is based on a lower level of direct interaction. Meaning that they do not operate without help from each other, but the part of the mining operation the component contributes to is different.

Components	NR.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Derrick	1	1		5	3					5									5																			5	5
Trident Crane	2		2				4	5			2	1							5	3																			
Pipe Handling Crane	3	5		3	5		5			5									5																				5
Working Crane	4	3		5	4	5	5				5	2							5																				
Outside Work Area	5				5	5	5																																
Equipment Storage	6		4	5	5	5	6																																
Trench Cutter	7		5					7	5	5						2			5	5															2				
Seabed Slurry Lift System	8							5	8	5						3			5																4				
Riser	9	5		5				5	5	9										5															4			5	
Subsea Basket	10		2		5						10	5	5	5					5	4																			
ROV	11		1		2						5	11	5	5	5																								
ROV Hangar	12										5	5	12	5	5																								
Launch and Recovery system	13										5	5	5	13	5				5	5																			
Pilots Control Room	14											5	5	5	14				5																				
Cargo Hold	15							2	3							15	5																4		4				
Cargo Hatches	16															5	16		5														5						
Propulsion Power	17																	17		5									5							5			
Auxiliary Power	18	5	5	5	5			5	5		5			5	5		5		18		5	5	5	5	5	5	5			5			5	5	5	5		5	5
Dynamic Positioning	19		3					5		5	4			5				5		19						5	5					2							
Cabins	20																		5		20																		
Mess	21																		5			21																	
Galley	22																		5				22																
Recreation Room	23																		5					23															
Washroom	24																		5						24														
Radar	25																		5	5						25	3	3	3	3									
ECDIS	26																		5	5						3	26	3	3										
Steering Console	27																									3	3	27	5										
Engine Control	28																	5								3	3	5	28										
Communication Instruments	29																		5							3				29	5								
Safety Equipment	30																													5	30								
Helideck	31																			2												31							
Conveyor System	32															4	5		5														32	5	5				
Boom	33																		5														5	33	5				
Dewatering	34							2	4	4						4			5														5	5	34				5
Tanks	35																	5	5																	35			
Storage	36																																				36		
Moonpool	37	5								5									5																			37	
Slurry Disposal System	38	5		5															5																5				38

Figure 29: Process DSM for a deep sea mining vessel

The last matrix, Figure 30, is location-oriented. It illustrates which components need to be in proximity to each other to be able to work efficiently, not which components that are physically close. This is done to be able to get a visual presentation of the locational dependencies. A purely location-based DSM is not mentioned in *Design*

Structure Matrix Methods and Applications [38]. However, the process of creating a location-based DSM is considered to be similar, almost identical, to the process- and product DSM. Meaning that the general DSM approach is suitable for a location-based DSM as well. The outcome will be discussed further in Section 6.

Components	NR.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Derrick	1	1		5	3	3	3			5																									1			5	5
Trident Crane	2		2				4	5			2	1																											
Pipe Handling Crane	3	5		3			5			5																												3	5
Working Crane	4	3			4	5	5				5	2																											
Outside Work Area	5	3			5	5	5	3		4	5																												4
Equipment Storage	6	3	4	5	5	5	6	5		5	5																								4				5
Trench Cutter	7		5			3	5	7	5	5																													
Seabed Slurry Lift System	8							5	8	5																													
Riser	9	5		5		4	5	5	5	9																									4	5			4
Subsea Basket	10		2		5	5	5				10	5																											
ROV	11		1		2						5	11	5	5																									
ROV Hangar	12											5	12	5																									
Launch and Recovery system	13											5	5	13																									
Pilots Control Room	14														14																								
Cargo Hold	15															15	5																4		4				
Cargo Hatches	16															5	16																5						
Propulsion Power	17																	17																		5			
Auxiliary Power	18																		18																	5			
Dynamic Positioning	19																			19																			
Cabins	20																				20	4	4	4	4														
Mess	21																				4	21	5	4	4														
Galley	22																				4	5	22	4	4														
Recreation Room	23																				4	4	4	23	4														
Washroom	24																				4	4	4	4	24														
Radar	25																									25	3	3	3	3									
ECDIS	26																									3	26	3	3										
Steering Console	27																									3	3	27	5										
Engine Control	28																									3	3	5	28										
Communication Instruments	29																									3				29	5								
Safety Equipment	30																													5	30								
Helideck	31																															31							
Conveyor System	32															4	5																32	5					
Boom	33																																5	33					
Dewatering	34	1					4			4						4																			34				5
Tanks	35									5								5	5																	35			
Storage	36																																				36		
Moonpool	37	5		3																																		37	5
Slurry Disposal System	38	5		5		4	5			4																									5			5	38

Figure 30: Location-oriented DSM for a deep sea mining vessel

5.10 Illustration of a deep sea mining vessel

The description of the DSMin vessel has been illustrated in Figure 31. The focus has been to visualize the modules described above. Their placement in comparison to each other and roughly the sizes of the modules are shown. The hull of the vessel is as described in *Technology Transfer in Novel Ship Design: A Deep Seabed Mining Study* by Solheim et al. [17]. Although most of the components are included in the illustration, some of the non-DSMin-related components are not visualized. This is for instance the machinery and the thrusters. The model has been made using the hull modeling program DELFTship [77].

The modules from Section 5.7 are color-coded in Figure 31. The *topside* module is shown in red. The cranes and the derrick are located on the area defined as the outside work area and equipment storage. The two latter are a part of the *topside* module but are not red due to better visualizing the mining components. The module *mining operation*, which includes the trench cutter, seabed slurry lift system, the riser, and the subsea basket, is shown in green. The squares at the aft of the vessel represent the subsea basket and the trench cutter. At the side of the superstructure, the *ROV* module is shown in black. The main part of the module is located inside, but the black area is where the LARS will lower the ROV into the water. *Accommodations* is the module presented in white on the superstructure. This area includes but is not limited to, cabins, mess, galley, recreation rooms, and washrooms. On top of this module, the *bridge* is found in dark gray. All navigation components as well as the helideck are located in this module. Further, the conveyor systems, dewatering plant, and boom is visualized in yellow. This is the *payload handling* module. The last module is the *tween deck*. Only the moonpool is visible, but the tanks and general storage space are included as well. The module is shown in pink on Figure 31.

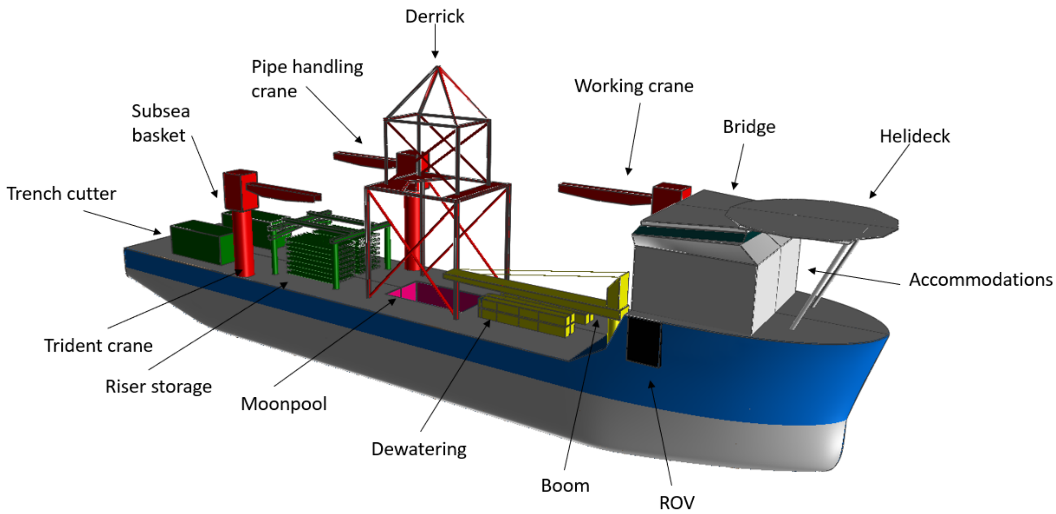


Figure 31: Illustration of deep sea mining vessel

5.11 Proven DSM

In the book *Design Structure Matrix Methods and Applications* by Eppinger et al. [38], five criteria are listed that need to be met for a DSM to be successful. The first criterion is that the model needs a clear purpose. For this to be achieved, the DSM needs to be a part of the solution for the problem described in Section 1. In this case, the DSM illustrates the configuration and the dependencies of the DSMin vessel, which is the goal. The clarifications linked to the DSM in Appendix D elaborate the framework of the vessel.

The next criterion that needs to be fulfilled is that the model uses the appropriate amount of detail for the intended purpose. The level of detail for this task is considered low-level. There is no intention of describing a fully designed vessel in detail, but rather getting an overview of the most important components. These components are chosen with regard to what is special for a DSMin vessel and a few other function that is necessary for a vessel to operate like living quarters and machinery. The detailed descriptions for the mining-specific components are found in Section 3 and not the DSM. This is to limit the amount of information in the DSM and make it easier to interpret. An example with a similar amount of detailing can be seen in

[38] p. 58-60.

That the modelers have access to sufficient knowledge or expertise regarding the system is the next element on the list. Throughout the process of writing this thesis, a lot of literature studies have been conducted, described in Section 2. This has been a combination of general studies connected to deep sea mining as well as theoretical literature with regard to engineering design theory. In addition, numerous meetings and conversations with professors and Ph.D. candidates from the Norwegian University of Science and Technology, NTNU have contributed to the outcome of the DSM. Additionally, the knowledge gained from almost five years as a marine technology student proves that the knowledge is sufficient for making the DSM.

For the fourth criterion, it is stated that the DSM is maintained as a "living model", continuously improving it by incorporating new knowledge as it becomes available. There has been an ongoing development of the DSM throughout the writing of this thesis. However, the development, with regard to new knowledge, will be a continuous process for the time to come. The DSMin industry is an industry in fast development and this DSM is not a final product, but rather a work in progress as new technology and knowledge comes along.

The last criterion states that having a DSM model often prompts the emergence of otherwise latent knowledge. To fulfill such criteria depends on the knowledge level of the reader. The information presented in this DSM is not considered common knowledge if the reader has little to no prior involvement in the DSMin industry. Especially the level of interactions described is considered latent knowledge in this perspective.

6 Discussion

The main goal for this master's thesis is to utilize well-known engineering design theory, as well as proven methods from the oil and gas industry, to obtain a theoretical foundation for the configuration of a deep sea mining vessel. This has been shown in Section 5. Through the systematic approach, all relevant components have been argued for. Although these results are based on the theory from Section 2, there is room for interpretations as well as the author's opinions. The section most exposed to this is the choice of mining equipment and the numerical dependencies in the DSM.

For an entirely new industry like deep sea mining of SMS, the need for experiments and testing is a necessity to determine which solution is preferable. This can not be done with just a theoretical approach. As of today, no one knows exactly what the needs, function, and form of a deep sea mining vessel are. However, a well-founded study will give the basis needed to have a plausible starting point.

Equipment

Vertical transportation of slurry has the potential to be a challenge. The riser solution for SMS is not a proven method, but similar technology has been utilized in the oil and gas industry and for polymetallic nodules [71]. As described in *Deep sea mining: Towards conceptual design for underwater transportation* by Lesage et al. [29], there is a lot of possible solution to this problem. A change in solution would affect the configuration. A technology readiness level (TRL) analysis would be beneficial to conduct in this case.

A seabed slurry lifting system is not a well-tested system, but it consists of components that have been used in the mining industry for years. A slurry pump as described in Section 3 is a plausible solution, but it is uncertain if it is able to handle the change in viscosity and flow rate that may occur. In this case, it would be beneficial to study the pumping solutions from offshore well drilling even further. An ultra-deep subsea well utilizes mud and pressure through a riser. This might be interesting to evaluate in a DSMin context. [Further work?]

In addition to the seabed slurry lifting system, the slurry disposal system is new to this type of use. The concerns regarding the depth of waste disposal are a serious environmental matter that needs to be analyzed for this solution to be sustainable. Physically, this might only affect the storage on deck, but for the operation, this is a necessity. Additionally, the dewatering plant needs a thorough evaluation. The amount of sediments that will pass through the plant may be damaging for the marine environment to release back into the ocean. A filtration system needs to be considered. If the slurry contains large pieces of ore, a crushing plant might be needed as well. This is not known until the trench cutter is tested in a real life situation.

Design structure matrix

The DSM is a valuable tool in engineering design, but it has the potential to be biased in favor of the author's opinion. Usually, and in this case, the concept that needs to be evaluated in the DSM is made by the author or it is a solution the

author has worked with for a long time. This often causes the outcome to not be objective. The numerical dependencies are particularly susceptible to this issue. A solution to this is to work closely with experts in the specific area. Meaning both for vessel configuration and specialists on the specific types of equipment.
Another possibility is to do a sensitivity analysis of the DSMs. In a sensitivity analysis, the numerical values in the DSM would be changed and the outcome of the DSM would be analyzed once again. Some dependencies, like the auxiliary power and its dependant components, are established through decades of shipbuilding and would not be subjective to this. On the other hand, there are a lot of new components with uncertain dependencies. An example is the riser and the slurry disposal system. Connecting the two is not a proven method and it needs further analysis to be able to decide if this solution is viable. So far the solution is a result of research and the author's qualified opinions.
For the DSM, and the vessel in general, the equipment detail level is important. The DSM presented in Figure 28 has a low level of detail, only presenting the overall systems. These systems help to create the modules and gain an overview of the vessel. One of the challenges whit this level of detail is the lack of resource allocation information. This information would help identify the specific resources required for each equipment or subsystem, such as power, manpower, materials, or specialized tools. Without this information, it becomes challenging to allocate resources efficiently and plan for maintenance, repairs, or upgrades. This will affect the vessel configuration. Another challenge is the identification of critical paths. A rough estimate can be made, but it is very difficult to identify bottlenecks and detailed sequences of activities that are essential for the functioning of the vessel. Additionally, the dependencies of subsystems will not be visualized. It is likely that it is favorable for some subsystems to either be located in close proximity to each other or that they have a level of dependency. This can lead to an incomplete understanding of how changes or failures in one sub-system can affect others. On the other hand, there are several advantages of making the DSM as detailed as in Figure 28. In the early phase of the design process, it is favorable to not decide on too many details. This makes it easier to make changes later on in the process. Additionally, the DSM makes it easier to understand the bigger picture of the system, especially for stakeholders with little technical knowledge. This understanding is important in the early stages of a project to make sure everyone involved is familiar with the basic foundation of the system. This makes collaboration and further work more comprehensible. Furthermore, the basis that is set creates a foundation for gathering more detailed information and refining the matrix as the design progresses goes on. The DSM with limited detail will serve as an initial foundation for subsequent in-depth analysis and discussion.

The process DSM, Figure 29, and location-oriented DSM, Figure 30, present a dilemma for the vessel configuration: What is most important for the given components? The individual components need to be assessed by themselves, but as a general rule, the location-oriented DSM has to be prioritized. This is because the components with a high degree of dependence in the location-oriented DSM must be in close proximity to each other to be able to fulfill the main goal for the vessel: to conduct deep sea mining. The process DSM does not consider if the location of the component with regard to other components is important.

The components described in the DSM are considered necessary for the DSMin vessel to carry out a mining operation. The challenge is to know if all needed components are taken into consideration. This is challenging to confirm for a new mining concept like the one presented in this thesis. If this is the case, the system breakdown and the configuration might look quite different. On the other hand, the mining operation presented is based on existing technology and systems from the oil and gas industry. This fact supports the selection of components that have been made.

7 Conclusion

The findings of this thesis show a functioning base configuration for a deep sea mining vessel. The low level of detail presents an overall solution to a plausible vessel configuration. Through a systematic approach, the deep sea mining system has been broken down into a system structure with a main function and the contributing sub-functions. Then the working principles for the mining solution are established and argued for. Further, the vessel equipment is selected to fulfill the requirement of the main function, sub-functions, and hence the working principle. Then all the equipment is put into modules. From this, the design structure matrix is made and an illustration of the deep sea mining vessel basis is created. However, further work and detailing are needed to make this a finalized deep sea mining vessel.

The goal of this master's thesis is to create a basis for a deep sea mining vessel configuration based on well-known engineering design theory together with technology solutions from the oil and gas industry. From the results section, one can see the approach used and the resulting illustration of a low-detailed deep sea mining vessel. The mining equipment selected is a plausible, but not proven, solution to seafloor massive sulfide mining. This especially applies to the vertical trench cutting system and the riser solution. The uncertainty of the feasibility of such components is important to take into consideration during further work.

The approach utilized in this thesis shows a systematic, well-proven, and reliable way of creating a vessel configuration. The system breakdown is a good starting point for further elaboration of sub-functions. It leaves room for some modifications, but the basis for the chosen solution is set. Further, the modules created show a general break-up of the vessel and the components which are working together. The chosen configuration is considered a functioning framework. The design structure matrix is proven as a useful tool in vessel configuration, but it is not a final product. Further development is needed as time goes and technologies are tested.

8 Further work

The design spiral is a well-known strategy within ship design. This simply means that the design process needs to be done numerous times as one gains knowledge, requirements from the stakeholders, and new insight into challenges as the process goes on. A natural way forward from this thesis is to go back to the start and adapt the basis to get one step further.

An assessment of the technology readiness level for the mining equipment will provide useful information for the feasibility of building the vessel with the chosen mining equipment. Acknowledged criteria for which level a technology is at today do exist, but it will be wise to modify them to apply to this special usage. A TRL analysis is both advantageous and required for further work.

As of now, the level of detail for the DSMin vessel is limited. Continuation of this work will require the details of the equipment to be described in greater depth. Additionally, the amount of non-mining related parts of the vessel needs to be a part of the modules, DSM, and final illustration. The results from the detailing might change some of the set dependencies and configuration, but that is a part of the previously mentioned design spiral.

Bibliography

[1] J. R. Hein, K. Mizell, A. Koschinsky and T. A. Conrad, *Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources*, Jun. 2013. DOI: 10.1016/j.oregeorev.2012.12.001.

[2] M. Hannington, J. Jamieson, T. Monecke and S. Petersen, 'Modern sea-floor massive sulfides and base metal resources: Toward an estimate of global seafloor massive sulfide potential.', *GeoScienceWorld*, Jan. 2010.

[3] S. Scarminach, *Diving into the history of seabed mining*, Oct. 2019.

[4] J. L. Mero, 'Minerals on the ocean floor', *Scientific American*, vol. 203, pp. 64–73, 6 Dec. 1960.

[5] J. L. Mero, *The Mineral Resources of the Sea*. Elsevier Publishing company, 1965.

[6] V. Dover and C. Lee, 'Mining seafloor massive sulphides and biodiversity: What is at risk?', *ICES Journal of Marine Science*, vol. 68, pp. 341–348, 2011.

[7] T. Treves, 'United nations convention on the law of the sea', 2008. [Online]. Available: www.un.org/law/avl.

[8] IMO, *United nations convention on the law of the sea*, 2019.

[9] A. Samland, *Åpning av områder for mineralvirksomhet på deler av norsk kontinentalsokkel*, Oct. 2021.

[10] E. C. Alberts, *Norway proposes opening germany-sized area of its continental shelf to deep-sea mining*, Apr. 2023.

[11] N. O. Exploration, *What is the mid-ocean ridge?*

[12] C. R. German, S. Petersen and M. D. Hannington, 'Hydrothermal exploration of mid-ocean ridges: Where might the largest sulfide deposits be forming?', *Chemical Geology*, vol. 420, pp. 112–126, Jan. 2016.

[13] P. N. G. M. Watch, *For nautilus mineras, the debt comes due*, Jan. 2019.

[14] C. Lauber, *'hidden gem' arrives in rotterdam to be transformed into nodule collection vessel for the metals company*, Aug. 2021.

[15] Allseas, *Hiddem gem*, 2022.

[16] F. Post, *Tmc and allseas achieve historic milestone: Nodules collected from the seafloor and lifted to the production vessel using 4 km riser during pilot trials in the clarion clipperton zone for first time since the 1970s*, Oct. 2022.

[17] A. V. Solheim, P. O. Brett, J. J. G. Agis, S. O. Erikstad and B. E. Asbjørnslett, 'Technology transfer in novel ship design: A deep seabed mining study', Onepetro.org, 2022.

[18] P. H. Ramberg, 'Preliminary work for vessel optimization within deep sea mining', NTNU, Dec. 2022.

[19] A. Crawford, S. Hollingshead and S. Scott, 'Geotechnical engineering properties of deep-ocean polymetallic sulfides from 21n, east pacific rise', *Marine Mining*, pp. 337–354, 1984.

[20] R. E. Boschen, A. A. Rowden, M. R. Clark and J. P. Gardner, *Mining of deep-sea seafloor massive sulfides: A review of the deposits, their benthic communities, impacts from mining, regulatory frameworks and management strategies*, Nov. 2013. DOI: 10.1016/j.ocecoaman.2013.07.005.

[21] UIB, *Research cruises 2010*, 2010.

[22] S. Petersen, A. Krätschell, N. Augustin, J. Jamieson, J. R. Hein and M. D. Hannington, 'News from the seabed – geological characteristics and resource potential of deep-sea mineral resources', *Marine Policy*, vol. 70, pp. 175–187, Mar. 2016, ISSN: 0308597X. DOI: 10.1016/j.marpol.2016.03.012.

[23] N. Parkins, *Staking a claim: Deep-sea mining nears fruition*, May 2014.

[24] N. M. N. Limited, 'Envirnonmental impact statement solwara 1 project', 2008.

[25] G. Spagnoli, J. Rongau, J. Denegre, S. A. Miedema and L. Weixler, 'A novel mining approach for seafloor massive sulfide deposits', Offshore Technology Conference, May 2016.

[26] G. Spagnoli, S. A. Miedema, C. Herrmann, J. Rongau, L. Weixler and J. Denegre, 'Preliminary design of a trench cutter system for deep-sea mining applications under hyperbaric conditions', *IEEE JOURNAL OF OCEANIC ENGINEERING,*, vol. 41, 4 Oct. 2016.

[27] S. Whiteford, *How does deep water drilling work?*, Mar. 2022.

[28] F. Roelofsen, 'Preliminary powerplant concepts of a dsm production support vessel', NTNU, 2022.

[29] A. V. Solheim, M. Lesage, B. E. Asbjørnslett and S. O. Erikstad, 'Omae2020-18655 deep sea mining: Towards conceptual design for underwater transportation'. [Online]. Available: www.ntnu.edu.

[30] G. Pahl and W. Beitz, *Engineering Design: A systematic Approach*. Springer, 2007, vol. 3.

[31] M. Lesage and S. O. Erikstad, *Finding the generic function structure of a deep-sea mining system*, 2020.

[32] M. Lesage and S. O. Erikstad, *A conceptual design framework for deep-sea mining*, 2020.

[33] K. Roth, *Design catalogues and their usage*, A. Chakrabarti, Ed. Springer, 2002.

[34] B. E. Asbjørnslett, *Modularity and design structure matrices.*

[35] Ulstein, *What is a better ship?*, Mar. 2016.

[36] W. Kenton, *Lead time: Definition, how it works, and example*, Aug. 2022.

[37] S. O. Erikstad, 'Product platforms and modularisation in shipbuilding', *NTNU*, 2009.

[38] S. D. Eppinger and T. R. Browning, *Design Structure Matrix Methods and Applications*, J. Moses, R. de Neufville, M. Heitor, M. Granger, elisabeth Paté-Cornell and W. Rouse, Eds. The MIT Press, 2012.

[39] T. R. Browning, 'The many views of a process: Towards a process architecture framework for product development processes.', *Systems Engineering*, pp. 69–90, 2009.

[40] Oceaneering, 'Millennium plus heavy work class rov', 2017.

[41] Skybrary, *Fly-by-wire*, 2022.

[42] Oceaneering, 'Millennium ® plus with rips it3', 2018.

[43] SMD, *Work-class-rov-v1-lt smd*, 2023. [Online]. Available: https://www.smd.co.uk/our-products/work-class-rovs/.

[44] D. Hambling, *Giant robots are the future of underwater mining*, Feb. 2018.

[45] BAUER, *"vertical approach" in deep-sea mining: Bauer maschinen gmbh and the harren & partner group establish joint venture*, 2021.

[46] GMC, 'Reliable connected technology solutions! seafloor mining risers riser and lifting system', 2016. [Online]. Available: www.gmcdeepwater.com.

[47] NOR, *Nor-ds-subsea-basket-40ft*, 2023.

[48] FSubsea, *Mudrise™ subsea slurry system*, 2021.

[49] E. Edge, *Centrifugal pumps review*, 2023.

[50] NOV, *Lifting & handling product portfolio*, 2018.

[51] OUCO, *A-frame crane*, 2013.

[52] W. Marine, *Lt series rov lars data sheet*, 2013.

[53] McLanahan, 'Fine material screw washer'. [Online]. Available: https://www.mclanahan.com/resource-library/fine-material-screw-washer-brochure.

[54] Constmach, *Screw washer*, 2002.

[55] McLanahan, *Hydrocyclones*, 2023.

[56] M. Dlamini, M. S. Powell and C. Meyer, *A cfd simulation of a single phase hydrocyclone flow field*, Nov. 2005.

[57] D. M. Franks, D. V. Boger, C. M. Côte and D. R. Mulligan, 'Sustainable development principles for the disposal of mining and mineral processing wastes', *Resources Policy*, vol. 36, pp. 114–122, 2 Jun. 2011, ISSN: 03014207. DOI: 10.1016/j.resourpol.2010.12.001.

[58] J. C. Castilla, 'Environmental impact in sandy beaches of copper mine tailings at chaharal, chile', 1983, pp. 459–464.

[59] W. Ma, D. Schott and G. Lodewijks, 'A new procedure for deep sea mining tailings disposal', *MDPI*, Mar. 2017.

[60] Wartsila, *Drilling derrick*.

[61] Transocean, *Ocean rig olympia*, Jun. 2022.

[62] Helis, *Bristow norway as*, 2023.

[63] WinAir, *The essential guide to the sikorsky s-92 helicopter infographic*, 2018.

[64] CSL, *Gravity-fed self-unloaders*, Apr. 2018.

[65] Skuld, *Ship to ship transfer safety*, Nov. 2020.

[66] T. Abramowski and T. Cepowski, ‘Preliminary design considerations for a ship to mine polymetallic nodules in the clarion-clipperton zone’, Isope.org, Sep. 2013.

[67] C. Tardi, *Value chain: Definition, model, analysis, and example*, Sep. 2022.

[68] T. M. Company, *Nori and allseas lift over 3,000 tonnes of polymetallic nodules to surface from planet’s largest deposit of battery metals, as leading scientists and marine experts continue gathering environmental data*, Nov. 2022.

[69] A. Thaler, *Major brands say no to deep-sea mining, for the moment*, Apr. 2021.

[70] T. M. Company, *The metals company and allseas announce successful deepwater commissioning of riser pipe and jumper hose designed to lift polymetallic nodules from seafloor to surface*, May 2022.

[71] T. M. Company, *Innovative tmc and allseas achieve historic milestone: Nodules collected from the seafloor and lifted to the production vessel using 4km riser during pilot trials in the clarion clipperton zone for first time since the 1970s*, Oct. 2022.

[72] R. Robotics, *What are underwater rovs & what can they be used for?*, Oct. 2021.

[73] E. McCauley and G. Tyler, *Rocks vacuumed off the seafloor can power electric cars. but is mining the ocean worth it?*, Jan. 2023.

[74] C. Coumans, ‘How is submarine tailings disposal done?’, MiningWatch Canada, 2002.

[75] B. Verger, *To move cargo with less mess, these ships unload themselves*, Mar. 2021.

[76] Techoil, *Types of modular interface design*, Dec. 2017.

[77] DELFTship, *Delftship maritime software*, 2023.

Appendix

A DSM

Components	NR.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Derrick	1	1		5	3	3	3			5									5																1			5	5
Trident Crane	2		2				4	5			2	1							5	3																			
Pipe Handling Crane	3	5		3			5			5									5																			3	5
Working Crane	4	3			4	5	5				5	2							5																				
Outside Work Area	5	3			5	5	5	3		4	4																												4
Equipment Storage	6	3	4	5	5	5	6	5		5	5																								4				5
Trench Cutter	7		5			3	5	7	5	5						2			5	5															2				
Seabed Slurry Lift System	8							5	8	5						3			5																4				
Riser	9	5		5		4	5	5	5	9										5															4			5	4
Subsea Basket	10		2		4	5	5				10	5																											
ROV	11		1		2						5	11	5	5	5				5	4																			
ROV Hangar	12											5	12	5	5																								
Launch and Recovery system	13											5	5	13	5				5	5																			
Pilots Control Room	14											5	5	5	14				5																				
Cargo Hold	15							2	3							15	5																4		4				
Cargo Hatches	16															5	16		5														5						
Propulsion Power	17																	17		5									5							5			
Auxiliary Power	18	5	5	5	5			5	5			5		5	5		5		18		5	5	5	5	5	5	5			5			5	5	5	5		5	5
Dynamic Positioning	19		3					5		5		4		5				5		19						5	5					2							
Cabins	20																		5		20	4	4	4	4														
Mess	21																		5		4	21	5	4	4														
Galley	22																		5		4	5	22	4	4														
Recreation Room	23																		5		4	4	4	23	4														
Washroom	24																		5		4	4	4	4	24														
Radar	25																		5	5						25	3	3	3	3									
ECDIS	26																		5	5						3	26	3	3										
Steering Console	27																									3	3	27	5										
Engine Control	28																	5								3	3	5	28										
Communication Instruments	29																		5							3				29	5								
Safety Equipment	30																													5	30								
Helideck	31																			2												31							
Conveyor System	32															4	5		5														32	5	5				
Boom	33																		5														5	33	5				
Dewatering	34	1					4	2	4	4						4			5														5	5	34				5
Tanks	35																	5	5																	35			
Storage	36																																				36		
Moonpool	37	5		3						5									5																			37	5
Slurry Disposal System	38	5		5		4	5			4									5																5			5	38

Figure 32: Design structure matrix for a deep sea mining vessel

B Process DSM

Components	NR.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Derrick	1	1		5	3					5									5																			5	5
Trident Crane	2		2				4	5			2	1							5	3																			
Pipe Handling Crane	3	5		3	5		5			5									5																				5
Working Crane	4	3		5	4	5	5				5	2							5																				
Outside Work Area	5				5	5	5																																
Equipment Storage	6		4	5	5	5	6																																
Trench Cutter	7		5					7	5	5						2			5	5															2				
Seabed Slurry Lift System	8							5	8	5						3			5																4				
Riser	9	5		5				5	5	9										5															4			5	
Subsea Basket	10		2		5						10	5	5	5					5	4																			
ROV	11		1		2						5	11	5	5	5																								
ROV Hangar	12										5	5	12	5	5																								
Launch and Recovery system	13										5	5	5	13	5				5	5																			
Pilots Control Room	14											5	5	5	14				5																				
Cargo Hold	15							2	3							15	5																4		4				
Cargo Hatches	16															5	16		5														5						
Propulsion Power	17																	17		5									5							5			
Auxiliary Power	18	5	5	5	5			5	5		5			5	5		5		18		5	5	5	5	5	5	5			5			5	5	5	5		5	5
Dynamic Positioning	19		3					5		5	4			5				5		19						5	5					2							
Cabins	20																		5		20																		
Mess	21																		5			21																	
Galley	22																		5				22																
Recreation Room	23																		5					23															
Washroom	24																		5						24														
Radar	25																		5	5						25	3	3	3	3									
ECDIS	26																		5	5						3	26	3	3										
Steering Console	27																									3	3	27	5										
Engine Control	28																	5								3	3	5	28										
Communication Instruments	29																		5							3				29	5								
Safety Equipment	30																													5	30								
Helideck	31																			2												31							
Conveyor System	32															4	5		5														32	5	5				
Boom	33																		5														5	33	5				
Dewatering	34							2	4	4						4			5														5	5	34				5
Tanks	35																	5	5																	35			
Storage	36																																				36		
Moonpool	37	5								5									5																			37	
Slurry Disposal System	38	5		5															5																5				38

Figure 33: Process DSM for a deep sea mining vessel

C Location-oriented DSM

Components	NR.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Derrick	1	1		5	3	3	3			5																									1			5	5
Trident Crane	2		2				4	5			2	1																											
Pipe Handling Crane	3	5		3			5			5																												3	5
Working Crane	4	3			4	5	5				5	2																											
Outside Work Area	5	3			5	5	5	3		4	5																												4
Equipment Storage	6	3	4	5	5	5	6	5		5	5																								4				5
Trench Cutter	7		5			3	5	7	5	5																													
Seabed Slurry Lift System	8							5	8	5																													
Riser	9	5		5		4	5	5	5	9																									4	5			4
Subsea Basket	10		2		5	5	5				10	5																											
ROV	11		1		2						5	11	5	5																									
ROV Hangar	12											5	12	5																									
Launch and Recovery system	13											5	5	13																									
Pilots Control Room	14														14																								
Cargo Hold	15															15	5																4		4				
Cargo Hatches	16															5	16																5						
Propulsion Power	17																	17																		5			
Auxiliary Power	18																		18																	5			
Dynamic Positioning	19																			19																			
Cabins	20																				20	4	4	4	4														
Mess	21																				4	21	5	4	4														
Galley	22																				4	5	22	4	4														
Recreation Room	23																				4	4	4	23	4														
Washroom	24																				4	4	4	4	24														
Radar	25																									25	3	3	3	3									
ECDIS	26																									3	26	3	3										
Steering Console	27																									3	3	27	5										
Engine Control	28																									3	3	5	28										
Communication Instruments	29																									3				29	5								
Safety Equipment	30																													5	30								
Helideck	31																															31							
Conveyor System	32															4	5																32	5					
Boom	33																																5	33					
Dewatering	34	1					4			4						4																			34				5
Tanks	35									5								5	5																	35			
Storage	36																																				36		
Moonpool	37	5		3																																		37	5
Slurry Disposal System	38	5		5		4	5			4																									5			5	38

Figure 34: Location-oriented DSM for a deep sea mining vessel

D DSM Descriptions

Components	Dependant Component	Dependancy	Description
1 - Derrick	3 - Pipe handling crane	5	Feeds derrick with riser parts
	4 - Working crane	3	Feeds derrick with general equipment
	5 - Outise work area	3	Location of riser storage
	6 - Equipment storage	3	Location of riser storage
	9 - Riser	5	Riser assembly
	18 - Auxiliary power	5	Powers the derrick
	34 - Dewatering	1	Located next to derrick
	37 - Moonpool	5	Located below derrick
	38 - Slurry disposal system	5	Assembled by derrick
2 - Trident crane	6 - Equipment storage	4	Picks up equipment from storage
	7 - Trench cutter	5	Hoists trench cutter into water column
	10 - Subsea basket	2	Backup for subsea basket retrieval
	11 - ROV	1	Backup for ROV retrieval/ avoid entanglement
	18 - Auxiliary power	5	Powers the trident crane
	19 - Dynamic positioning	3	Keeps hoisted equipment in place
3 - Pipe handeling crane	1- Derrick	5	Feeds derrick with riser parts
	6 - Equipment storage	5	Placement of riser pipes
	9 - Riser	5	Riser parts moved by crane
	18 - Auxiliary power	5	Powers the crane
	37 - Moonpool	3	Moves pipes to the moonpool
	38 - Slurry disposal system	5	Moves slurry disposal system pipes to derrick
4 - Working crane	1 - Derrick	3	Feeds derrick with general equipment
	5 - Outisde work area	5	Picks/moves up equipment
	6 - Equipment storage	5	Picks up equipment from storage
	10 - Subsea basket	5	Hoisting of subsea basket
	11 - ROV	2	Backup for ROV retrieval/ avoid entanglement
	18 - Auxiliary power	5	Powers the crane
	1 - Derrick	3	Location of riser storage
	4 - Working crane	5	Feeds derrick with general equipment

Figure 35: Descriptions of all dependencies in the design structure matrix

Components	Dependant Component	Dependancy	Description
1 - Derrick	3 - Pipe handling crane	5	Feeds derrick with riser parts
	4 - Working crane	3	Feeds derrick with general equipment
	5 - Outise work area	3	Location of riser storage
	6 - Equipment storage	3	Location of riser storage
	9 - Riser	5	Riser assembly
	18 - Auxiliary power	5	Powers the derrick
	34 - Dewatering	1	Located next to derrick
	37 - Moonpool	5	Located below derrick
	38 - Slurry disposal system	5	Assembled by derrick
2 - Trident crane	6 - Equipment storage	4	Picks up equipment from storage
	7 - Trench cutter	5	Hoists trench cutter into water column
	10 - Subsea basket	2	Backup for subsea basket retrieval
	11 - ROV	1	Backup for ROV retrieval/ avoid entanglement
	18 - Auxiliary power	5	Powers the trident crane
	19 - Dynamic positioning	3	Keeps hoisted equipment in place
3 - Pipe handeling crane	1- Derrick	5	Feeds derrick with riser parts
	6 - Equipment storage	5	Placement of riser pipes
	9 - Riser	5	Riser parts moved by crane
	18 - Auxiliary power	5	Powers the crane
	37 - Moonpool	3	Moves pipes to the moonpool
	38 - Slurry disposal system	5	Moves slurry disposal system pipes to derrick
4 - Working crane	1 - Derrick	3	Feeds derrick with general equipment
	5 - Outisde work area	5	Picks/moves up equipment
	6 - Equipment storage	5	Picks up equipment from storage
	10 - Subsea basket	5	Hoisting of subsea basket
	11 - ROV	2	Backup for ROV retrieval/ avoid entanglement
	18 - Auxiliary power	5	Powers the crane
	1 - Derrick	3	Location of riser storage
	4 - Working crane	5	Feeds derrick with general equipment

5 - Outside work area	6 - Equipment storage	5	Shares deck space
	7 - Trench cutter	3	Location during transport and maintenance
	9 - Riser	4	Riser storage location
	10 - Subsea basket	5	Location during transport, maintenance and unloading
	38 - Slurry disposal system	4	Slurry disposal system storage location
6 - Equipment storage	1 - Derrick	3	Location of riser storage
	2 - Trident crane	4	Picks up equipment from storage
	3 - Pipe handling crane	5	Placement of riser pipes
	4 - Working crane	5	Picks up equipment from storage
	5 - Outside work area	5	Shares deck space
	7 - Trench cutter	5	Location during transport and maintenance
	9 - Riser	5	Riser storage location
	10 - Subsea basket	5	Location during transport, maintenance and unloading
	34 - Dewatering	4	Location
	38 - Slurry disposal system	5	Slurry disposal system storage location
7 - Trench cutter	2 - Trident crane	5	Hoists trench cutter into water column
	5 - Outside work area	3	Location during transport and maintenance
	6 - Equipment storage	5	Location during transport and maintenance
	8 - Seabed slurry lift system	5	Pumps crushed ore from drill head to riser
	9 - Riser	5	Transports crushed ore from drill head
	15 - Cargo hold	2	Receives mined ore
	18 - Auxiliary power	5	Powers trench cutter
	19 - Dynamic positioning	5	Keeps trench cutter in place
	34 - Dewatering	2	Dewaters mined ore from trench cutter
8 - Seabed slurry lift system	7 - Trench cutter	5	Pumps crushed ore from drill head to riser
	9 - Riser	5	Pumps crushed ore from drill head through riser
	15 - Cargo hold	3	Pumped ore ends up in cargo hold
	18 - Auxiliary power	5	Powers seabed slurry lift system
	34 - Dewatering	4	Pumps ore to dewatering plant
	1 - Derrick	5	Riser assembly

9 - Riser	3 - Pipe handling crane	5	Riser parts moved by crane
	5 - Outside work area	4	Riser storage location
	6 - Equipment storage	5	Riser storage location
	7 - Trench cutter	5	Transports crushed ore from drill head
	8 - Seabed slurry lift system	5	Pumps crushed ore from drill head through riser
	19 - Dynamic positioning	5	Keeps riser at desired location
	34 - Dewatering	4	Receives slurry
	37 - Moonpool	5	Riser launched through moonpool
	38 - Slurry disposal system	4	Connected to the riser
10 - Subsea basket	2 - Trident crane	2	Backup for subsea basket retrieval
	4 - Working crane	4	Hoisting of subsea basket
	5 - Outside work area	5	Location during transport, maintenance and unloading
	6 - Equipment storage	5	Location during transport, maintenance and unloading
	11 - ROV	5	Unload SMS chimneys at seabed
11 - ROV	2 - Trident crane	1	Backup for ROV retrieval/ avoid entanglement
	4 - Working crane	2	Backup for ROV retrieval/ avoid entanglement
	10 - subsea basket	5	Unload SMS chimneys at seabed
	12 - ROV hangar	5	ROV storage and maintenance
	13 - Launch and recovery system	5	Launch and recovery of ROV
	14 - Pilots control room	5	Controls ROV
	18 - Auxiliary power	5	Powers ROV
	19 - Dynamic positioning	4	Seakeeping
12 - ROV hangar	11 - ROV	5	ROV storage and maintenance
	13 - Launch and recovery system	5	Located within hangar
	14 - Pilots control room	5	Located within hangar
13 - Launch and recovery system	11 - ROV	5	Launch and recovery of ROV
	12 - ROV hangar	5	Located within hangar
	14 - Pilots control room	5	Controls deployment of ROV
	18 - Auxiliary power	5	Powers ROV
	19 - Dynamic positioning	5	Seakeeping for deployment

14 - Pilots control room	11 - ROV	5	Controls ROV
	12 - ROV hangar	5	Located within hangar
	13 - Launch and recovery system	5	Controls deployment of ROV
	18 - Auxiliary power	5	Powers the pilots control room
15 - Cargo hold	7 - Trench cutter	2	Receives mined ore
	8 - Seabed slurry lift system	3	Pumped ore ends up in cargo hold
	16 - Cargo hatches	5	Unloads payload from cargo hold
	32 - Conveyor system	4	Transports payload away from cargo hold
	34 - Dewatering	4	Removes unwanted water for storage
16 - Cargo hatches	15 - Cargo hold	5	Unloads payload from cargo hold
	18 - Auxiliary power	5	Powers the cargo hatches
	32 - Conveyor system	5	Located beneath hatches and transports payload away
17 - Propulsion power	19 - Dynamic positioning	5	Powers thrusters for DP
	28 - Engine control	5	Controls power output from engines
	35 - Tanks	5	Provides engines with fuel/lube etc.
18 - Auxiliary power	1 - Derrick	5	Powers derrick
	2 - Trident crane	5	Powers trident crane
	3 - Pipe handling crane	5	Powers pipe handling crane
	4 - Working crane	5	Powers working crane
	7 - Trench cutter	5	Powers trench cutter
	8 - Seabed slurry lift system	5	Powers seabed slurry lift system
	11 - ROV	5	Powers ROV
	13 - Launch and recovery system	5	Powers launch and recovery system
	14 - Pilots control room	5	Powers pilots control room
	16 - Cargo hatches	5	Powers cargo hatches
	20 - Cabins	5	Powers living quarters
	21 - Mess	5	Powers living quarters
	22 - Galley	5	Powers living quarters
	23 - Recreation room	5	Powers living quarters
	24 - Washroom	5	Powers living quarters

	25 - Radar	5	Powers radar
	26 - ECDIS	5	Powers ECDIS
	29 - Communication instruments	5	Powers communication instruments
	32 - Conveyor system	5	Powers conveyor system
	33 - Boom	5	Powers the boom
	34 - Dewatering	5	Powers dewatering plant
	35 - Tanks	5	Powers pumps in tanks and heating / provides fuel
	37 - Moonpool	5	Powers moonpool hatches
	38 - Slurry disposal system	5	Powers slurry disposal pump
19 - Dynamic positioning	2 - Trident crane	3	Keeps hoisted equipment in place
	7 - Trench cutter	5	Keeps trench cutter in place
	9 - Riser	5	Keeps riser at desired location
	11 - ROV	4	Seakeeping
	13 - Launch and recovery system	5	Seakeeping for deployment
	17 - Propulsion power	5	Powers thrusters for DP
	25 - Radar	5	Gives DP systems information
	26 - ECDIS	5	Gives DP systems information
	31 - Helideck	2	Seakeeping for helicopter landings
20 - Cabins	18 - Auxiliary power	5	Powers living quarters
	21 - Mess	4	Location
	22 - Galley	4	Location
	23 - Recreation room	4	Location
	24 - Wash room	4	Location
21 - Mess	18 - Auxiliary power	5	Powers living quarters
	20 - Cabins	4	Location
	22 - Galley	5	Dining area
	23 - Recreation room	4	Location
	24 - Wash room	4	Location
	18 - Auxiliary power	5	Powers living quarters
	20 - Cabins	4	Location

22 - Galley	21 - Mess	5	Dining area
	23 - Recreation room	4	Location
	24 - Wash room	4	Location
23 - Recreation room	18 - Auxiliary power	5	Powers living quarters
	20 - Cabins	4	Location
	21 - Mess	4	Location
	22 - Galley	4	Location
	24 - Wash room	4	Location
24 - Wash room	18 - Auxiliary power	5	Powers living quarters
	20 - Cabins	4	Location
	21 - Mess	4	Location
	22 - Galley	4	Location
	24 - Wash room	4	Location
25 - Radar	18 - Auxiliary power	5	Powers radar
	19 - Dynamic positioning	5	Gives DP systems information
	26 - ECDIS	3	Navigation
	27 - Steering console	3	Navigation
	28 - Engine control	3	Navigation
	29 - Communication instruments	3	Shows nearby vessels
26 - ECDIS	18 - Auxiliary power	5	Powers ECDIS
	19 - Dynamic positioning	5	Gives DP systems information
	25 - Radar	3	Navigation
	27 - Steering console	3	Navigation
	28 - Engine control	3	Navigation
27 - Steering console	25 - Radar	3	Navigation
	26 - ECDIS	3	Navigation
	28 - Engine control	5	Navigation
28 - Engine control	17 - Propulsion power	5	Controls power output from engines
	25 - Radar	3	Navigation
	26 - ECDIS	3	Navigation

	27 - Steering console	5	Navigation
29 - Communication instruments	18 - Auxiliary power	5	Powers communication instruments
	25 - Radar	3	Shows nearby vessels
	30 - Safety equipment	5	Shows nearby vessels
30 - Safety equipment	29 - Communication instruments	5	Shows nearby vessels
31 - Helideck	19 - Dynamic positioning	2	Seakeeping for helicopter landings
32 - Conveyor system	15 - Cargo hold	4	Transports payload away from cargo hold
	16 - Cargo hatches	5	Located beneath hatches and transports payload away
	18 - Auxiliary power	5	Powers conveyor system
	33 - Boom	5	Unloads payload from conveyor belts
	34 - Dewatering	5	Dry cargo
33 - Boom	18 - Auxiliary power	5	Powers the boom
	32 - Conveyor system	5	Unloads payload from conveyor belts
	34 - Dewatering	5	Dry cargo
34 - Dewatering	1 - Derrick	1	Located next to derrick
	6 - Equipment storage	4	Location
	7 - Trench cutter	2	Dewaters mined ore from trench cutter
	8 - Seabed slurry lift systrem	4	Pumps ore to dewatering plant
	9 - Riser	4	Receives slurry
	15 - Cargo hold	4	Removes unwanted water for storage
	18 - Auxiliary power	5	Powers dewatering plant
	32 - Conveyor system	5	Dry cargo
	33 - Boom	5	Dry cargo
	38 - Slurry disposal system	5	Disposes unwanted slurry
35 - Tanks	17 - Propulsion power	5	Provides engines with fuel/lube etc.
	18 - Auxiliary power	5	Powers pumps in tanks and heating
36 - Storage	-	-	-
37 - Moonpool	1 - Derrick	5	Located below derrick
	3 - Pipe handling crane	3	Moves pipes to the moonpool
	9 - Riser	5	Riser launched through moonpool

	18 - Auxiliary power	5	Powers moonpool hatches
	38 - Slurry disposal system	5	Launched through moonpool
38 - Slurry disposal system	1 - Derrick	5	Assembled by derrick
	3 - Pipe handling crane	4	Moves slurry disposal system pipes to derrick
	5 - Outside work area	4	Slurry disposal system storage location
	6 - Equipment storage	5	Slurry disposal system storage location
	9 - Riser	4	Connected to the riser
	18 - Auxiliary power	5	Powers slurry disposal pump
	34 - Dewatering	5	Disposes unwanted slurry
	37 - Moonpool	5	Launched through moonpool

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