Master's thesis

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

Pauline Sundvor Opstad

Concept study of slurry lifting from deep sea mining in an arctic environment

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Supervisor: Gary Harald Isaksen
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Abstract

In the deep sea there are deposits that can contain large volumes of high-grade ore containing minerals and metals used in new renewable energy technology. A boost in the demand for these metals are expected to increase due to focus towards the green energy transition.

Mid ocean spreading ridges are often associated with hydrothermal vents, that can accumulate significant Seafloor Massive Sulphide (SMS) deposits, due to the stable conditions allowing for long-lived venting activity. Metals are also found in polymetallic nodules, metal-rich crusts and as rare-earth elements (REE). Norway has sovereignty of a part of the northern Mid-Atlantic Ridge, where hydrothermal vents and SMS deposits are confirmed.

A technical challenge of extracting minerals from deep waters (800-5000 meters) is to lift the ore from the seabed to the surface. The current state-of-the-art lifting systems consists of a riser hanging off the production vessel and utilises a submersible pump to lift the slurry to the surface vessel. A limitation of this design is that it cannot be operated during harsh environmental conditions, like in the arctic.

This thesis consists of a conceptual design study of a lifting system suitable for arctic environments. The design is based on a literature review and an evaluation of this design by the use of a Failure Modes Effects and Criticality Analysis (FMECA). The design was limited to slurry lifting, where the slurry enters the system premixed with seawater delivered by a flexible jumper. The goal of the FMECA is to expose the most critical components in the design. The main focus of the FMECA has been towards the operational phase and the possibilities for maintenance and rough downtime estimates. There has not been a detailed design of the suggested system, more an exploratory study of the possible concepts. Due to this lack of detail there are no detailed dimensions and economic estimates.

The final suggested design is a hybrid riser configuration, standing on the seabed and connected to the surface vessel by a flexible jumper. The slurry is lifted by the use of a positive displacement pump, powered by the pressurised return water of the slurry. This concept decouples the riser from the motions of the surface vessel, but the riser is stationary. A consequence of this is that more bottom infrastructure is needed as a field expands, but this also opens up for new possibilities; a central lifting hub serving several smaller fields and the hub can host several subsea service capabilities.

Hammerfest was the harbour of choice as the logistics harbour. It is a town located on the Norwegian mainland and has approximately 616 km sailing distance to the sites along the northern Mid-Atlantic Ridge where hydrothermal vents and SMS deposits are confirmed. It is assumed it will take five days for an unplanned mobilisation of a vessel to deliver goods. This was used to estimate downtime. A conclusion from this exercise was that the logistics of the operations are important, and the potential wait of lacking spares, equipment or personnel can lead to serious extensions to unplanned downtime. To avoid unplanned downtime it is important to monitor the state of the equipment used. The tools for data assisted condition monitoring can be helpful to track the degradation of the monitored equipment and one can perform preventive maintenance on the degraded equipment during the planned maintenance cycles.

The FMECA resulted in 106 failure modes and the most critical component was the slurry pipe failing due to fatigue. A few selected failures are selected for the discussion. Some of the frequency estimates and repair time estimates was selected from the OREDA 2015 subsea equipment reliability data handbook (OREDA 2015). The true match of the reliability data is uncertain, but this is one of the few available offshore reliability databases. The focus of the FMECA was mainly towards technical failures, resulting in downtime due to repair and some failures due to environmental spillages. There are little data to compare the results with and one is unable to check the validity of these results.

For further work it is suggested to complete a more detailed design to check technical feasibility, and to explore the use of a collective lifting hub further to see what size deposits are of interest.

Sammendrag

Ved store havdyp finnes det mineral- og metallrike avsetninger. Flere av disse metallene brukes i dagens teknologi for produksjon og lagring av fornybar energi. Videre er det forventet en økning i etterspørselen av metallene brukt i teknogi forbundet med det grønne skiftet.

Midhavsrygger forbindes ofte med hydrotemale skorsteiner og de stabile forholdene rundt midthavsrygger tillater at det over tid kan samles opp store avsetninger av massive sulfider, også referert til som SMS (Seafloor Massive Sulphides) som felles ut av væsken som kommer ut av skorsteinene. Norge har suverenitet over en del av den nordlige Midtatlantiske ryggen i forbindelse med suverenitet av Jan Mayen og Spitsbergen er noen av disse områdene interessante for undersjøisk guvedrift. I tilegg er det bekreftet flere aktive skorsteiner med tilhørende SMS avsteninger i disse områdene.

En teknisk utfordring med å hente ut disse mineralene fra havdyp på 800-5000 meters dyp er å løfte den brutte malmen til overflaten. Dagens løsning med å løfte malmen er å bruke en stiv riser som henger fra et produksjonsfartøy i overflaten, mens malmen løftes ved hjelp av en nedsenkbar pumpe som pumper opp malmen som en slurry til produksjonsfartøyet. En ulempe med denne løsningen er at den ikke tåler store værlaster, for eksemper bølger, som er vanlige i arktis.

Denne masteroppgaven består av et konseptuelt design av et løftesystem som kan brukes i arktiske strøk. Designet er basert på en litteraturstudie og designet er evaluert ved hjelp av en FMECA (Feil Moduser Effekt og Kritikalitets Analyse, “Failure Modes Effects and Criticality Analysis”). Design studien ble avgrenset til løfting av en slurry, hvor slurryen blir sendt inn til systemet ferdig blandet med sjøvann i et fleksibel rør. Et resultat av FMECAen er hvilken komponent som er mest kritisk for svikt. Fokuset i denne FMECAen var teknisk svikt og estimat av påfølgende nedetid. Det er ikke blitt foretatt et detaljert design av det foreslåtte konseptet, men en mulighetstudie av ulike konsepter. Grunnet denne mangelen av detaljer har ikke detaljerte dimensjoner blitt etablert og kostnadsestimat er ikke utført.

Det foreslåtte designet er en hybrid riser løsning som står på havbunnen og er koblet til overflatefartøyet ved hjelp av et fleksibelt stigerør. Slurrien blir løftet ved hjelp av en fortregningspumpe drevet av trykksatt returvann. Dette konseptet frigjør stigerøret fra overflatefartøyets bevegelser, men stigerøret blir da ikke mobilt. En konsekvens av dette er at det er et større behov for infrastruktur på havbunnen. Men dette kan gi muligheten for å skape en løftesentral for flere mindre felt. En mulighet med en slik sentral er at en kan samle ressuser som trengs for undervanns sørvis.

Hammerfest ble valgt som logistikk havn for operasjonen og har en seilings avstand på circa 616 kilometer fra Lokeslottet. Det ble antatt en uplanlagt mobilsering av et skip med last vil ta fem dager til det er på plass ved Lokeslottet. Dette ble brukt til estimat av uplanlagt nedetid. En observasjon av dette var at det å ikke ha deler, utstyr eller personell tiljengelig ved behov kan medføre mye ekstra nedetid. For å unngå ikke planlagt nedetid kan det være lurt å bruke tilstandovervåkning til å overvåke tilstanden på installert utstyr, slik at nødvendig vedlikehold kan bli utført ved planlagte stans.

FMECAen endte med 106 feilmoduser, den mest kritiske feilen var utmatting i “slurry pipe”. Noen flere feil er vurdert i diskusjonsdelen. Flere frekvensestimater og nedetidsestimater er hentet fra “OREDA 2015 subsea equipment reliability handbook” (OREDA 2015). Hvor overførbare pålitlighetsdataene er til undersjøisk gruvedrift er uvisst, men det er en av få tiljengelige åpne pålitlighetsdatabaser. Det er lite data å sammenligne resultatene i FMECAen med, så en validering av disse resultatene var ikke mulig.

Til videre arbeid er det foreslått å utføre et mer detaljert design slik at et skikkelig grundighetstudie kan utføres, et videre studie i å bruke en riser kollektivt til løfting fra flere felt og se på hvilken størrelse på avsetningene som er av interesse.

Preface

This master thesis has been written at the end of my studies in Marine Technology at the Norwegian University of Science and Technology (NTNU) in 2022.

This work is based on the course “TMR 4450 - Safety and asset management, specialisation project” performed in the fall 2021 containing a wide literature study on deep sea mining and the possibilities around Bouvét Island in the southern Atlantic. Originally this thesis intended to continue the exploration of the lifting operations and general operation in an sub-antarctic environment, but due to the generally scantness of data in the area, the focus shifted towards the arctic and the Loki’s Castle hydrothermal vent site in the northern Atlantic.

The work in this thesis involved an extensive literature review of both risers and lifting technology and the study was restricted towards slurry lifting. Conducting a design for an undefined operation was challenging and I had to constantly contemplate what assumptions are reasonable or if decisions belong at later phases of design. Progress was made by endless speculation on the possible alternatives and weighing the benefits and possible consequences of details of design. Forming a Failure Modes Effects and Criticality Analysis (FMECA) was challenging due to the lack of data on components and systems related to deep sea mining. Both activities are usually performed in teams, but some unforeseen events caused this not to take place, and only the author’s experiences and assessments are reflected.

My initial experience with deep sea mining equipment and riser design was limited, but my studies for this thesis has greatly developed my knowledge of this topic and my skills as an engineer.

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There are several that deserve a token of appreciation for their contributions to my completion of this thesis. Firstly, my main supervisor Prof. Gary Harald Isaksen, whose guidance laid the main structure of my thesis and his aid in the final edits of this thesis. This thesis also had a co-supervisor, Prof. Steinar Løve Ellefmo, who provided advise on how to build a good thesis and argumentation. Both my supervisors has generously shared their knowledge where relevant.

An acknowledgement to Prof. Svein Sævik who found the time for a meeting to discuss the design of risers and Dr. Maxime Lesage for sharing his PhD thesis with me before it was published to NTNU open.

Finally I would like to thank my mates at the office for them always being available for conversations on subjects in need of discussions.

Contents

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List of Abbreviations

ART	Active Repair Time
AUV	Autonomous Underwater Vehicle
CAPEX	Capital Expenditures
COR	Cocentric line Offset Riser
CPI	Corruption Perception Index
DEA	Drag Embedment Anchor
DRC	Democratic Republic of Congo
DSM	Deep Sea Mining
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EOL	End Of Life
EV	Electric Vehicle
FMECA	Failure Mode Effects and Criticality Analysis
FPSO	Floating Production Storage and Offloading
H_s	Significant wave height [m]
HSE	Health Safety and Environment
ISA	International Seabed Authority
MBES	Multi Beam Echo Sounder
METI	Ministry of Economy, Trade and Industry (of Japan)
MIDAS	Managing Impacts of Deep-seA reSource exploitation
NCS	Norwegian Continental Shelf
OPEX	Operational Expenditures
PCIJ	Philippine Centre for Investigative Journalism
PD	Positive Displacement
PRC	Peoples Republic of China
RALS	Riser And Lifting System
REE	Rare Earth Element
ROV	Remotely Operated Vehicle
RPN	Risk Priority Number
RW	Return Water
SBP	Solid Buoyant Particles
SCR	Steel Catenary Riser
SLOR	Single Line Offset Riser
SPV	Surface Production Vessel
SSLP	Subsea Slurry Lift Pump
$T_{p,\ max}$	Peak period [s]
TDP	Touch Down Point
TLP	Tension Leg Platform
TTR	Top Tensioned Riser
VIM	Vibration Induced Motions
VIV	Vortex Induced Vibrations
VLA	Vertically Loaded Anchor
WOW	Waiting On Weather

1 Introduction

1.1 Motivation and background

Technology developments are needed to keep global warming below the two degree centigrade threshold of annex two in the Paris Climate agreement (United Nations 2015). Furthermore, the way we produce and transport energy needs to be revolutionised to reduce CO2 emissions from the burning of fossil fuels. Several low emission technologies under development require a host of metals and rare earth elements. Given the declining ore grade in terrestrial deposits one has started to prospect new areas for extraction, with the deep sea as one of them. Large volumes of high-grade deposits are known to be present in deep sea sediments, and opportunities for extraction are being explored (Hund et al. 2020).

Extracting minerals from the seafloor is challenging. The operation is in deep water, from 800 to 5000 meters (Cuyvers et al. 2018), and has to be autonomous because of Health, Safety and Environmental (HSE) concerns. The loads in the deep sea create operational design challenges as lifting ore approx 2000 meters vertically is an energy demanding process. Today's state of the art technologies were designed for the more benign waters in places such as the Bismarck Sea and off the south-west coast of Japan.

Nautilus's system has designed a concept for benign waters, but modifications needs to be made if one is to move to more exposed waters, like in the arctic. Therefore has the following qualities been evaluated when designing the system for the to be analysed in the FMECA; Harsh environmental loads, mobility of the riser, compatibility with the DSM operation and technological readiness.

Norway has initiated reconnaissance and exploration studies to establish a framework for deep sea mining in the waters where Norway has sovereignty. Some of these areas in the arctic parts of the Mid-Atlantic ridge within the Exclusive Economic Zone (EEZ) of Norway have hydrothermal activity, associated with Seafloor Massive Sulphide deposits (Olje og energi departementet 2021). An arctic Deep Sea Mining (DSM) operation will place additional demands on mining operations due to environmental sensitivities.

1.2 Problem formulation

To make these minerals more accessible one needs to efficiently move the mined ore from the mining site to the surface. The production rate is not constant and the mining site is a dynamic environment that needs to be connected with the mining system. Today's state-of-the-art technologies are for calmer sea states, but arctic environment provides some extra challenges to the operation, like ice, storms and heavy seas. This thesis investigates some of the key technology challenges for DSM and provides a concept proposal for the lift operation in an arctic setting at Loki's Castle hydrothermal vent site. The study also evaluates what components are the most critical through the use of a Failure Modes, Effects and Critical Analysis (FMECA).

1.3 Scope of work

The foundation for this thesis is a literature review establishing the characteristics of deep sea minerals, where they may be present, why such minerals are needed for the global economies, and wrapped up with the policy and legislative side of extracting deep sea mineral. The study provides and overview of the state-of-the-art technologies for DSM and their operational layout and structure. Extra focus is directed to the lift system and operation, and possible technical solutions for sub problems are explored. With this in mind, a conceptual study has been undertaken for the vertical lifting operation of ore mined in the arctic parts of the Mid-Atlantic Ridge. It is assumed that the ore will be delivered to the lifting system premixed in a slurry mixed with seawater at desired concentration. This mix is delivered by a flexible jumper from a collecting or mixing device. The proposed system is further evaluated by a FMECA. This analysis exposes critical components for the operation and offers the opportunity to suggest remedies for mitigation of potential failure areas. An extra focus has been placed on the operational phase and the possibilities for condition monitoring and maintenance of the suggested system. Rough estimates of downtime are made with regard to the nature of potential failures.

This thesis does not contain a detailed design of the suggested lifting system. Rather, it is an exploratory study of possible concepts for use in arctic conditions. Due to the lack of available details there are no economical estimates, and adverse impacts are quantified as estimated downtime. Only the transport of extracted mineral-rich sediments in the form of slurry is considered. Horizontal transport is not extensively explored.

The suggested design considers the lifting process from its introduction as a slurry in a jumper to the slurry emerging at the surface on the Surface Production Vessel (SPV).

1.4 Structure of thesis

This thesis starts with a background study to DSM, what it is how it is done, why we need more minerals mined and challenges related to deep sea minerals and deep sea operations. Then follows the theory, section 3, with a literature review into different riser types, lifting solutions and maintenance. Then in section 4 follows a presentation of the methodology used for the design and the FMECA. Section 5 presents the data used for weather requirements and section 6 shows the results of the design and the FMECA. After the results follows the conclusion of this work in section 8.

2 Background

2.1 What is deep sea minerals?

According to Cuyvers et al. 2018 the deep sea considered to be the water volume below 200m depth, and this volume represents 95% of the earth's oceans. Of greatest economic interest are polymetallic nodules, crusts and Seafloor Massive Sulphide Deposits (SMS). Polymetallic nodules are potato-sized lumps found on the abyssal plains with low sedimentation rates. SMS deposits are formed by mineral precipitation from the interaction of hot fluids from hydrothermal vents and the surrounding seawater. These deposits can form on and under the seabed. The crusts are generally formed on seamounts without any loose sediments (Beaudoin and Baker 2013a, Beaudoin and Baker 2013b).

Hydrothermal vents are often associated with tectonic plate boundaries, this due to the seawater penetrates the seafloor trough fissures and fault zones for several kilometers and is heated to temperatures above 400°C by the hot magma under the earths crust. At high temperatures and pressures, water can dissolve several metals and minerals from the surrounding rock, - even gold becomes soluble (Beaudoin and Baker 2013b). The result of this process is a hot, lightly acidic fluid that is rich in sulfur and metals. The hot fluid becomes buoyant and is driven up trough the bedrock, focused in a flow that exits the seafloor trough hydrothermal vents. When these mineral-rich fluids mix with the cold surrounding water the dissolved minerals precipitate in vents or as debris around the vent. Typically, 90% of the metals are precipitated during horizontal disbursement of the plumes, and therefore the largest deposits are expected to be found under the seafloor where the seafloor sediments most efficiently trap, or impede, the fluid flow facilitating the reactions to take place between pore fluid and and host sediments. The process of accumulation of SMS deposits from a black smoker vent is illustrated in Figure 1. Another factor for the size of the deposit is the longevity of the vent sites. The deposits accumulate over time and the stable conditions along the mid ocean spreading ridges are ideal for sites to remain active over longer periods resulting in accumulation of larger deposits. Typical metals in these sulphide and sulphate deposits are iron, copper and zinc, but some deposits are enriched by silver, gold and Rare Earth Elements (REE). The chemical composition of the deposit differ for every vent site, and this compositional variation is a decisive factor for the profitability of a project (Beaudoin and Baker 2013b).

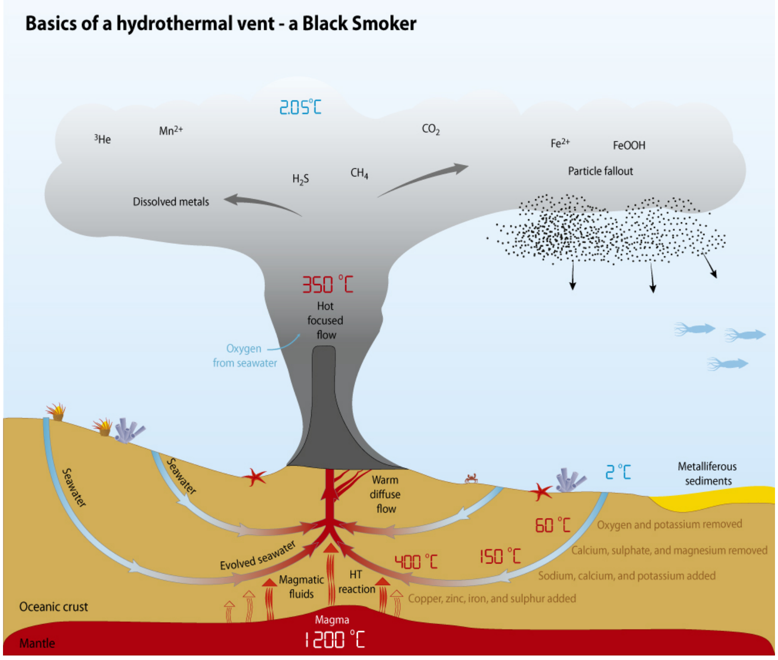


Figure 1: The process of accumulation of SMS deposits from a black smoker vent. Courtesy: GRID-Arendal https://www.grida.no/resources/8166

Polymetallic crusts form on nearly all subsea rock surfaces. Seamounts are typically sediment free and provide a solid surface for the precipitation of metals. Crusts with sufficient thickness to be of economic interest are typically found at depths of 800m-2500m. Hydrothermal activity may dilute the minerals of interest from the crust, thus the crusts close to vents sites mostly consists of iron- and manganese oxides. Some deposits can be enriched in lithium, molybdenum, tellurium, platinum, zirconium, niobium, bismuth and REEs (DNV Energy Systems 2021).

2.2 History of deep sea mining

In the 19^{th} century there was a great interest in discovering what kind of life existed in the deep sea. To find out, the explorers used nets and dredges that they lowered several kilometers, returning with peculiar organisms and dark potato sized lumps identified as manganese nodules (Cuyvers et al. 2018).

By the 1960s these manganese nodules had been studied in more detail and it was revealed that they did not only contain manganese, but also high concentrations of nickel, copper and cobalt, all useful in high-performance alloys. Deposits on land were not scarce at the time, but mainly located in the Soviet Union and thus market access was subject to geopolitical issues. The deep sea deposits were viewed as a more reliable resource option for these minerals. This political independence caught the mining industry's attention, and several companies spent millions of dollars on technology development. By the mid 1970s they were operating prototype systems and extracted a few hundred tons of nodules, but for an operation to become commercially viable they needed to extract several millions of tons of nodules. Nonetheless, several concepts had been proven and they succeeded in extracting the nodules. A start of a commercial operation required billions of dollars in investments and a project start would require an increase in the metal prices, but instead there was a crash in the metal prices and the projects were abandoned. Another factor that stopped further development was legal concerns. The mining industry argued that the deep sea did not belong to anyone, and that the extracted values belonged to whomever made the effort to extract them. As deep sea deposits started to gain commercial interest there was a call for a claim of ownership. This lead to a revision of the legal framework of the resources in the deep sea, leading to the foundation of the International Seabed Authority (ISA). By the start of this millennium there was more stability and the conditions for deep sea mining seemed to be more favourable. Laws were ratified and the ISA was given the responsibility to administer the mining industry in international waters (Cuyvers et al. 2018).

2.3 The mining process

The steps of starting an extraction of deep sea minerals will in broad strokes consist of an exploration phase where one searches for, and discoverers the deposits, an extraction phase where the minerals are extracted and processed, and a shutdown phase. No full scale commercial operations are currently up and running but, there are several suggestions for concepts with a different degree of technological readiness. A major challenge is how to reduce the environmental impact from the mining activity (Olje og energi departementet 2021).

2.3.1 Discovery of deep sea minerals

Before starting a mining operation one needs to find an area with deposits with the right mineral composition and of a create enough size for the operation to be feasible. So how does one prospect areas that are in remote and dark parts of the ocean? Deep sea exploration has been going on since the 19^{th} century, by the use of nets and dredges, but the present day technology bring several new more advanced tools for discovery. With the knowledge of how and where the deposits are likely to form one can use bathymetric maps and geological experience from similar settings to select areas of interest for further prospecting. This is referred to as the reconnaissance phase. The exploration of the interesting area is continued by seafloor imaging generating more detailed bathymetric maps over the appointed areas. These maps and images are used to identify geological structures such as domes, faults and slopes (Olje og energi departementet 2021). The equipment used for such exploration is typically hull mounted or deep towed multi-beam echo sounders (MBES) or Autonomous Underwater Vehicles (AUV) sidescan sonar.

When maps have been generated, one can highgrade areas for further exploration and start specific target testing, sampling, analyses and confirmation. This is done by direct inspection by using underwater vehicles like AUVs and ROVs and by physical sampling of the seafloor rocks by the help of grabs or dredges. Vent sites associated with sulfide deposits can create plumes with a distinctive chemistry that can be traced back to the vent site, a technique called plume hunting. One can also continue with higher resolution bathymetric surveys. Figure 2 illustrates a selection of instruments used in deep sea exploration. To evaluate the size of mineral deposits, the area is evaluated first by two-dimensional images and the deposit's thickness is estimated by drilling. Such point-data can be interpolated to create a volume estimate (Beaudoin and Baker 2013b).

Seismic surveys have proven ineffective at adequately imaging the uppermost layers of the seafloor

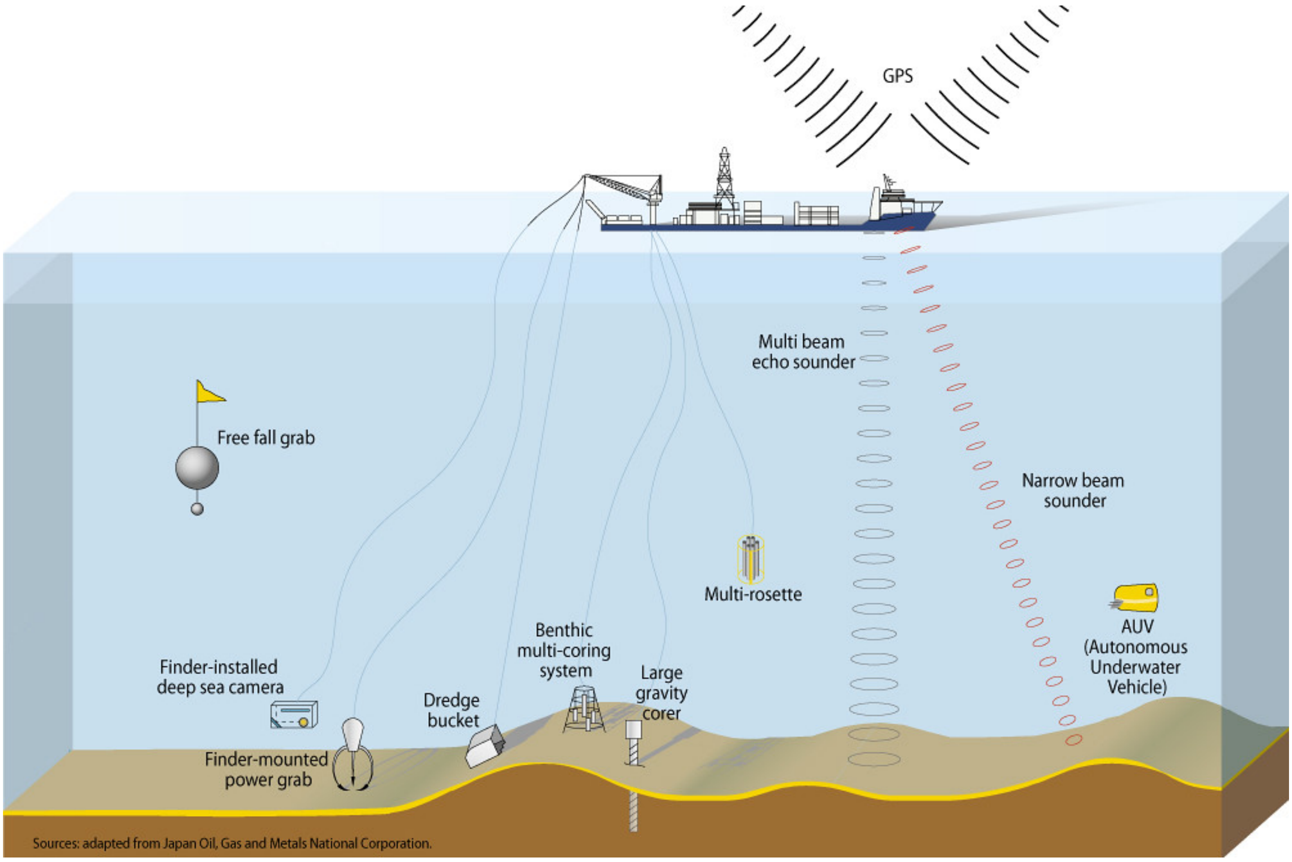


Figure 2: Different seafloor survey tools. Figure from: GRID-Arendal https://www.grida.no/resources/8165

sediments, because today's technology does not provide a high enough resolution to distinguish the sulphide deposits from the rest of the sea bottom. On the other hand magnetic measurements have proven effective in the search for sulphide deposits. In the manganese crusts one has found a higher emission of gamma radiation than the surrounding rock. This feature can be used to identify crusts by the help of radiometric sensors (DNV Energy Systems 2021).

2.3.2 Extraction process

Offshore mineral extraction has some advantages over land based mining; an offshore mining operation does not need permanent construction or infrastructure, this claims less area and does not require fresh water from the mined area. And given that the operation as far from the shore, are there no adverse impact on local human communities. Furthermore, is equipment reusable, especially the surface vessels, additionally are the ore grades and amounts often greater than the terrestrial ores. There are also some new challenges; to start an operation offshore will require major investments in both technology development and production equipment, both carrying significant risks for investors. The uncertainties about the potential environmental impacts and the potential size of the area affected by the operation. Presently it is unknown what strategies will prove effective to protect the marine environment from the potential adverse impacts (Cuyvers et al. 2018).

It is desirable to separate out the waste (non-ore sediments) from the ore as early as possible to avoid using energy on non-profitable material. The lifting from seafloor to sea-surface is an energy demanding process and some concepts for pre-processing at the seafloor are being suggested, for example, by the use of hydro cyclones, magnetic concentration, or a sensor-based sorting system (Ecorys and Delft

2014).

2.3.3 Shutdown phase

The true extent of the process of shutting down a production site is still not certain, but the laws ratified by the Norwegian government and ISA's draft of "Regulations on Exploitation of Mineral Resources" are Closure plans presented.

The Norwegian law on mineral extraction on the continental shelf from 2019, "Havbunnsmineralloven", states that a plan for the shutdown is to be presented two years before the planned end of production (Lover 2021). ISA's draft requires the plan to be presented twelve months before shutdown and the plan has to contain a time frame of the shutdown, an Environmental Impact Assessment (EIA), a plan for environmental monitoring post production and initiatives to mitigate potential residual environmental effects.

2.4 State of the art technology

2.4.1 The NAUTILUS SOLWARA project

One of the current commercial non-governmental project that came the close to realisation is at the SOLWARA 1 site licensed to NAUTILUS Inc. in the Bismarck Sea, this area has several hydrothermal vent sites and the project was for mining SMS deposits. The project was made bankrupt in November 2019 (Stutt 2019).

The Nautilus' concept consisted of three bottom crawling ROVs with specialized tasks, a Riser And Lift System (RALS), a surface production vessel and the ore was to be transported to shore by hopper barges. The three ROVs had the following tasks: one ROV levels the area for a second high production unit and the last ROV collects the mined ore and pumps it to the lifting pump on the RALS. The ore is transported as a slurry and pumped up to a surface production vessel trough a rigid riser hanging from the surface production vessel (DNV Energy Systems 2021).

The Jankowski et al. 2010's report evaluates a captial expendutures (CAPEX) and operating expenses (OPEX) for the NAUTILUS system. The CAPEX is estimated with a 17.5% contingency at 383 Million US$ and an OPEX estimate with 10% contingency of 261 million US$ in 2010.

2.4.2 JOGMEC

The Japanese government is running a project for Japan to become more self sufficient in its supply of minerals. Two of the explored sources is deep sea minerals and recycling. In 2017 JOGMEC and the Japanese Ministry of Economy, Trade and Industry (METI) succeeded with the world's first pilot test of continuous lifting ore from the seafloor at 1600 meters depth to the surface by the help of a submersible pump. METI 2017 reports that this test was carried out near the Okinawa Prefecture with the goals of verifying the technologies for lifting ore with seawater and to expose challenges and potential environmental impacts from the operation.

JOGMEC 2020 reports in 2020 the success to be the first organisation to excavate 649kg of cobalt crusts and lift it to the surface. Environmental impact analyses were done prior, during and after the excavation to investigate the potential impact from such an operation.

2.5 Why we need more minerals

To meet the Paris agreement climate goals and limit global warming below 2°C, major innovations to energy production and storage are required to reduce emissions. Most of the new low carbon energy technologies under development require several minerals and Rare Earth Elements (REE). Examples of these technologies are: batteries, solar energy (both photo voltaic and concentrated solar power), windmills, geothermal, hydrogen and carbon capture facilities. Consequently, the so-called "green shift" requires fairly high amounts of certain minerals and elements.

The elements with the highest expected increase of demand are, according to Hund et al. 2020: aluminium, copper, iron, lead, neodymium and zinc. Many of these are expected to have more than 200% increase in demand by 2050. An increase in the copper demand is almost certain, because it is needed in several new technologies. Copper's superior qualities for electric power transmission makes it a desired metal for the upgrade and expansion of the energy infrastructure that is needed to transport the power from the production site to the consumers. Renewable energy production has to happen on site and when the energy is available, leading to spikes and lows in the availability of energy from a power plant.

IEA 2021 states that coal is currently the most profitable product for mining companies, but a decline in coal production is anticipated due to an expected transition from coal based energy to new renewable sources, and in 2040 are the revenues from energy transition minerals projected to be greater than from coal.

2.6 Re-use and recycling

Another possible source for metals is to recycle when a product has reached its End-Of-Life (EOL). Some metals can be recycled several times without any significant degradation of the metal quality, but metal alloys can complicate the recycling process. Hund et al. 2020 show that 90% of the aluminium is recycled in some countries, but the global average is between 42%-70% for aluminium recycling. The amount of recycled aluminium in new products is about 35%, suggesting that the consumption of aluminium is greater than the recycled volume. Similar trends are found for copper, cobalt and nickel. Some applications, e.g. batteries, require very pure metals and recycled metal products are typically not of an adequate quality for battery use, examples of these are cobalt and lithium.

An alternative to recycling is re-use or re-purposing of a discarded product. For example one can use discarded batteries from electric vehicles in trucks or power storage. According to Hund et al. 2020 if one assumes that 50% of batteries from electric vehicles will be re-used in stationary power storage, one can expect a 3% decrease in the total cumulative lithium demand in 2050. Lithium is mainly used for power storage in the automotive sector, because this sector requires many charge cycles with a quick recharge rate. Unless new battery technology is developed for Electric Vehicles (EV), the lithium demand will continue to increase. If one decides to reuse products it is important to be attentive to where they end up. Products for reuse can end up in developing regions as an excuse for reuse and might not be disposed properly, thus becoming a safety and environmental hazard, creating more waste than an earlier recycle.

2.7 Political challenges

Today's mineral production are more geographically concentrated than the present oil and gas production. This can lead to an unstable delivery of minerals and can act as a political bargaining chip. The People's Republic of China (PRC) is currently the largest producer of REE's with more than 70%

of the global production. The Democratic Republic of Congo (DRC) produces over 80% of all globally recovered cobalt. Cobalt is often a byproduct of copper or nickel production and is primarily used as a cathode in lithium-ion batteries. A stable cobalt supply is important to ensure the production of batteries for electric vehicles.

Copper is widely used in clean energy technologies and is difficult to substitute due to its superior electric conductive qualities. However, copper production is expected to peak during the next few years and prospected mines contains lower ore quality. According to IEA 2021 the refinement process of several minerals, including copper, requires a substantial amount of water, while several production sites of copper are in areas with limited water resources. For a local sustainable development one needs to mine responsibly, because, mineral extraction can contribute to lifting economically poor regions out of poverty and generate local social revenue. In contrast, poor management can lead to increase in greenhouse gas emissions, adverse environmental impacts (water strain, loss of biodiversity and local pollution) and adverse social impacts in the form of corruption, poor safety measures, and human right abuses. If a country dominates the extraction and supply of a certain metal, it may decide to use its dominant position as political leverage, leading to an unstable supply of the metal. Such actions could delay the development and production of new greener technology or a gradual acceptance of violations of human rights to ensure the supply of said metal. If one looks at the further downstream of the production the trend is similar for the mineral processing operations. IEA 2021 has compiled a list with the total global processing volume of selected metals, the People's Republic of China is dominant in processing of all the aforementioned minerals and were processing over 80% of REEs in 2019.

Due to the uncertainties around potential environmental impacts from deep sea mining, there are a few companies that have invoked a moratorium on using minerals from deep sea mining, for example BMW, Samsung SDI, Volvo and Google (Thaler 2021, IEA 2021). On the other hand, moving the mining operation offshore will require a higher competence of the crew and is also likely to improve the working conditions while eliminating the practice of child labour.

Corruption is also a factor. Transparency International has made a global index on the perceived risk of corruption the score in 2021 of selected countries are presented in Figure 3 where a high score is considered a law-abiding country and a low score is a more corrupt country. Many energy transition mining countries score below average on the Corruption Perceptions Index (CPI). These countries are associated with a weak rule of law and political instability. Several of the high volume producing countries have a low score on this list. This may also indicate poor working conditions in the country. Norway is on a fourth place in this index with a score of 85, while DRC is ranked in 169^{th} with 19 points. Most companies show commitment towards ensuring good working conditions for its employees, but according to IEA only 2/3 backs it up with resources. In general, the mining industry is lagging in several areas, such as gender equality, women are often hired for auxiliary tasks associated with poorer working conditions (IEA 2021, Transparency International 2021).

2.8 Norway's interests in deep sea mining

The Norwegian government has started the process for opening up areas for deep sea mining on its continental shelf. Norway has a long tradition with maritime industries and has gained a high level of competence from its offshore oil and gas industry. The government has also started to ratify laws related to deep sea mineral extraction and is in the process of conducting a preliminary EIA. The goal of the EIA is to gain knowledge about the potential impacts a deep-sea mining industry may have on the environment. Results from the EIA will be used to establish a more comprehensive set of rules and an operational regime to safely open areas for mining activity. For this to meet the requirements of a good assessment more data needs to be collected (Olje og energi departementet 2021).

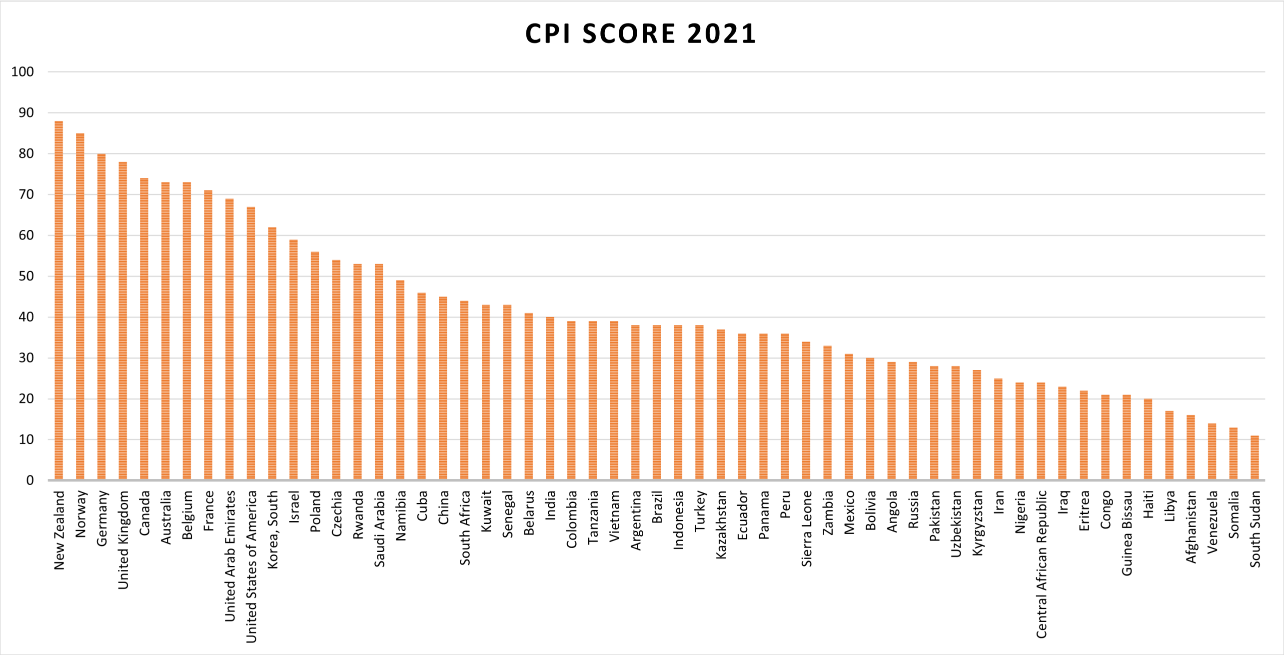


Figure 3: Perceived corruption index for selected countries in 2021. Data source: CORRUPTION PERCEPTION INDEX (2021) by Transparency International is licensed under CC BY 4.0

The EIA process is the first step in the opening of mining activity on the Norwegian continental shelf. This will be followed by allocation of reconnaissance licenses. Following the high grading of areas of interest there will likely be an application for acreage and another EIA within the new license area. Finally there will likely be another EIA before the completion and shutdown of the extraction process to make sure the site is left in a safe state (Olje og energi departementet 2021).

Previous research studies have identified deposits of massive sulfide deposits and manganese crusts in the deeper parts in the Norwegian Continental Shelf (NCS). It is not expected to find polymetallic nodules in the Norwegian-Greenland Sea areas because of the close proximity of the mid-Atlantic Ridge to the coasts of Norway and Greenland. In contrast, the EEZ around Norway's Bouvét Island in the southern Atlantic Ocean has some areas where it is possible for nodules to have formed (Olje og energi departementet 2021). The area around Bouvét Island is not part of the NCS, and is currently not a part of the deep sea mining opening process.

The Mid-Atlantic ridge is a slow spreading ridge expanding with almost 1 cm per year. This means that the deposits will move about 10 km in 1 million years and after 2 million years it is assumed that the deposits will be too deeply covered in sediments to be extracted, with today's technology. Consequently, one can expect that the feasible area to extract sulfide deposits has a width of 30-40 km along the Mid-Atlantic Ridge. Larger deposits are considered most likely around some of the inactive vents. The active vents are generally spaced with about 100 km distance, but if one includes the inactive vents the sulfide deposits should have a higher geographic density (Olje og energi departementet 2021). The manganese crusts are expected to be located in the subsea mountain formation that is located 200-300 km from the Mid-Atlantic Ridge. Generally this mountain area formed from volcanic peaks with a height of 500-1500 m above the surrounding seafloor. The manganese crusts on the NCS can have large concentrations of scandium and lithium, these are rare earth elements that can increase the economic value of the crusts, but the concentrations of cobalt are generally quite low. The technological development for mining of crusts is less developed than for the mining of nodules and sulfide deposits (Olje og energi departementet 2021).

Norway also has sovereignty of Bouvét Island, a small island in the South Atlantic sea, near the triple juncture of the South American plate, African plate and the Antarctic plate. Areas around triple junctures are often associated with hydrothermal activity and might hold significant mineral deposits (Beaudoin and Baker 2013b). Within the possible area for an extended economic zone there one can find indications of both abyssal plains and seamounts. So in the long term this area might be interesting area to prospect. Currently has Norway not claimed this extended economic zone, but are entitled to the areas (Justis- og beredskapsdepartementet 2021).

2.9 Environmental challenges

For public acceptance and ”license to operate” it is important to have a transparent process for the exploration and production phases. According to Purser and Marcon 2016, continuous interactions between the industry and stakeholders is recommended to ensure that the industry’s activities remain environmentally and financially sound. It should be noted that there is still a big knowledge gap of the potential impact deep sea mining can have on marine ecosystems.

DNV Energy Systems 2021 has identified the most important environmental impacts from deep sea mining:

- Removal of habitats and substrate
- Change of the geo-chemistry and physical traits of the sea bottom
- Plumes
- Contamination of the water column
- Noise, vibrations and light

The main challenge in assessing the potential environmental impact is the relatively limited knowledge about how deep sea ecosystems and biodiversity function and how well the ecosystems can recover from anthropogenic stressors. According to Cuyvers et al. 2018 seafloor mining activities will disturb habitats and may result in either temporary or longer term habitat changes or even losses. The impact on the outer surrounding areas is poorly known and will depend on the extraction technology used. One concern is the environmental impact of a sediment plume from either stirring up bottom finer-grained sediments (silt and mud) from the mining process itself. Several factors will affect the environmental impact. To map out the areas potentially affected, the extent of a sediment plume spreading needs to be modelled. The disbursement will depend on local currents. Nonetheless, the issue is disputed between environmentalists and mining companies. Modeling will be important but, the answer might not be known before a mining project has begun since the plume is dependent on particle size and local hydrodynamics.

The effects on organisms within the water column is also largely unknown, but one should avoid mixing the layers in the water column because it may have unfortunate effects on the fauna in the water column. Therefore, the return water and mine tailing has to be released at deep waters to hinder such mixing, but a concern expressed by Cuyvers et al. 2018 is that the return water has a higher temperature than the surrounding water and will be more buoyant, leading to a wider dispersion of the returned sediments. However, it is also argued that the surroundings will quickly cool the returned water and thus keep it within the designated water depth zones. The plumes can affect bottom fauna by for example clogging filter feeding organisms. Secondary effects of the presence of the mining activity like noise, light pollution, vibration and risk of leaks may, in certain cases, have adverse impacts effects, but the degree of harm remains unknown.

According to Purser and Marcon 2016 (The Managing Impacts of Deep-seA reSource exploitation (MIDAS) project) plumes from deep sea mining activities will not be visible on the ocean surface.

According to Purser and Marcon 2016 the mining process might release metal ions into the sea water column which can travel with the plumes for hundreds of kilometres and may impact larger areas. The existing protocols for laboratory assessments of lethal toxicity at standard temperature and pressure (20° C, 0.1 MPa) have little ecological relevance to the deep sea where temperatures are down to 2° C and pressures up to 60 MPa. MIDAS performed tests on copper and cadmium exposures on shallow water shrimps with lower water temperature and higher pressure. The study concluded with that the copper toxicity was greater than the cadmium toxicity at 10° C and 10 MPa, but in standard conditions, cadmium has a higher toxicity. Purser and Marcon 2016 points out the issue with these laboratory tests is that they only consider a single metal in a single oxidisation state or a single mixture. This makes it difficult to predict the potential toxicity in general and one has to asses the toxicity of the individual deposits to identify potential risks. On the other hand it might only be relevant to consider the bulk lethal toxicity for a proxy of organisms, both for the mining operation and the return water.

Purser and Marcon 2016 also points out that metals may be released either as an aqueous phase, adsorbed on to sediments or flocculate. Dissolved metal ions can be taken up by gills, body walls and digestive tracts, while adsorbed metal can be ingested. Experiments show that different organisms react differently to the exposure of finely-ground particles of chalcopyrite ($CuFeS_2$). For example, shrimp showed no results in mortality at a copper equivalent of 37 times greater than the acute lethal threshold. Furthermore, the respiration rate was not affected at concentrations 1000 times greater than the dissolved copper. However, experiments on other species show contrasting results: a cold water coral showed no significant increase to mortality when exposed to inert quartz particles for 27 days, but when exposed to SMS particles for 27 days 95% of the corals nubbins died. When the particles were examined it was found that the SMS particles were sharp, while the quartz particles were more round. The sharp edges may have caused physical damage to the coral tissues in addition to the potential toxic effect of the metals in the particles. There is a risk that organisms around a mining site may be subject to a chronic exposure of the metals. This exposure might be much lower than the acute lethality limit. Some organisms are able to detoxify lower concentrations. An other study by Purser and Marcon 2016 demonstrated that even shrimp that have evolved in the metal rich environment around hydrothermal vents are sensitive to copper exposure. Some fauna species can avoid sediments contaminated with for example copper. A 96 hours laboratory experiment on a shallow water sea cucumber climbed on to the side of the treatment tank to avoid the exposure to the metals, resulting in no sign of self repair and the sea cucumber took no injury from the exposure. To mitigate these effects, the potential cumulative impact of plumes of adjacent mining sites over longer periods of time should be given proper attention. Operators should continue to work with environmental scientists during the exploration and exploitation phases and iterate regulations practises for impact monitoring and designation of exposure limits.

Cuyvers et al. 2018 expects a high level of endemism (the state of a species being found in a single defined geographic location), because of differences in temperature, chemicals and plume flow between different vent sites. Therefore, different vents host different species and ecosystems. The longevity of these ecosystems is affected by tectonic activities like earthquakes and shifts in volcanic activity and fluid chemistry that may have substantial impacts on development of the ecosystems around the vent sites. The ability to assess the biodiversity of the deep sea requires baseline data over time. Once this is gathered, one can begin to asses the potential impacts in an area. Cuyvers et al. 2018 points out that to benefit from baseline data, it needs to be supplemented with long-term monitoring to quantify any changes, establish cycles and potential adverse impacts in the monitored area. Such studies could identify areas of special interest for conservation. Monitoring programs rely on completed baseline studies to identify and track changes.

2.9.1 Habitat recovery

Cuyvers et al. 2018 points the importance of ensuring that the development of the deep sea not only benefits our generation, but also for generations to come, DNV Energy Systems 2021 says it is expected that the extraction of sulphide deposits or crusts will lead to a reduction of niche micro habitats and Purser and Marcon 2016 has found that even small scale disturbances in nodule fields are detectable after 40 years and have some degree of impact on the ecosystem for decades. Mitigation measures should continue to be developed such that any adverse biological impacts from commercial scale mining is minimized.

The recovery rate of vent fauna is largely unknown. According to Cuyvers et al. 2018 it is expected that there are large differences between active sites and inactive sites. At very active sites with volcanic eruptions it has been observed that the fauna can recover rapidly. Fauna at active sites are also able to adapt to higher concentrations of heavy metals, maybe even levels that are toxic for fauna at inactive sites. The recovery rate at slow spreading ridges with more stable conditions are less well known, but these areas are expected to have largest deposits and be the most interesting deposits for mining activities. The recovery rate at inactive sites are probably much slower and it is less likely that all organisms will recover (Cuyvers et al. 2018).

DNV Energy Systems 2021 points out that noise and vibrations from the extraction equipment is not expected to be severe enough to cause permanent damage on the marine biology in the area. Acoustic communications among whales might experience some degree of masking in the vicinity of the operations area. Modeling would be needed to determine the 3D soundscape (decibels and frequencies in particular), its areal extent and its potential impact on marine mammals. Also, localised light pollution on deep water fauna is poorly understood.

2.9.2 Environmental impacts from terrestrial mining

From an environmental impact point of view, deep sea mining can ease the pressure from onshore mining. IEA 2021 estimates that today's terrestrial mining claim 0.3%-1% of the global land surface, while mining can be very intense on the local resources by claiming land, water and power. In addition is there a long term risk of contamination in the mined area, even after the mining operation has been ended. To create a sustainable industry it is important to reduce the use of land and water and create less waste during extraction and processing.

Terrestrial mining has regional impacts. IEA 2021 points out three environmental challenges that affects the local region: land use, water use and waste generation. "Land use" refers to the fact that the land cover is changed, especially for open pit mines, creating a surface impact that can cover several square kilometers. Although under ground mines impact surface areas less, they still require areas for processing.

Mining processes typically require large volumes of water and the water is needed throughout the production process. Although this water use may not have long lasting effects, the waste water drainage from the mines can be acidic (due to reactions with sulfide rich materials) and this drainage can last for a long time after the mine is closed (IEA 2021). The tailings produced are sometimes stored in ponds, and these have the potential to contaminate downstream water bodies. Tailing-dam failures can have catastrophic effects downstream. Some mines perform dewatering operations which has the potential to decrease the level of the local water table or pollute local aquifers. Some mines are located in arid areas where water strain is high and it has to be shared with local consumption, agriculture and other industries, thus creating local water constraints.

Increasing production volumes and decreasing ore grades leads to an increased production of waste.

Waste management is a significant challenge. The waste rock is often left in piles or heaps close to the mine, but the tailings from processing are often stored in embankment dams, with the potential for severe local contamination. For mines with a lower stripping ratio, one can use more stable methods for disposal such as thickening or drying of the tailings. A method which also enables water to be recovered (IEA 2021).

Although mines can strain the local environment, many local communities depend on the income from the mines. This creates challanges for local governments. In some cases mining companies may pressure local governments to act in their favor. For example, the Philippine Center for Investigative Journalism (PCIJ) disclosed that the Palawan authorities are rezoning areas of the rain forest for the expansion of the nickel mine (Ilagan et al. 2021).

2.10 Offshore operations

When performing site specific engineering, is it important to consider the local environmental loads on the installation, and by the set weather restriction of the operation one can use hindcast data to estimate time for waiting on weather. The duration of the planned operation defines it as either weather restricted, duration less then 72 hours, or weather unrestricted, duration exceeds 72 hours. The operations duration includes a contingency time, extra time that accounts for unforeseen delays. The difference between a weather restricted and weather unrestricted operation is that the start of a weather restricted operation is decided by a reliable weather forecast, where one is fairly certain that the weather will not exceed certain parameters during the operation, hence one can set a design limit for the operation and wait on a suitable weather window. When one has to wait for suitable weather is this called Wait On Weather (WOW), and is time one can estimate from hindcast data. A weather unrestricted operation uses extreme value statistics to set the design criteria for the operations. The statistics are based on historical data or from time domain simulations. Further requirements and processes of operational planning are described in DNV-RP-H103 2014.

2.11 Challenges with underwater communications

Due to high attenuation losses of electromagnetic magnetic waves in water, conventional means of wireless communications are quite limited underwater, and acoustics are used instead. The speed of sound depends on the density of the medium in which it is propagating. As water is denser than air the underwater speed of sound is greater and the transmission losses are lower than in air, resulting in a useful range of acoustic signals in water and acoustics are therefore often used for underwater communications. Another alternative for underwater communications is by the use of a cable. The advantages of using a cable is that it is reliable and can supply the power to an operational unit at the same time, but the cable management can be challenging as entanglement and drag forces are issues to consider when deploying a tethered device. A third issue is that there has to be a direct link between the two units (Ludvigsen 2020).

Another effect of this attenuation of electromagnetic waves is that there are no GPS signals underwater. This creates challenges for underwater positioning. The two main methods of underwater positioning is by the use of dead reckoning, summing the accelerations and velocities to estimate the position, although this has an unbound error growth. Another positioning method is by the use of underwater transducers, either bottom mounted or hull mounted, and using the travel time of acoustic signals to calculate a relative position of the unit (Ludvigsen 2020).

Equation (1) states the pressure drag force on an object in a moving stream. F_D is the drag force, ρ is the density of the surrounding medium, C_D is the drag coefficient, depending on the shape of the object, A is the projected area in the stream and the U is the velocity of the stream.

$$F_D = \frac{1}{2}\rho C_D A U^2 \tag{1}$$

When it comes to a cable A will grow with the length of the cable. For a long cable the drag force from the cable can become significant. A self propelling unit has to overcome this drag force to move.

2.12 Other theses on deep sea mining

Some theses has been written on the topic of deep sea mining with Loki's Castle as an example case. Three of these are presented here and all are published from NTNU.

A master thesis from 2016 titled "Feasibility of Deep-Sea Mining Operation Within Norwegian Jurisdiction" by Erik Kristian Thon Frimanslund. Frimanslund uses the Monte Carlo simulations to create distribution of costs estimates of a mining operation with the layout of NAUTILUS's SOLWARA 1 operation at Loki's Castle. He concludes that currently are the profit margins low, mainly due to high CAPEX (Frimanslund 2016).

Astrid Vamråk Solheim's thesis from 2019 titled "Transportation for deep sea mining using underwater vehicle" performs a conceptual design on a diagonal lifting, by using an AUV to transport the ore to shore and use a marine railway at the port to lift the AUV out of the water. Diagonal lifting is to combine the lifting process with the horizontal transport to shore (Solheim 2019).

Maxime Lesage wrote his PhD. thesis on the topic of deep sea mining and is titled "A framework for evaluating deep sea mining systems for seafloor massive sulphide deposits". The thesis was delivered in 2020. His thesis consists of three main modules: (a) an economic block model, to enable future open-pit studies, (b) A simulation model to predict the performance of a DSM system with a given environment and (c) a framework for conceptual design to provide alternative solutions and enable the evaluation of concept of an early stage for a given deposit and environment. The economic block model was used in a sensitivity analysis that established that the performance of the DSM system has a great influence on the value of a deposit. Further did the simulation framework conclude that adverse weather conditions has a significant impact on an operation's cost and production rate. Another result from the simulation was that the ability to perform logistics and lifting operations are paramount for the operation. These are used in the conceptual design to present four DSM concepts (Lesage 2020).

3 Theory

3.1 Deep sea risers in the oil and gas industry

The oil and gas industry has decades of experience using deep sea riser systems and has driven the technological development to face the challenges that come with deep water. Examples of important design factors of the riser are: wave forces and Vortex Induced Vibrations (VIV), a cyclic load leading to fatigue damages, and floater motions. VIV are caused by an external flow passing the riser, like a steady current, and the current shed vortices on the hind side of the object. The VIV can excite in both inline and crossflow directions, these directions are shown in Figure 4 for a circular cross section. In this figure one can see that asymmetric vortex shedding induces crossflow vibrations, while symmetric shedding induces in-line vibrations. A lot of work has been done to predict the response from VIV to further predict the fatigue life. If the shedding frequency matches the resonance frequency of the riser the fatigue damage can be significant in a short amount of time. The response depends on several parameters such as: current profile, frequency, magnitude and the properties of the riser. To mitigate the effects of VIV one can redesign the riser or add VIV suppression devices, this can for example be strakes or fairings. Other sources of fatigue damages are Vortex induced motions (VIM), where the vortexes are generated by the motions of an object, and fatigue loads during installation (Y. Bai and Q. Bai 2005).

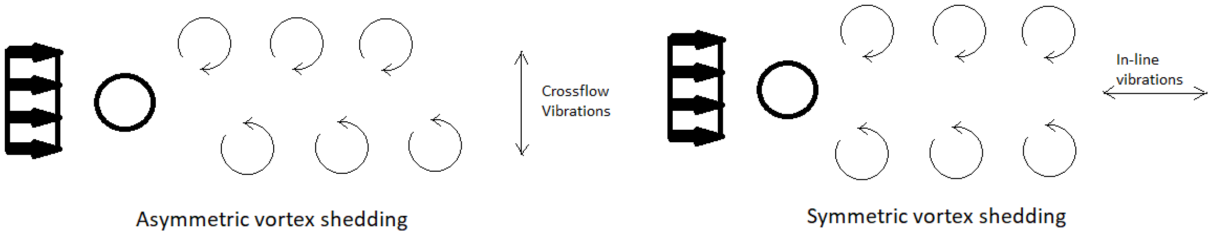


Figure 4: Definition of crossflow and inline direction of vibrations. Figure adopted from Y. Bai and Q. Bai 2005

The floater offset of position also have a load on the riser. According to Carter and Ronalds 1998 are typical horizontal offsets for a Floating Production Storage and Offloading (FPSO) ship is 30%, semi-submersibles 20% and Tension-Leg Platforms (TLPs) have a 10% of their installed depth, this relation is close to constant for all water depths. In contrast to the floaters heave motions that remain relatively depth independent of the water depth. The maximum design values depend on the site, but typical maximum design value for FPSOs is in the magnitude of ±15 meters and TLPs and spars is around ±1.5 meters, hence as the depth increases, the fraction of heave motion decreases. The main riser configurations used in oil and gas industry is Steel Catenary Risers (SCR), Top Tensioned Risers, flexible risers and hybrid risers. Carter and Ronalds 1998 states in general that SCRs are the most cost competitive if used on satellite wells, due to the geometry of the catenary. For the same reason can hybrid risers be the most cost competitive option when developing wells close to the floater. More specifics about typical anchors in oil and gas industry are found in appendix A.

3.1.1 Steel catenarys used in oil and gas

Steel catenary risers are a common in deep water applications and they are often installed on semi-submersible and TLP installations with a medium dynamic response. One of the primary challenges with deepwater SCR is the high hang-off tensions caused by the riser's own weight and the compression and high stresses in the touchdown zone. Other design considerations are hull motions, VIV and installation fatigue. SCRs are commonly installed by J-lay time consuming process that requires specialized vessels and special requirements for pipe stiffness and diameter (Y. Bai and Q. Bai 2005).

Typically the SCR is installed in a simple catenary configuration, but double catenary configurations (Steep and lazy wave) can be used. The simple catenary and lazy wave configurations does not need an installation of a riser base. As the floater has an horizontal offset, the shape of the catenary will change and so will the stresses and the location of the touchdown point (TDP). The weight of the riser hangs off the floater and has to be considered when designing the floater (Carter and Ronalds 1998).

The horizontal offset of the floater requires a joint capable of accommodating the accompanied angle changes in the top connection. According to Carter and Ronalds 1998 cab the mean position be between 10° and 20°. This angle and tension affects whether VIV occurs and the moments experienced at the lower sections. A section of the riser of particular interest is the touchdown zone, which is the area of the SCR that is the most at risk for fatigue failure. In theory the SCR configuration may contribute to the mooring of the floater, reducing the total mooring. The rigidity of steel makes SCR a less viable option for waters shallower than 300 meter, but other riser options are more feasible for shallow waters. SCRs are an alternative to consider for depths down to 2000 meters. Furthermore, SCRs are fully compliant with vessel motion without the need of heave compensation, hence SCR is a simple and inexpensive configuration.

3.1.2 Top tensioned risers used in oil and gas

Top Tensioned Risers (TTR) are used on floating production units as the connection to the reservoir and bottom production units. It is traditionally constructed from steel, but on compliant platforms where stress joints are commonly used, is the material of choice for these joints often titanium. An advantage of such riser systems is that the floating production unit can perform workovers at the reservoir and perform the tasks of production, injection, drilling and export. TTRs are typically used on steel jacket and concrete gravity structures, but have also been used on compliant platforms such as Tension Leg platforms (TLP) or spar buoys due to their low dynamic responses. The riser is tensioned to the seabed by anchors and the floating production unit in the top, but there may be buoyancy elements on the riser as well to reduce the required tension from the platform. On the production unit there is a tensioning system that keeps the riser's tension constant while the platform is moving due to external loads. Some main considerations during design is the allowable motions of the floater and tensioning system, maximum riser top tension, size and strength of stress, flex and keel joints, clashing between adjacent risers and vortex induced vibrations (Y. Bai and Q. Bai 2005, Carter and Ronalds 1998).

3.1.3 Flexible pipes used in oil and gas

Flexible risers and flowlines are composite pipes with a relative low axial stiffness. According to Y. Bai and Q. Bai 2005 today's pipes can handle depths over 2400 meters and internal pressures over 680 bars. A motivation for the progress in flexible pipes is the ability to withstand large motions, for example, caused by harsh weather conditions. Traditionally flexible risers have mostly been used with floating platforms in shallow to moderate water depths in compliant configurations, but more recently the flexible pipes have been used in ultra deepwater field developments. Its compliant nature eliminates the need for heave compensation and tensoning devices. A challenge stated by Carter and Ronalds 1998 can the layered structure of flexible pipes allow for gas permeation, and corrosion in the armour might lead to failure.

Two main types of flexible pipes are used: unbonded and bonded flexible pipes. In the bonded pipes the different layers in the pipe are bonded by a vulcanization process. These are only used for shorter segments such as jumpers. The unbonded are used in longer lengths and can take more motions, and these are the ones used in flexible riser systems. The five main components of a flexible pipe is the carcass, internal polymer sheath, pressure armor, tensile armor and the external polymer sheath. And an example of a cross section from the innermost layer: carcass, internal fluid barrier, pressure armor, anti-wear layer, tensile armor, anti-wear layer, armor wire, anti-birdcaging layer and external fluid barrier. The point of the anti wear layers is to reduce friction between the layers when they are sliding relatively to each other. These layers can also prevent birdcaging, a phenomenon where the wires twist out of their pre-set configuration caused by axial compression due to hydrostatic pressure (Y. Bai and Q. Bai 2005).

The part of the riser most exposed to fatigue damage is in the top hang off region, where the pipe is restricted from over bending by either a bell mouth or a bend stiffener. There are several possible configurations for how a flexible riser can be installed. What configuration to install depends on design requirements and environmental conditions. Figure 5 illustrates the main configurations of flexible risers, one can see that the more complex configurations require some extra bottom infrastructure (Y. Bai and Q. Bai 2005). What configuration to choose depends on what response is required and what is available infrastructure on the seabed. For deep water applications the pipe's own weight may become a problem, because the top of the riser has to carry all of the riser. This might be handled by either an internal strengthening of the pipe or by the addition of buoyancy elements along the pipe.

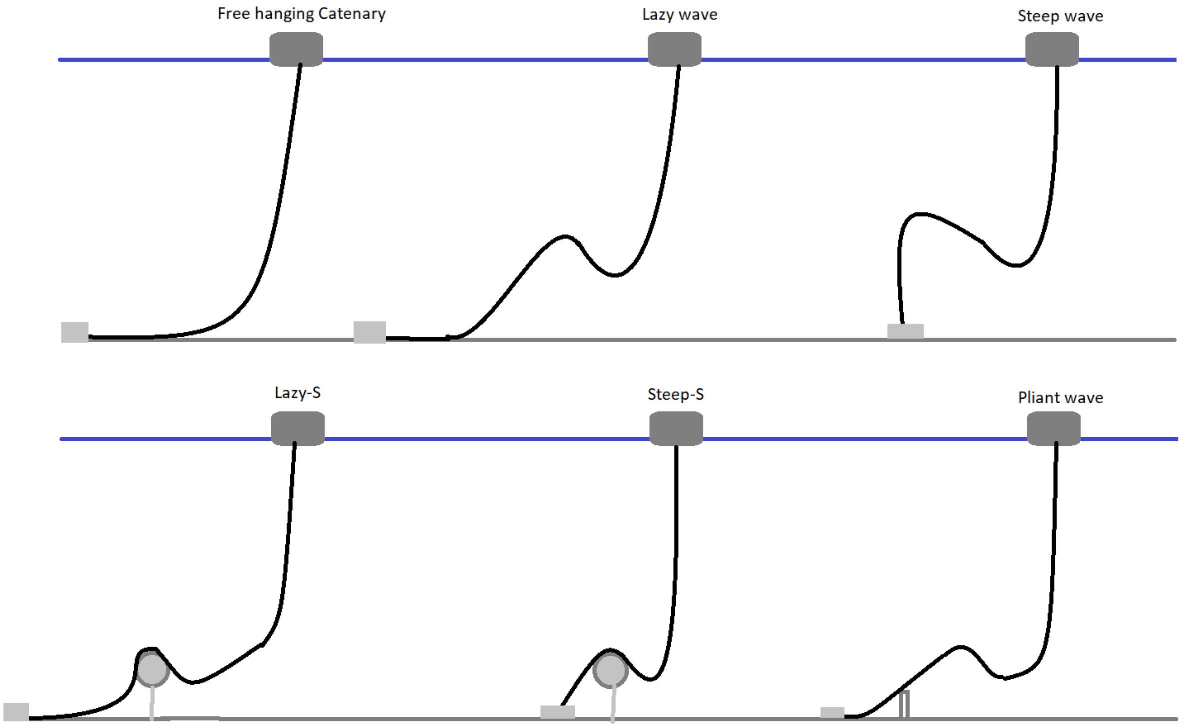


Figure 5: The most common riser configurations of flexible pipes. Figure adapted from Y. Bai and Q. Bai 2005.

3.1.4 Hybrid risers used in oil and gas

A hybrid riser is, as the name implies, a combination of several types of risers that utilize the different strengths of the chosen concepts. Commonly an anchored steel pipe with a subsurface buoyancy tank and a flexible jumper to the surface. The main components of a hybrid riser system is: anchor base foundation, bottom section jumper spools, free standing vertical section, sub surface buoyancy tank and the top section jumper (Y. Bai and Q. Bai 2005).

A self carrying configuration facilitates rapid connection and disconnection and reduces the weight that is carried by the platform. The rigid part is also self righting and the platform does not have to offer lateral support to the rigid section. The flexible jumpers creates a compliant link to the floater. Therefore, one of the parameters that affect the maximum motions of the rigid part of the riser is the depth of transition from flexible to rigid riser. The depth of the transition from the rigid riser to the flexible riser is a critical parameter with regards to the motions in the rigid riser section, but to allow larger floater motions, the length of the flexible riser can be increased to mitigate the motions from the floater. So the top flexible riser becomes analogous to a flexible riser configuration from the floater to the top of the rigid riser. Hybrid risers have a relatively compact footprint on the seafloor and Carter and Ronalds 1998 claims that its compact design in some cases can require shorter lengths of pipe than SCRs and flexible risers. The flexible riser is more maintainable due to shallower water depths than for a full length flexible riser. Hybrid risers are a viable option for water depths greater than 100 meters, but they become a more attractive option in deeper water. The hybrid riser is very compliant and does not contribute significantly to the mooring system of a floater. The pipe diameter is limited by the size of the flexible riser. If one wants to use a larger diameter for the rigid pipe one would have to install a manifold at the top of the rigid riser (Carter and Ronalds 1998).

Hybrid risers have been reused at different sites, Hatton et al. 2005 mentions as an example the multi-pipe bundled riser first installed on Placid's Green Canyon development in the Gulf of Mexico at 469 meters depth. This riser was retrieved, refurbished and reused on Enserch's Garden Banks at 670 meters depth. What made this repeated recovery possible was that the riser was designed and installed like a drilling riser, by flanging together individual joints by using the vessels derrick and moonpool.

A freestanding riser configuration allows pre-installation of the riser before the floater arrives, thus simplifying the logistics at remote locations where the mobilisation cost of a vessel is significant. A risk with this freestanding configuration is that the a drive off is possible. Meaning that the floating vessel offset becomes larger than the length of the flexible jumper. The main configurations of a freestanding riser is Single Line Offset Riser (SLOR), Concentric line Offset Riser (COR) or several pipes can be bundled in an internal or external bundle. The response of the riser depends on several factors, such as: location of buoyancy, offset distance from floater, length and weight of flexible jumper, the depth of the upper aircan and the resulting base tension (Hatton et al. 2005).

The riser base must be designed for vertical, horizontal and bending loads over a longer duration. The mean offset of the riser can be can be $3° - 7°$ with the flexible risers installed and $\pm 5°$ deflection can occur due to the environmental loads and vessel station keeping. The challenge of designing the riser base lies in the ability to handle these angle variation within the foundation of the base. There are two main designs: Pinned base, allowing free rotation, and a fixed base, restricting the riser rotation. The advantage of the pinned riser base is that the moment around the base is low but the jumper arrangement around the base becomes more complex. The fixed riser base has the opposite qualities. The choice of base impacts the jumper design at the connection into the riser (Hatton et al. 2005).

3.1.5 Drilling risers

The two main types of floating drilling risers are completion and workover risers. A completion riser is used to run the tubing trough the drilling riser and into the wellbore. The workover riser is used to reenter the well (Y. Bai and Q. Bai 2005). Drilling risers are typically temporary risers and can be retrieved in case of severe environmental conditions. A temporary riser will normally be run and retrieved several times during its lifetime. If environmental or operational conditions demand it, a temporary riser can be designed to be disconnected, retrieved or hung-off. Condition monitoring is common on temporary risers to ensure that it is operated inside the prescribed limits (DNV-ST-F201 2021).

3.1.6 Installation of risers in oil and gas sector

Y. Bai and Q. Bai 2005 mentions four common ways of installing pipelines and risers; J-lay, S-lay, reel lay and control depth tow. The first three require a specialized vessel, and the installation can be quite weather sensitive and the tensioning capabilities of the vessel might demand that the pipeline is installed in a empty condition, leading to large strains from the pressure difference between the inside and outside of the pipe. Controlled depth tow often uses two tugs, one leading and one trailing, to tow out the pipe segments that can be up to 7km long, and places it on the seabed. The towing can lead to fatigue due to vortex shedding during the tow. The installation will load the riser differently than during operation and it is important to consider the installation during the design phase. A final installation method is by a drilling derrick where the riser segments are placed in the derrick and lowered, this is the preferred method for TLPs and risers that go directly to the seabed, but a derrick can be used for J-lay as well (Burgess and Lim 2006).

3.1.7 Risers for deep sea mining

Nautilus Inc. has designed a riser system for the purpose of lifting the mined slurry from the seabed to the surface. The system is inspired by technologies developed by the oil and gas industry. The riser system is a hybrid type, where the riser hangs from the ship's moon pool. At the lower end is the subsea slurry lift pump connected to a flexible jumper hose that is connected to the gathering machine. The riser hanging of the ship is a rigid steel riser bundle and the wear estimates on the components are inspired from the seafloor diamond mining industry. This riser solution is designed for benign waters with a significant wave height of max 2.6 meters. And the lift and lower operation of the riser takes about four days (Jankowski et al. 2010).

There are several ways of connecting the pipe sections. Welding is the most common, due to a large experience base from shallow water applications. Lately the use of threaded connections has become more common (Burgess and Lim 2006).

3.2 Lifting technology

There are several suggestions on how to lift the mined ore from the seabed up to the surface. The two main groups of lifting are hydraulic and mechanical lifting. When it comes to large transport volumes the hydraulic systems are preferred (due to several fundamental technical issues in the mechanical systems) (DNV Energy Systems 2021). Some of the hydraulic concepts are: Air lift, solid buoyant particles or a submersible pump. A downside of hydraulic concepts is that you have to grind the ore in to small particles and mix the payload with water before pumping. The additional water has to be lifted with the slurry, hence one has to lift more weight than just the mined ore.

3.2.1 Air lift

The air lift is based on compressed air or light hydrocarbons is injected in to the riser and the buoyant air drives the slurry upwards with an isothermal expansion, this air expansion can be challenging to handle (Verichev et al. 2012). Air lift is generally power consuming, and according to J. Halkyard et al. 2014 this is due to the air slipping trough the slurry. One way of coping with the expanding air and increasing flow velocity is to gradually increase the pipe diameter. An advantage of the air lift method is that there are no subsea moving parts. Compared to mechanical pumps there are no contacts with impellers or actuating elements, thus reducing the generation of fine particles (J. Halkyard et al. 2014).

There are three effects to consider when describing how an air lift works:

- The reduction of specific gravity in the slurry in the riser
- The buoyancy of the air bubbles driving upwards

- The displacement of the slurry by the introduced air expanding

The efficiency is expected to increase with a deeper point of air injection, but the required starting pressure also increases with the depth of air injection, because to start the pumping the air pressure must overcome the surrounding static pressure. Once the pumping has started, the pressure only maintains the flow, hence a lower pressure is needed after startup. The air lift concept was tested by several industry partners in the 1970s with regards to lifting of polymetallic nodules (Doyle and J. E. Halkyard 2007). Doyle and J. E. Halkyard 2007 refers to a successful test in 1976 by Kennecott Exploration a lifting test on an onshore rig. The test lifted a concentration up to 24 vol% of simulated nodules 100 feet up.

3.2.2 Solid buoyant particles

The solid buoyant particles (SBP) are similar to the airlift concept, but instead of compressed gas, solid buoyant particles are injected to the stream. It can be challenging to separate these particles when the slurry reaches the surface (Verichev et al. 2012). One also has to be able to clean them and sort out the damaged particles.

The solid buoyant particles require no moving parts under sea, because it can be pumped down as a slurry. The transported water is silted out and the particles are injected into the slurry mix. One of the major advantages of SBP over air lift is that it does not expand as the stream rises and the particles do not easily slip trough the slurry, hence, the particle lift is more efficient than the air lift and in turbulent flow the particles do not form slugs, thus creating a more reliable flow. J. Halkyard et al. 2014 states that SBP lifting is more power efficient than both air lift and by the use of a submerged centrifugal pump. Some of the main disadvantages of the SBP is that the particles used can be costly and a high recovery rate is needed to make the system economical and a substantial effort needs to be made to recover close to 100% of the particles in the stream, this depends on the type of SBP used. The environmental impacts from potential spillage are unknown, will this again also depend on the type of particles used. It has been suggested to use hollow glass spheres as the particles. It is possible to design for minimal breakage of the spheres. Glass is a chemically inert compound that does not react with the ore. One can expect that the particles wears on the system (J. Halkyard et al. 2014).

3.2.3 Centrifugal pump

Centrifugal pumps are known for their snail shaped casing and works by the fluid entering the middle of a rotating impeller where the fluid is flung outwards in to the scroll or diffuser, decelerating the fluid and further increasing its pressure. The centrifugal pumps can be installed in a series configuration to reduce the pressure gradient over the pump, which can ease the pump design (Verichev et al. 2012).

3.2.4 Positive displacement pump

The working principle of a positive displacement pump is fluid being sucked in to an expanding volume then pushed out when the volume contracts. These pumps are ideal for high pressure applications, like pumping viscous fluids and slurries, and for pumping metered amounts of liquid. In general, the pumps efficiency increases as the viscosity of the fluid increases. These pumps are better at handling shear sensitive liquids than dynamic pumps. Positive displacement pumps can be self priming and capable of creating a vacuum to lift a liquid several meters below the pump. The volume flow of a positive displacement pump depends on the pump rotation rate and is constant for a given speed (Chengel and Cimbala 2014).

Both the centrifugal pump and the positive displacement pump can experience blockage and clogging. If the flow fails the the particles in the slurry can settle and form a plug, - in worst case one might have to recover the pipe to remove the plug (J. Halkyard et al. 2014).

3.2.5 Parallel and series configurations of pumps

To increase the pressure rise from a pump one can add another pump in a series configuration. This has to be done carefully, especially if the pumps are of different sizes, because the volume flow trough the pumps has to be the same, while the pressure rise over the two pumps is equal to the sum of the pressure rise of all the pumps in series. An extreme case of this will be if the volume flow from the larger pump is greater than the free delivery flow rate of the smallest pump, and the smallest pump will act as a head loss, resulting in a reduction of the flow rate. Arranging dissimilar pumps in parallel might create problems with the flow too because the pressure rise over the branches has to be the same, while the volume flow is the sum of all the branches. If the pumps are dissimilar the increased head can be too large for the smaller pump and the flow can be reversed, resulting in a reduction of the total pressure rise. Hence it is recommended to combine identical pumps, but one has to be able to bypass pumps if the demand is unfixed (Chengel and Cimbala 2014).

3.2.6 Mechanical lifting

For mechanical lifting there are two main types of transport, continuous systems and modular systems. The most common concept of continuous systems are line bucket system, often used in dredging applications, the system consists of a continuous line of buckets transporting the payload from one end and is tossed out in the other end. For DSM applications are one of the main concerns the mixing of layers in the water column and environmental spillage if the buckets are not sealed. Modular system has some economical challenges due to low volume flow (DNV Energy Systems 2021). Other practical problems that follows continuous mechanical lifting concepts is that the whole weight of the chain and ore is hanging of the top link. Some of the advantages of mechanical lifting system are that the need for prepping the ore before lifting is limited and most system are of a low complexity. Because the ore is not mixed with water to a slurry the total mass per ore lifted is less, but one has to include the weight of the lifting system.

3.2.7 Choice of pump for NAUTILUS's SOLWARA 1 project

Nautilus did design a pump for slurry lifting at their Solwara 1 project. It is a challenge to design a pump for this purpose, in addition to pumping at a high ambient pressure it has to pump a fluctuation solids concentration. Judge and Yu 2010 explains Nautilus's process behind the chosen pump concept. It is desired to have a continuous flow at the required flow velocity, flow rate and pressure and a challenge with mixing with seawater is that the low viscosity demands a high velocity on the fluid for the particles to follow. Three concepts were studied: centrifugal pumps, positive displacement pump and air lift. The centrifugal pumps has to be in a multistage configuration to generate enough pressure to lift the slurry, with this follows several problems like rotor-shaft dynamics and regulation of pump speed to ensure a high enough flow velocity, both problems are solvable but it brings an extra complexity to the system.

The final choice was a positive displacement pump powered by pressurised return water from the slurry. The subsea part mainly consists pump chambers, hydraulic valves, hydraulic power system and a control unit. The flow in to the pump chambers are controlled by the hydraulic valves. In the pump chambers there are an elastic diaphragm separating the two flows, the strokes of the pump is driven by the return water,the slurry gets sucked in and pushed up by the motion of the diaphragm. The position of the valves during the strokes are listed in Table 1. The valves had to be hydraulically actuated to ensure that a proper seal and opening if there was any fragments stuck in the valve during closing. To reduce the pulsations in the flow there is a small decompression valve for each chamber, adjusting the chamber pressure to the inlet pressure when the chamber is empty of slurry (Judge and Yu 2010).

To emphasise some parts of the stroke and the working concept has Figure 6 been compiled, here is the corresponding position of the diaphragm and valves made more clear. The positions of the chambers does not necessarily match the position of the adjacent chambers in a true series of chambers and the decompression valves are not included in Figure 6. Chamber `A` in Figure 6 corresponds with the positions of the valves in Table 1 row `I`. Chamber `B` corresponds with row `III` and row `IV`, but with the decompression valve released and the RW outlet is opening. Chamber `C` corresponds row `II`. Chamber `D` is the emptying of slurry part of the stroke, this is where the pressurised slurry exits the chamber and in to the riser for lifting and corresponds with row `V` in Table 1.

Table 1: Position of the valves for different parts of the stroke, from Judge and Yu 2010

Row		RW outlet	RW inlet	Slurry inlet	Slurry outlet	Decompress
`I`	Filling slurry	Open	Closed	Open	Closed	Closed
`II`	Full of slurry	Closed	Closed	Closed	Opening	Closed
`III`	Filling RW	Closed	Open	Closed	Open	Closed
`IV`	Full of RW	Opening	Closed	Open	Closed	Decompressing
`V`	Emptying slurry	Closed	Open	Closed	Open	Closed

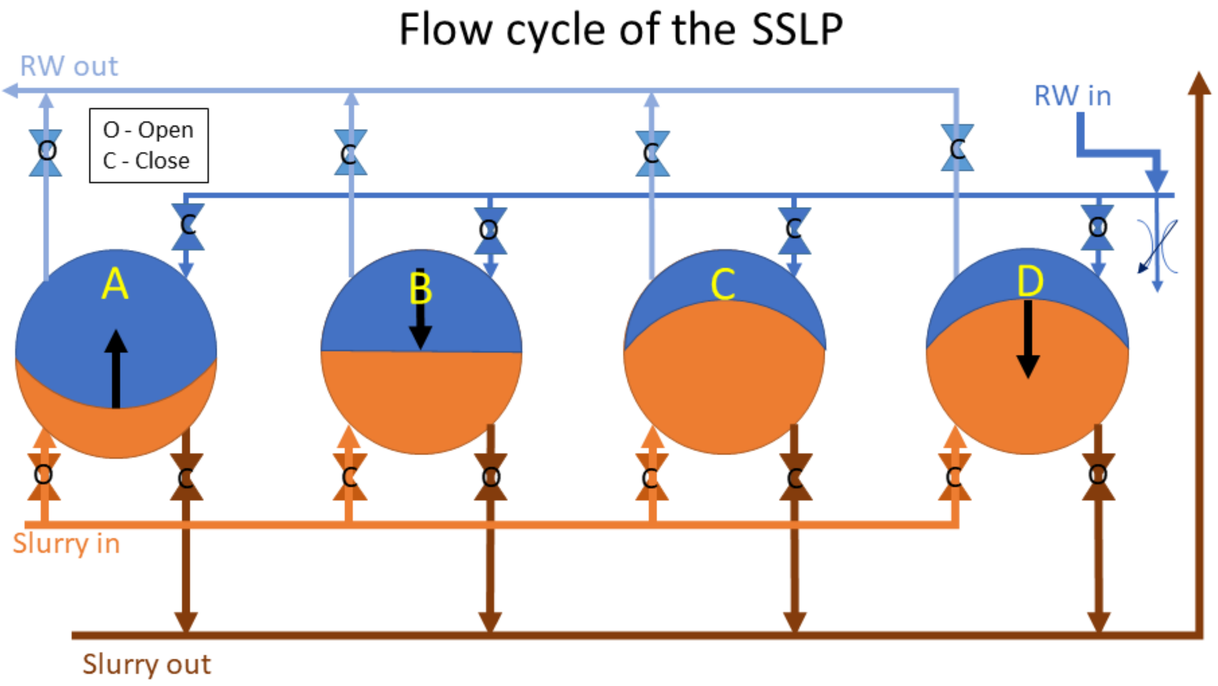


Figure 6: Position of valves and diaphragm for selected parts of the stroke. Figure adopted from Judge and Yu 2010.

3.2.8 JOGMEC's lifting pump

Okamoto et al. 2019 reports on JOGMEC's succeeded in being the first full scale test off lifting ore slurry from 1600 meters depth up to the surface. The lifting concept was a rigid riser with a submersible double multistage volute pump (centrifugal pump). This concept requires the ore to be crushed and mixed into a slurry with an average 3-5 vol% ore mix, but a maximum of 10 vol% is possible. With an inner pipe diameter of 100 millimeters and a slurry speed of 3.8m/s allowed this configuration a maximum grain size of 30 millimeters. For design it was assumed that a 5000 tons/day production rate was needed and yearly average of operation days 268 days and a planned maintenance cycle of 25 consecutive days with 5 days of maintenance.

Okamoto et al. 2019 explains the layout of the performed ore lifting test required three surface vessels: One for the ore lifting and supporting the lifting riser, one to carry the lifted seawater and a Collecting support vessel supporting the ROVs used to monitoring the operation. All vessels were equipped with dynamic positioning systems. The operation of launching and recovering the collector, pump system and riser takes at least three days, hence is four consecutive weather days needed to perform a lifting operation. The lifting test achieved in total to lift more than 16 tons of artificial and sulphide ore. The total lifting time was 96 minutes and 14 seconds. The temperature of the slurry fluid was measured to 15°C after lifting. The water temperature at the bottom was measured to 4°C. The temperature of the return water is important to consider when it is to be discharged.

The required high speed flow and need for fine crushing inspired a research project with a higher viscosity flow to allow lifting of larger particles at lower flow speeds. Orita et al. 2021 performed a study where this was done by using a carrier material, a mixture of a viscous fluid and fine particles. The study proposes a system with a pump on the surface vessel and a return pipe transferring the pressurised carrier material to the sea floor, where the coarse SMS ore is introduced to the flow and carried up the riser pipe. Their experimental results proved that concept and was able to lift coarser ore than the JOGMEC's subsea pump solution where the slurry is only mixed with seawater, with a denser test ore than typical SMS ore. The test succeeded in lifting the model sphere that was 1.7 times coarser at approximately the same density as typical SMS ore, but the test with a diameter of 50.8 millimeters and a density of 6.00 Mg/m^3 was unsuccessful.

3.2.9 Subsea pumping in oil and gas

There are both similarities and differences of the layout of an offshore oil and gas field and a deep sea mining operation, the main similarities are that you have something to transport from the seabed to the surface, some oilfields are low pressure and has to pump the oil to the surface production facility, an example of subsea compression is the Norwegian Åsgard B field (Time and Torpe 2016). Some of the differences are the duration of the operation, an oilfield can be active for several decades, while a deep sea mining operation has an unknown duration and will probably last from a few weeks to a few years depending on the deposits size and location. The layout of the subsea operations also look different, the components in oil and gas are stationary on the seabed, while most of the components for subsea mining will be mobile and moved around when operated. The deep sea mining slurry needs to be lifted to the surface by power provided by the production vessel if one does not establish power source close to the mining area.

3.3 Maintenance

A system is designed for a certain lifetime, by giving it some design load conditions. For these estimation are statistics often used, and maybe will the system fail before the design period is finished.

Depending on the system and the criticality of a potential failure one decides on safety factors, monitoring and maintenance regime. Condition monitoring is a strategy that has become more popular as databases are becoming digital, more traditional strategies are to change the components at certain intervals or run certain components until failure. When a failure is detected one uses diagnostics to find the failure. If condition monitoring is applied one has the opportunity to use prognostics as an estimate for when what will fail (Barros 2019). Because of the challenges of designing and consequences of a failure or unexpected downtime states Guzzo et al. 2016 that there has been some investigations in to the implementation of condition monitoring on the riser and machinery components in deep water oil and gas fields. Jankowski et al. 2010 States that the planned maintenance for the Solwara 1 project was 7 days every 100 days, the system was to be maintained by retrieving it onboard the surface vessel for maintenance.

The maintenance of subsea equipment today are typically done by cranes or by ROVs, both are depending on the weather conditions on the surface to be able to execute a maintenance operation. Currently there are developments for permanently subsea residing ROVs, that are capable of both inspections and interventions. An example of this is Eelume, a snake shaped vehicle built up by changeable modules to achieve desired properties (Eelume 2022).

3.3.1 Condition monitoring

Condition monitoring is a process of estimating the condition of a system and using its results to predict the components condition and remaining useful life. The most common way of this is to read of instruments and then an operator is interprets the readings in to a condition of the system. If these readings are fed in to a computer it can monitor the system with greater precision and use more advanced models for condition estimation and prognostics. When the system crosses a set alarm threshold it will notify the operator that action is required. If one gather an extensive statistic on components, system structure, boundary conditions, etc. one can use statistics or simulate by discrete event simulation and make an estimate of expected up- and downtime. A main motivation for condition monitoring is to reduce the unexpected downtime, reduce the unnecessary maintenance and to reduce the need for inspections (Barros 2019).

Typical tings that can be monitored are: pressure, strain, internal flow, accelerations and corrosion. Environmental loads can also be included in the monitoring program, for example temperature, waves and wind. In Guzzo et al. 2016 a system is proposed and tested to track the motion in a riser by the use of accelerometers mounted externally on the riser and communicates with the surface by the use of an acoustic link, while the power is provided by a battery. The system proposed gave results corresponding to the motions of the test rig. To make condition estimates these readings fed are into a model for calculation.

4 Methodology

4.1 Design study

There are several ways to start the hunt for possible solutions of a defined problem. The study can for example start with information gathering of state-of-the-art knowledge, a study of natural systems to adopt, an analysis of existing technical systems, study analogies or model testing. The goal of these studies is to gather relevant information to produce possible solutions of the given problem and the ideas generated are further developed and evaluated throughout the design process. Typically the process of concept generation is performed in teams and several methods can be used to stimulate the generation of ideas and to evaluate concepts at an early stage. But intuition is also considered as a vital part of the design process (Pahl et al. 2007).

In this study the constraints and main lifting concept were underpinned by a literature study. The final concept design was done with the help of the method suggested in Pahl et al. 2007 by setting up a requirements list that is used in the conceptual design process. This facilitated the generation of a possible solution space that was presented in a morphological matrix. The final design selection was based on possible combinations while considering the compatibility and strengths and weaknesses of every sub part.

4.1.1 Requirements list

To establish desired qualities one can establish a requirements list. The list can be used to clarify the tasks at hand and to specify the properties needed and the properties one does not want for the product. This can again be used to identify the system function and to evaluate the product design. A result of the list is the goal of the product and the properties needed. Some of the requirements are demanded by the design whereas others are "wishes" for the finished product. The requirements established should have qualitative and quantitative aspects to enable validation of the suggested design. Pahl et al. 2007 suggests a format of the list, but this has only been loosely adopted since the design process is performed by only one person. However, the checklist on page 149 in Pahl et al. 2007 has been followed.

4.1.2 Conceptual design theory

When performing a conceptual design, essential problems are identified by abstracting the task. This also helps identify the needed function structures. This can be used to search for appropriate task solutions. In this thesis the progress described in Pahl et al. 2007 has been followed. The process is organised in these six steps:

1. Abstracting to identify essential problems
2. Establish function structures
3. Search for working principles to fulfill sub-functions
4. Combine working principles into structures
5. Select suitable combinations
6. Tune principle solution variants
7. Evaluate against technical and economical criteria

Step one is performed to open the mind of the designers, especially towards unconventional solutions. It is done this way because the stakeholders have a tendency to avoid risks and chose more conventional methods, which might result in a less economic solution. Abstracting opens up for exploration of more novel solutions and one can find the crux of the task, revealing the system function and its constraints. When the task at hand is clarified the task can be expressed as a collection of sub-problems. To further distance oneself from the existing solutions one can attempt to progressively broaden the problem formulation such that as many possible solutions are included in the early phases of the design and that existing structures in the operation have less impact on the design. The next step is to analyse the requirements list with a regard to the established function and constraints to reevaluate the stated wishes and demands. From the requirements list a new list is generated where the functions and constraints are further refined and arranged in their order of importance. Thereafter the aspects and problems are revealed by the following steps stated in Pahl et al. 2007:

Step 1 Eliminate personal preferences

Step 2 Eliminate requirement that have no direct bearing on function or the essential constraints

Step 3 Transform quantitative data in to qualitative data and reduce them to essential statements

Step 4 Generalize the previous step

Step 5 Formulate the problem into solution neutral terms

After the problem formulation and function is established one can start to develop the function structure. It is often done by starting with a rough structure where one adds on more detail in an iterative manner and establishes more details in the function structure, this whole process is described in Pahl et al. 2007. When the function structure is established one can generate several solution variants based on working principles for each subfunction. This creates a solution field that can be represented graphically in a matrix with the subfunctions listed in the rows and different solution variants listed in the columns. When establishing the solution space; one should prioritise the main subfunctions and key classifying criteria and characteristics should be derived. Intuitively generated ideas are welcome, but idea characteristics should be carefully analysed. In preparation for the selection process the properties of the working principles should be noted. For one to be able to fulfill the main function one can combine the listed working principles into a working structure for the main function. The selection criteria can be presented in a selection chart or classification scheme. To reduce the number of possible outcomes in the selection chart, one can only focus on combinations that are compatible and show promise.

4.2 FMECA

Failure Modes Effects and Criticality Analysis (FMECA) is a systematic approach that tries to predict possible causes and failure modes on a component level. The criticality of these failures are assessed by quantifying the frequency and severity. Then different remedies can be suggested for the considered failures, or to test if the system is in a faulty state. This helps to select the design alternatives with the highest reliability and safety levels at an early phase in design. The FMECA is usually used during the design phase of technical systems to identify potential failures, but can also be used at a later phase to improve the system or for maintenance planning. A FMECA is more focused towards reliability than risk and includes failures more related towards reliability than events that can lead to harm, but when assessing the maintainability of a system these failure modes can be useful. The FMECA is a qualitative analysis, but there are a few quantitative elements, like failure rate and ranking of severity. The whole methodology of a FMECA is described in Rausand 2011 and Rausand and Høyland 2004.

The process described in Rausand 2011 starts with a break down of the system in to main functions and performance criteria. Thereafter one defines the operational performance criteria, including external factors like weather or internal factors like different fluxes in the system. Then one moves on to identify the potential failures and causes for the failures. After failures have been identified follows an evaluation of the consequences of the failure modes, an assessment of the risk, followed by suggestions for improvements or remedies. To help the team that is performing the analysis one can use a list of buzzwords to inspire the participants of possible failures. The buzzwords used during this FMECA are presented in Figure 7.

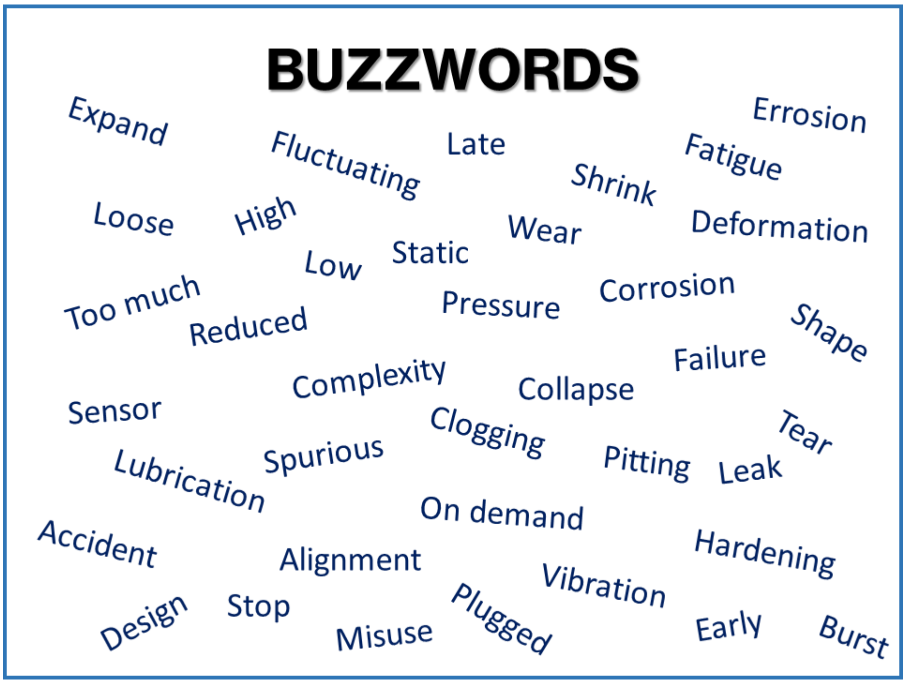
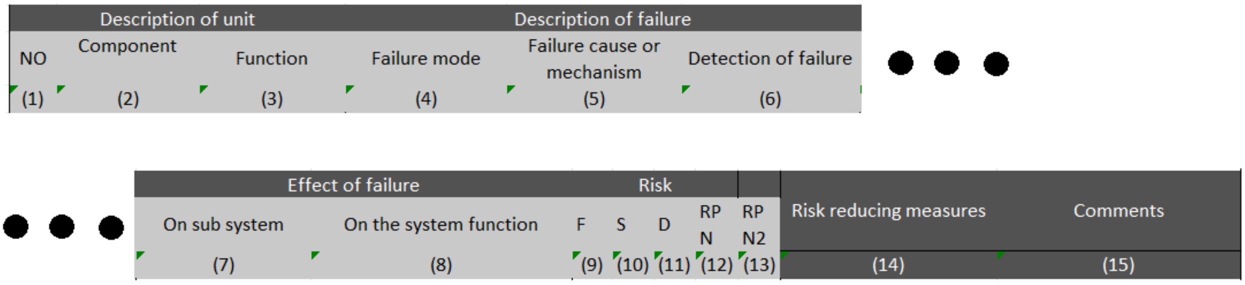


Figure 7: Compilation of buzzwords used during FMECA to set in motion the generation of possible failures

A FMECA is standardised in a tabular form, and some variations have extra columns after what is relevant to include. The first columns (1-3) are dedicated to describing the unit evaluated. The next columns (4-6) describes the failure mode, cause and how to detect the failure. Columns (7) and (8) explain the effect of the failure. Columns (9-13) report the risk by the use of semi-quantitative classes described in the assessment of risk section below. (9) is the frequency class, (10) is the severity class, (11) Is the detectability and (12), (13) are the Risk Priority Number (RPN) values. Column (14) and (15) are for risk reducing measures and comments, respectively. The column headers referenced are shown in Figure 8.



Description of unit			Description of failure			Effect of failure		Risk						
NO	Component	Function	Failure mode	Failure cause or mechanism	Detection of failure	On sub system	On the system function	F	S	D	RPN	RPN2	Risk reducing measures	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)

Figure 8: Column headers in the used FMECA sheet. The numbers in the parenthesis are for easy referencing to columns

4.2.1 Assessment of risk in the FMECA

To quantify and to rank the findings from the analysis one introduces the failure rate, severity ranking and the detectability of a failure mode. The Frequency classes are defined in Table 2 and is reported in column 9 in the FMECA worksheet. The severity classes are found in Table 3 and the detectability classes are found in Table 4. This creates a semi-quantitative aspect to the analysis and helps with ranking failures with sparse knowledge.

Table 2: Failure rate classes used in the FMECA

Frequency class	Rate	Failure rate [1/h]
1	Once per 1000 years or more seldom	$1.14 \cdot 10^{-7}$
2	Once per 100 years	$1.14 \cdot 10^{-6}$
3	Once per 10 years	$1.14 \cdot 10^{-5}$
4	Once per year	$1.14 \cdot 10^{-4}$
5	Once per month or more often	$1.37 \cdot 10^{-3}$

The severity classes are divided in four groups an are split in to three sub groups, safety, environmental and economical, the economical group includes loss of reputation. Table 3 reports the severity classes. The results are reported in column 10 in the FMECA worksheet, only the most severe consequence is reported. For the environmental damage the short term damage is considered as less than one year and the major damage is regarded as the area uninhabitable after the accident.

Table 3: Severity classes used in the FMECA

Severity class	Safety	Environment	Down time
1	minor injury or nuisance	minor nuisance	Less than a day
2	medical treatment	Short term minor damage	Less than one week
3	permanent disability	Short term major damage	Less than a month
4	one fatality	Long term minor damage	Less than half a year
5	several fatalities	Long term major damage	More than a month

The detectability is classified in five classes, where 1 is close to immediate detection and 5 is that the failure is normally not detected. The exact division is summarised in Table 4.

Table 4: Detectability classes used in the FMECA

Frequency class	class (failure rate [1/y])	Detected by
1	Instant	Stop in production
2	30 minutes to 24 hours	Sensor reading
3	24 hours to one week	
4	One week to one month	Inspection
5	Longer than one month	Not detected by inspection

The RPN is defined as the sum of the frequency class, severity class and the detectability class. This summarises the failure to one number and the most relevant failures can be singled out for further analysis. In addition has RPN2 been defined this is the sum of frequency and severity.

4.2.2 Estimation of total downtime

To estimate the total down time for a few factors are summed up depending on how the failure is detected, where the component and the spare are located and how long the Active Repair Time (ART) is. For the failures found in the OREDA database (See section 5.1) is this the recorded ART, but for failures not found is this estimate either based on similar components and failures. The time estimates are presented in Table 5. The ART and several other terms related to phases of running an equipment and its state is defined in Figure 9. From here we can see that ART is only the time actively used for repairs, not including the time spent on preparations, delays or startup/shutdown.

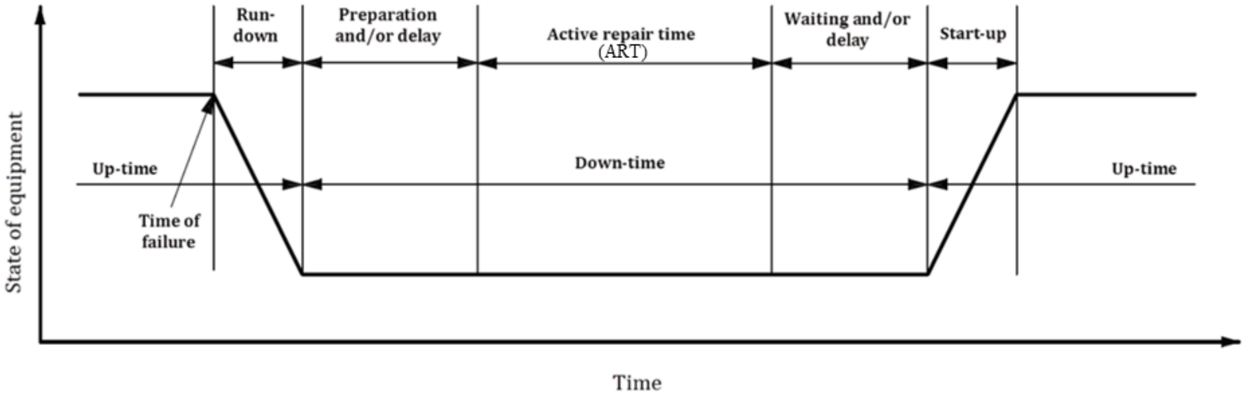


Figure 9: Definitions of terms related to downtime. Figure adopted from Figure 4 in Norsk Standard 2016

Table 5: Time added for repairs

Activity	**Duration**	
Detection of failure	Complete failure	Instant
	Sensor reading	30 minutes
	Inspection	1 month
Preparation	Diagnosis	1 hour
	Planning of routine failure	30 min
	Planning of rare failure	4 hours
Logistics	Spares at site	1 hour
	New spare from land	1 week
	Hoisting to seabed	30 min
Waiting on weather	Spare stored subsea	0 hours
	Summer	0 hours
	Winter	1 week
Active repair time	Depends on failure	
Wrap up	Inspection, etc.	2 hours

5 Data

5.1 OREDA

The OREDA project is a data bank of reliability data from onshore and offshore operations collected from several industry partners. The project was initialised in 1981 and has generated a comprehensive data bank. For this thesis the OREDA handbook for subsea equipment was used, specifically the 6th edition that was issued in 2015.

The data in the handbook is generalised and the component descriptions are generic without information about where the data is from and how the component is installed.

5.2 Loki's Castle

The example case for this thesis uses the environmental conditions around the Loki's Castle hydrothermal vent field. This vent field is located at approximately 2400 meters depth north-east of Jan Mayen in the Norwegian EEZ along the Mid-Atlantic spreading ridge at the coordinates of 73°N and 8°E. The field consists of four active black smoker chimneys. Around the venting area two 20-30 meter high and 150-200 meters wide sulphide mounds have developed (Pedersen et al. 2010).

The arctic waters and remoteness of the location bring several challenges to a potential operation. Areas around mid ocean ridges are associated with seismic activity. The registered earthquakes in the area around Loki's Castle with a magnitude greater than 4.5 in the period of 1960-2021 are shown in Figure 10. Earthquakes are important to consider due to the environmental load it imposes on the surrounding areas and has a destructive potential.

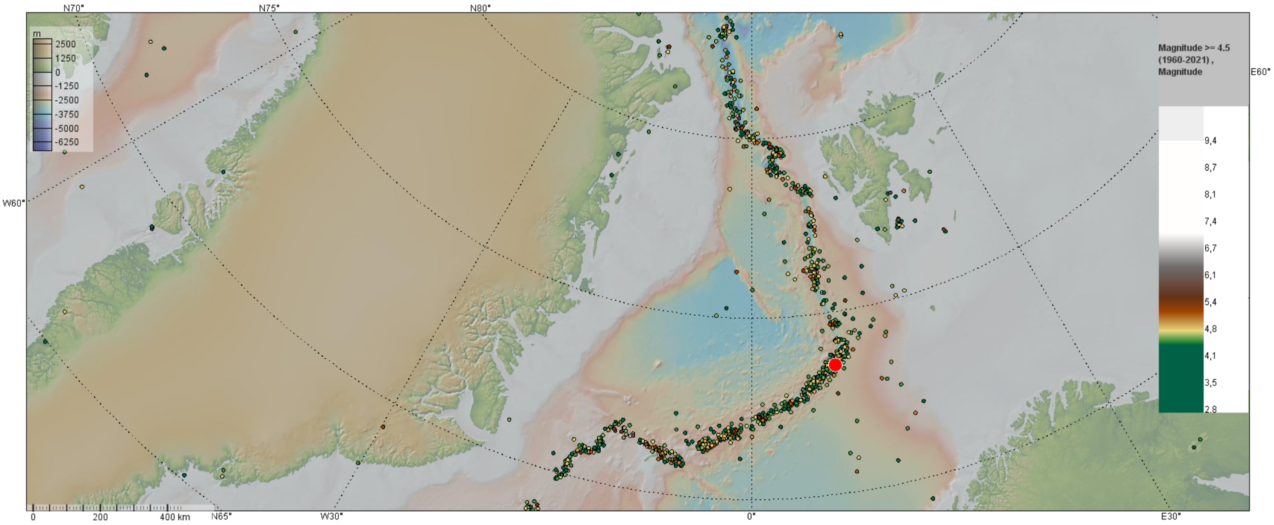


Figure 10: Registered earthquakes around Loki's Castle (Marked in red). Figure courtesy: GeoMapApp (www.geomapapp.org) / CC BY (Ryan et al. 2009).

5.3 Weather data

The weather data used in this thesis is based on the report "Knowledge of wind, waves, temperature, ice and visibility in the area of Jan Mayen" (Norwegian title: Kunnskap om vind, bølger, temperatur, isutbredelse, siktforhold mv. - "Jan Mayen"). The report was prepared by the Norwegian Meteorological Institute at the request of The Norwegian Ministry of Petroleum and Energy, on the occasion of opening the area for oil and gas activity. The report contains data on wind, waves, temperature in air and sea, probability of icing, visibility and polar lows. This report also includes the observed trends in the data. The data is based on hindcast data from the period of 1958 to 2011. The report concerns six locations, none exactly at the location of Loki's Castle vent site, but the available weather data for this area is generally sparse. Given that the design is at an early phase and that this is in the open ocean, the accuracy is considered to be sufficient for the Loki Castle site. The closest data point in

Iden et al. 2012 is on the west side of the island (71° 00N,09°85W), while Loki's castle is north-east of the island(73°33N,08°09E). For a full design study one should consider getting more accurate data from said location, but the weather is expected to be comparable for this position. The Report contains data about wind, waves, visibility and ice. The measured wind, wave and temperatures for this location are summarised in Table 6. The Probability of significant wave height (H_s) exceeding 2m is plotted in the maps in Figure 11. In the Figure one can see that in January the probability of H_s being higher than 2 meters exceeds 80%, while in the summer it is 12%. The significant wave height is defined as the average value of the top third highest waves.

Table 6: Summary of measured weather data at location 71°00N,09°85W. Data from Iden et al. 2012

Maximum wind	30.4 m/s from 33°
Maximum wave	$H_{s,\,max}$ = 13.8 m, $T_{p,\,max}$ = 14.9 s
Return year wave	1y= 9.0 m, 10y = 11.8 m, 100y = 14.3 m
Temperature air [°C]	max = 9.4, min = -27.6
Temperature sea [°C]	max = 10.5, min = -1.7

Traits of the arctic weather is during the summer months the areas with open water are often covered in fog, while October to April are affected by polar lows. These polar lows are dreaded because they are small but intense low pressure systems are generated over a short time frame, winds are known to increase from breeze to storm in a matter of minutes and the wave height has been measured to increase with five meters in an hour. An effect of this weather is dense snow showers with low visibility and ice freezing on the vessels affected by the storm. Because the polar lows appear in areas with few observations and the small size of the weather system compared to the resolution of the forecasting in the area, there is little knowledge on how to predict them (Iden et al. 2012). Figure 12 shows where the registered polar lows have been formed, with the sea surface temperature plotted. For marine operations the visibility is an important factor to consider. The Norwegian Meteorological Institute defines fog as visibility lower than 1 kilometer. The observations are made at the manned station on Jan Mayen and July is the month with the most fog (fog for 20% of the time), whereas the rest of the year experiences foggy conditions between 7-14% of the time. The reduced visibility can be a challenge for spotting icebergs and drifting objects or marine traffic in the area.

The sea in this area can be fully or partially covered in sea ice. There are two main mechanisms creating ice in the waters around Jan Mayen; cold surface waters from the eastern parts of Greenland driven towards Jan Mayen, called “Odden istunge” (Odden Ice Tongue), and prevailing western winds driving the pack ice from the eastern coast of Greenland to the east. The occurrence of the “Odden istunge” becomes more rare with the climate change. Figure 13 shows the maximum spread of the ice cover for the years 2001-2011 (Iden et al. 2012) This cut out does not cover the location of Loki's castle, which is located to the right of the frame on 73°N. From this one can see that the area of Loki's Castle is rarely covered in ice, but there is a possibility that pieces of ice drifts into this area.

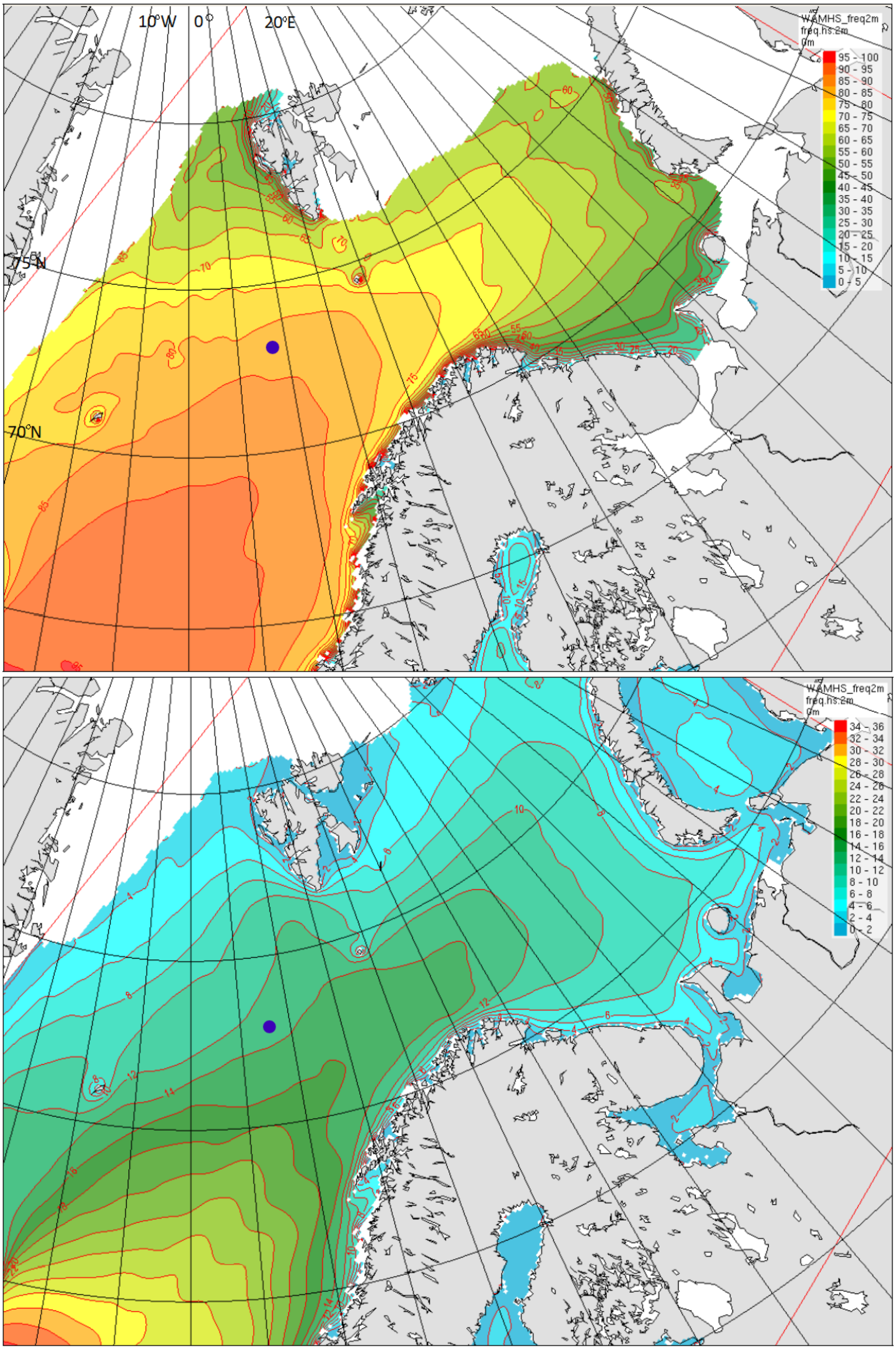


Figure 11: Probability of H_s exceeding 2 meter. Top Figure January, bottom Figure July. Location of Loki's Castle marked with Blue. Adapted from Iden et al. 2012

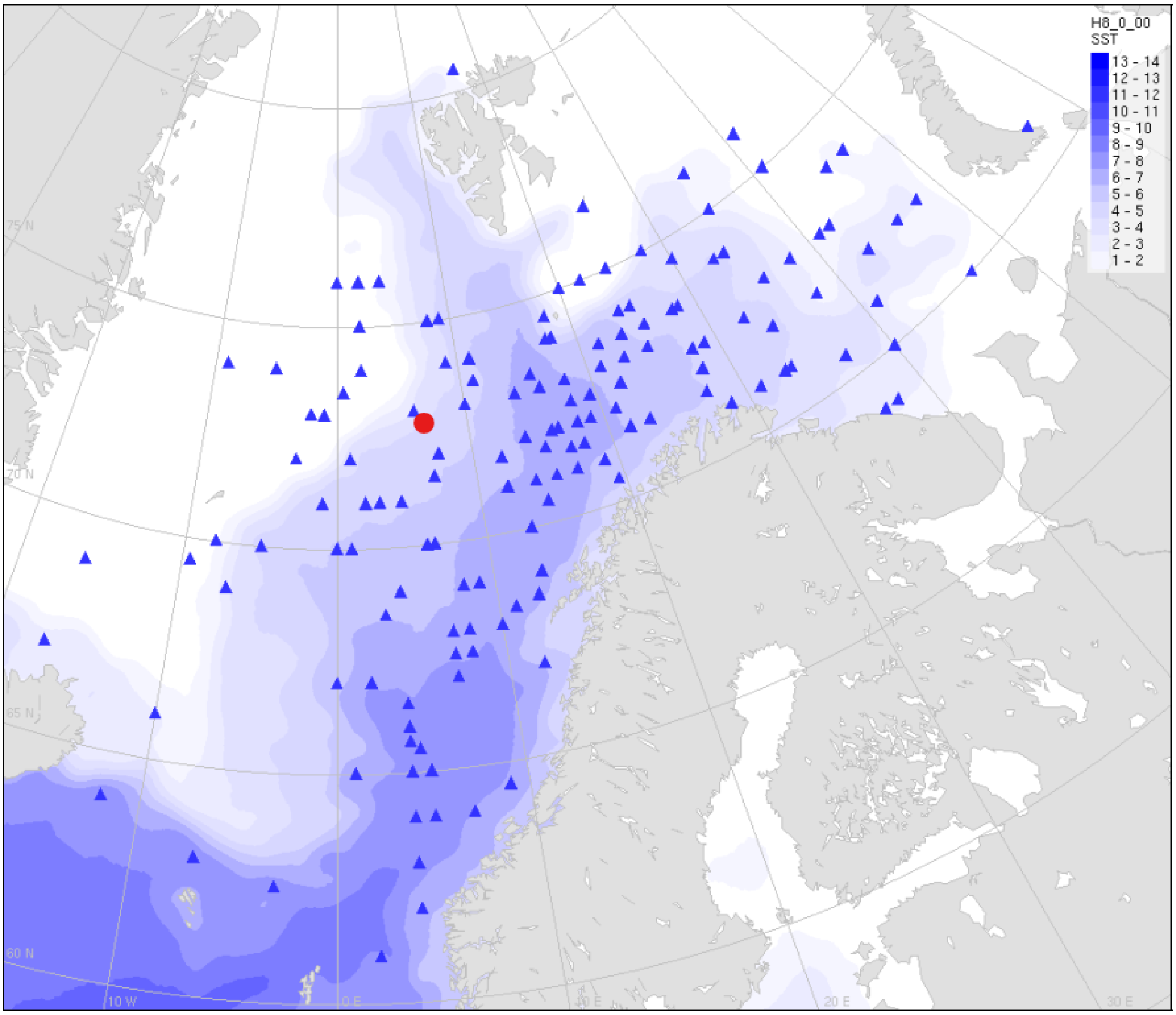


Figure 12: The registered point of formation of polar lows in the period of 2000 to 2012, 116 in total. The scale shows the temperature of the sea surface in degree celsius. Location of Loki's Castle marked with Red. Adapted from Iden et al. 2012

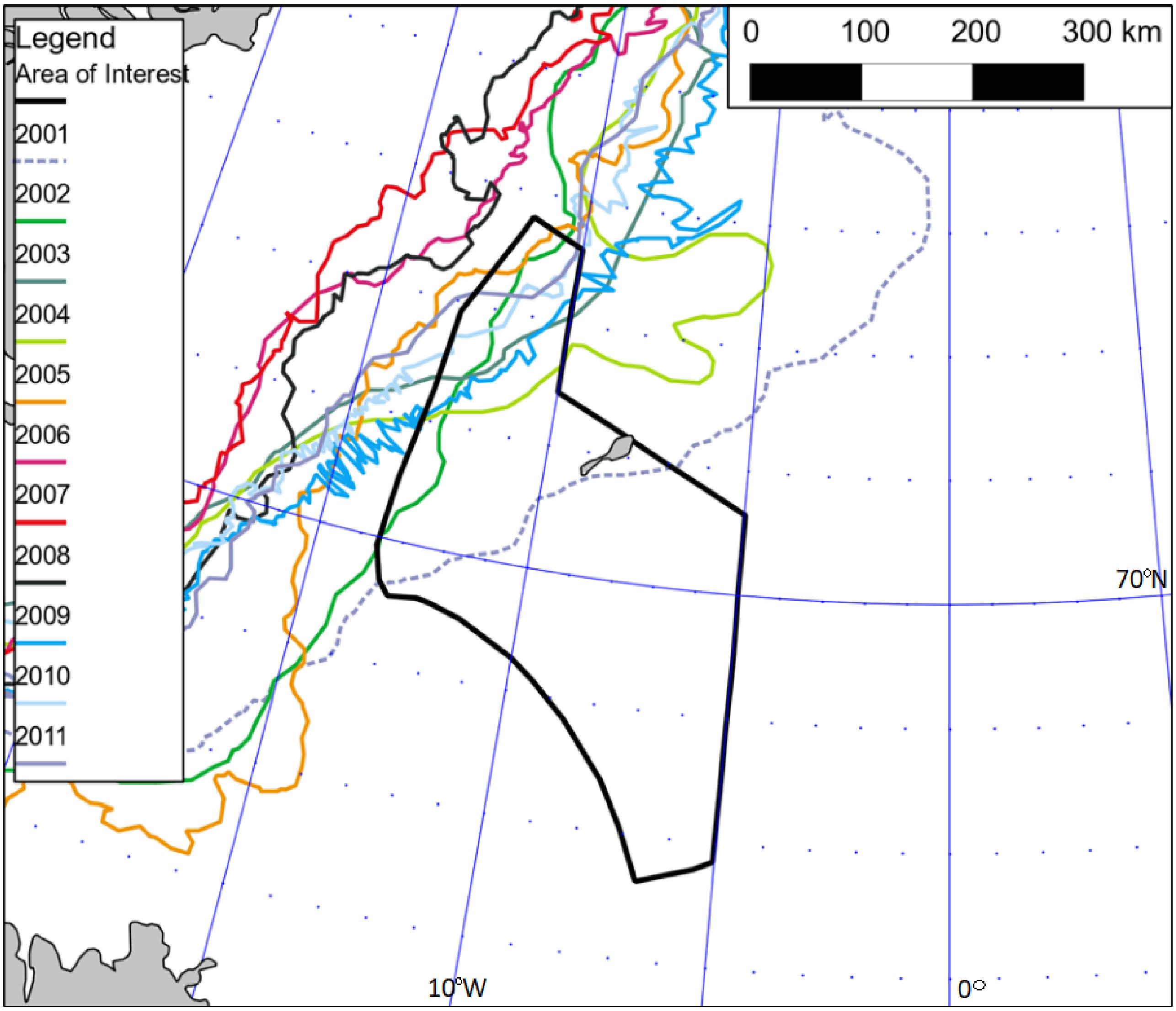


Figure 13: The yearly spread of sea ice in the years of 2001-2011. The years are drawn with dissimilar colours. Adapted from: Iden et al. 2012

6 Results

6.1 Assumed layout of the operation

The subsea operations are assumed to have a layout similar to the NAUTILUS operation although the NAUTILUS layout is mostly treated as a black box. The slurry is pumped from the collecting unit to the Subsea Slurry Lift Pump (SSLP) trough a flexible jumper. The slurry is then pumped to the surface vessel trough the lifting solution suggested below.

The surface support vessel is assumed to hold its position by the help of dynamic positioning to avoid the process of mooring the vessel and anchor lines running trough the work area.

6.2 Concept design

Before designing a system one has to establish what task the system is to perform. For the lifting system it has to lift the mined ore from the seabed to the SPV in a safe and reliable manner. The results from the process described in 4.1 are presented below.

6.2.1 Requirements list

By the process described in section 4.1.1 and the check list on page 149 in Pahl et al. 2007 has the requirements in the following list been identified. The (D) and (W) in the brackets indicate if the requirement is a demand or a wish.

REQUIREMENTS LIST

Geometry	(D) Able to transport the entire distance from the seabed to the surface
Kinematics	(D) Velocity of ore high enough to be lifted
Forces	(D) Pressure for depths of 3000 meters of water
	(D) Buoyancy and self-weight
	(D) Environmental forces (waves, wind and currents)
	(D) VIV and VIM resulting from environmental forces
	(D) Resonance loads
Energy	(D) Enough energy to lift the ore
	(D) Overcome the friction and losses in the system
Material	(D) Design life of 10 years
	(D) Corrosion resistant in marine environment
	(W) Withstand possible abrasive ore
	(W) Design for significant fatigue loads
Signals	(W) Control signals from SPV
	(W) Monitoring signals/stream from system
	(W) Positioning
	(D) Underwater communication

Safety	(D) Position monitoring
	(W) Accelerometers
	(W) Disconnectable from SPV
	(W) Leak monitoring
	(D) Controls at surface
Ergonomics	(W) Operable from control room
	(W) Intervention by crane or underwater vehicles
Production	(W) Minimise offshore installation operation
	(W) Easy to transport from factory to site
Quality Control	(W) Ore quality test
	(W) Slurry mix
Assembly	(W) Minimal offshore assembly
Transport	(D) From onshore production to site
	(W) Between mining sites
Operation	(W) Minimal Noise and vibrations
	(W) design for approximately one year operation at a site
Maintenance	(W) Long maintenance intervals (6 months)
	(W) Inspections by ROV
	(W) High availability of spares
Recycling	(W) Minimal environmental impact from materials and life cycle
Cost	(W) Low manufacturing and transportation costs
	(W) Low operational costs
	(W) Low decommissioning costs
Schedules	(W) Seasonal considerations
	(W) Remote location

By the process of abstracting and broadening the problem formulation was a the following function defined: *Lift slurry from seabed to surface vessel.* With this in mind was the following sub-functions identified:

A Contain slurry

B Move slurry

C Positioning in harsh environment

D Receive slurry

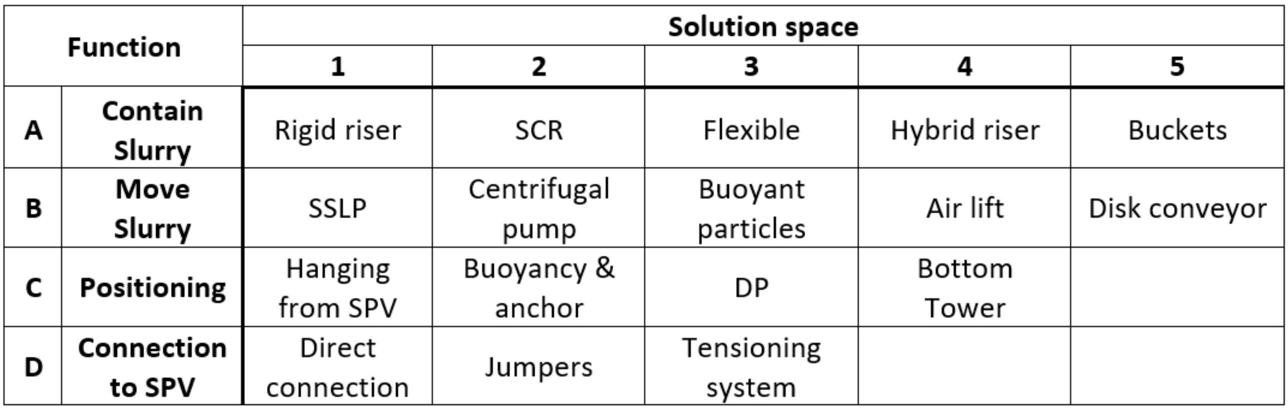
With the defined functions in mind the requirements list was analysed by using the steps described in section 4.1.2 and page 165 in Pahl et al. 2007 was the final problem formulated: *Lift the slurry from a deep seabed to the surface in areas with harsh environmental loads.* The design continued by searching for solutions of the sub-functions, the following was identified and some advantages and disadvantages are listed in Table 7.

Table 7: Possible solutions of sub-functions of lifting slurry from seabed to surface

SV	Solution	Strengths	Weaknesses
A1	Rigid riser	Cost efficient Installation by derrick	Low significant wave height Bottom installed SPV or free hanging Low dynamic response
A2	SCR	Mature technology Cost efficient J-lay installation	Severe bottom impact Installation time Distance from site Medium dynamic response
A3	Flexible Riser	Flexible installation layout High dynamic response	High cost per metre High self-weight Bottom infrastructure Limited inner diameter
A4	Hybrid riser	Flexible riser layout High dynamic response	Bottom infrastructure Inner diameter limited by jumpers
B1	SSLP	Possible to power by RW	Volume flow not dependent on density Subsea location of pump
B2	Centrifugal	Off the shelf	Volume flow dependent on density Subsea power transmission
B3	Buoyant particles	Few subsea components	Cleaning and wear of particles
B4	Air lift	Few subsea components	Isothermal air expansion
B5	Disk conveyor	Can handle variations in slurry mix	Long mechanical lift Low lifting speed
C1	Hanging off SPV	Riser follows SPV Low bottom impact	Riser and SPV motions are coupled
C2	Anchored with buoyancy	High reliability Decoupling SPV motions	Stationary Bottom impact
C3	DP	Mobile Low bottom impact Decoupled motions	Energy consuming Underwater positioning
C4	Bottom standing	Decoupled motions from SPV	Weight on seabed Stationary
D1	Direct connection	Simple	Direct coupling of motions between riser and SPV
D2	Jumpers	Decoupling of riser and SPV motions	Riser not hanging of connection
D3	Tensoning system	Low stress in riser	Stroke length limits maximum design load

These sub-solutions create several combinations that can be possible solutions for the function of lifting the slurry from the seabed to the surface, creating the solution space presented in Table 8

Table 8: The solution space created by the identified sub-solutions of lifting slurry from seabed to surface



Function		Solution space				
		1	2	3	4	5
A	**Contain Slurry**	Rigid riser	SCR	Flexible	Hybrid riser	Buckets
B	**Move Slurry**	SSLP	Centrifugal pump	Buoyant particles	Air lift	Disk conveyor
C	**Positioning**	Hanging from SPV	Buoyancy & anchor	DP	Bottom Tower	
D	**Connection to SPV**	Direct connection	Jumpers	Tensioning system		

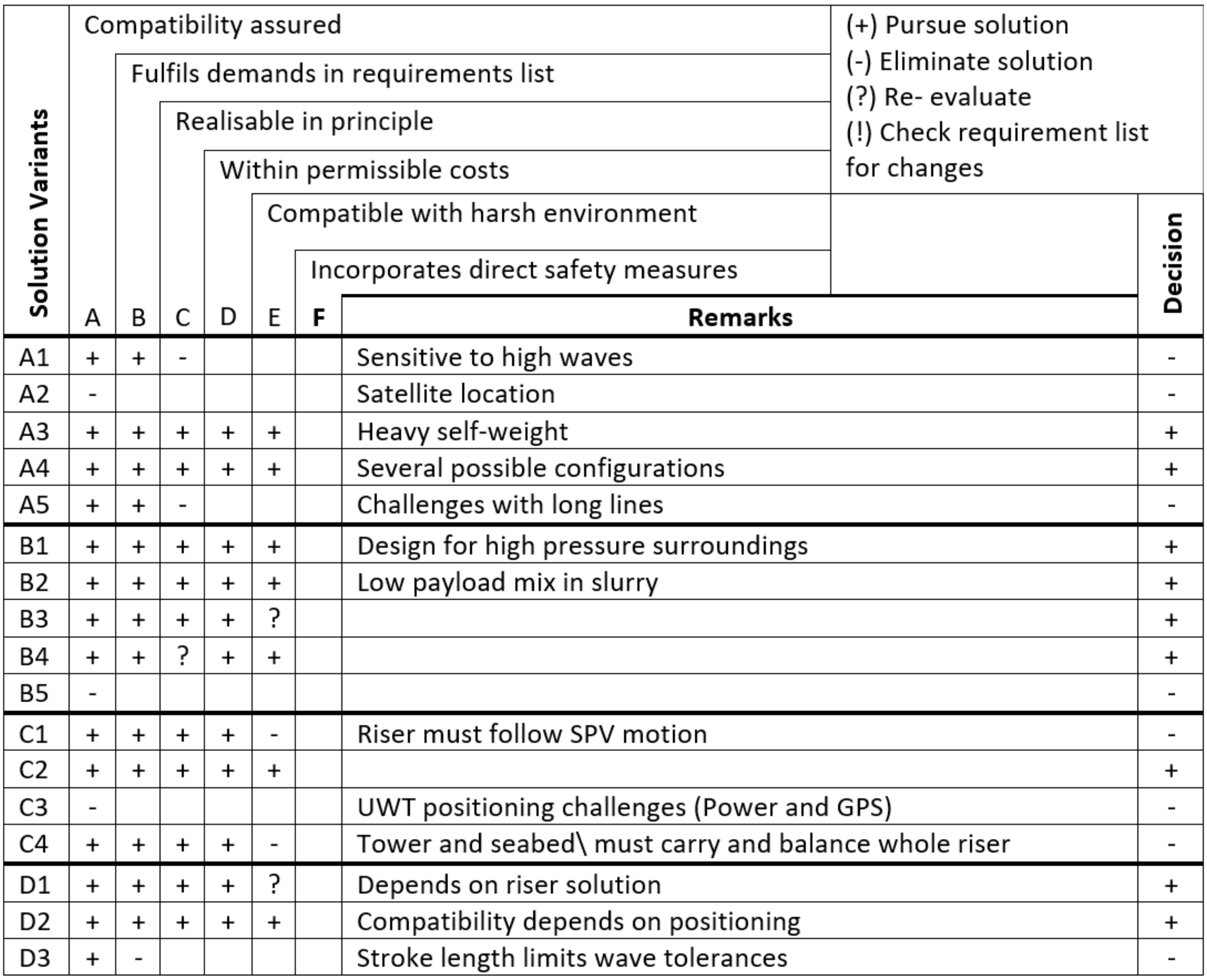
The sub-solutions can be further evaluated by using a classification scheme to identify solution concepts to further elaborate. The evaluation scheme produced is presented in Table 9.

From the scheme presented in Table 9 we can see that A3 and A4 are the most suitable riser configuration, but due to that hybrid risers in general have shorter line length than the flexible riser configurations, is the hybrid riser solution further pursued. The line length is important to reduce the friction losses during transport. For the hybrid risers the anchoring with buoyancy is the most suitable means of positioning and jumpers for connection between the rigid tower and the SPV. A sub-solution that is not clear from the classification scheme is how to move the slurry, because all the hydraulic alternatives are deemed as viable options. Hence the hybrid riser solution is further developed and the next step is to decide whether to design with a PD pump, centrifugal pump, solid buoyant particles or with an air lift. The next step in the design is to develop a higher level of detail for the lifting solutions. The needed infrastructure around the lifting concept discloses other challenges or advantages.

Figure 14 was compiled to clarify the needed infrastructures and different flows one will have by the different lifting concepts. This is helpful for further choices of lifting methods.

In Figure 14 one can see which of the lifting concepts can utilise the return water and what needs to be transported trough the water column and the state in which it is transported. These four concepts are all considered suitable for lifting and compatible for the hybrid riser configuration. For the final suggested design the following considerations have been made: the centrifugal pump is discarded because the need for a high power electric cable to be pulled from the SPV to the pump in the bottom of the riser. The SBP concept is discarded because of uncertainties of a potential spillage and because the required recovery rate of the particles is impractically high. The Air lift concept is discarded due to the challenges of the expanding air. All these challenges are possible to solve if one continues the design, but the positive displacement pump driven by the pressurised return water is currently the most complete design, and is chosen for the FMECA analysis.

Table 9: Classification scheme produced from the suggested sub solutions of lifting slurry from seabed to surface



A Compatibility assured
B Fulfils demands in requirements list
C Realisable in principle
D Within permissible costs
E Compatible with harsh environment
F Incorporates direct safety measures

(+) Pursue solution
(-) Eliminate solution
(?) Re- evaluate
(!) Check requirement list for changes

Solution Variants	A	B	C	D	E	**F**	**Remarks**	**Decision**
A1	+	+	-				Sensitive to high waves	-
A2	-						Satellite location	-
A3	+	+	+	+	+		Heavy self-weight	+
A4	+	+	+	+	+		Several possible configurations	+
A5	+	+	-				Challenges with long lines	-
B1	+	+	+	+	+		Design for high pressure surroundings	+
B2	+	+	+	+	+		Low payload mix in slurry	+
B3	+	+	+	+	?			+
B4	+	+	?	+	+			+
B5	-							-
C1	+	+	+	+	-		Riser must follow SPV motion	-
C2	+	+	+	+	+			+
C3	-						UWT positioning challenges (Power and GPS)	-
C4	+	+	+	+	-		Tower and seabed\ must carry and balance whole riser	-
D1	+	+	+	+	?		Depends on riser solution	+
D2	+	+	+	+	+		Compatibility depends on positioning	+
D3	+	-					Stroke length limits wave tolerances	-

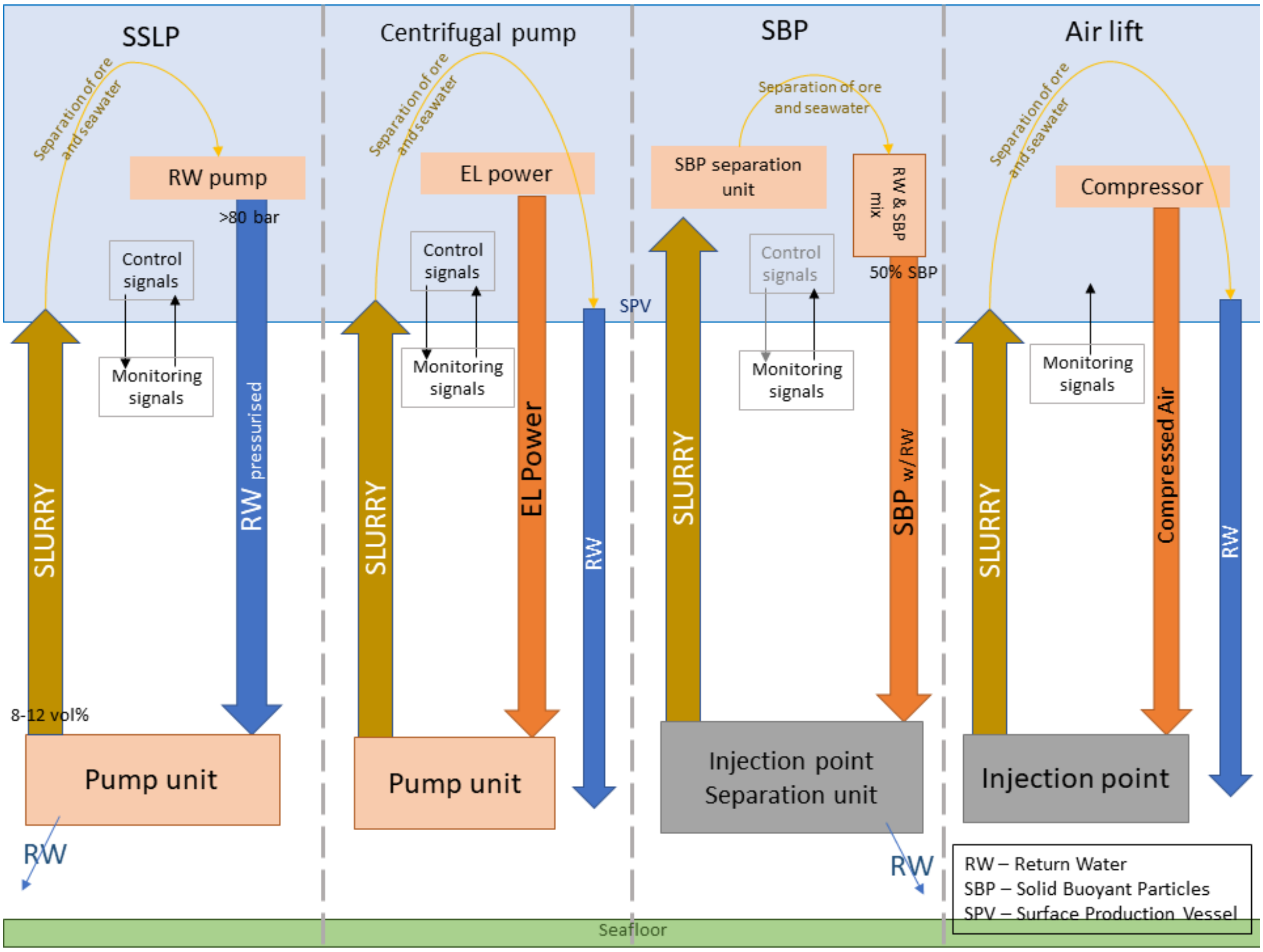


Figure 14: Illustration of what is transported trough the water column for the different lifting concepts

6.2.2 Further details for the final design

Given that the parameters are not set around the operation, there is no basis to set requirements for the production rate and direct economics of the operation. Hence, has several production parameters have been adopted from the NAUTILUS SOLWARA 1 project described in Jankowski et al. 2010. The project uses the same type of pump for lifting, therefore the slurry parameters have been set equal. Table 10 summarises the parameters set. Some of the parameter values are later chosen for discussion. It is assumed that the NAUTILUS concept was a working concept even if the full system never was tested.

Table 10: Gathered parameters for production

	Value	Source
Production parameters		
Production rate	1.8 Mtpa	Jankowski et al. 2010
Mining power	13.8 MW	Jankowski et al. 2010
Design life mine	3-5 years	
Design life System	10 years	
Site specific		
Design depth	2400 m	Pedersen et al. 2010
Slurry		
Nominal pumping rate	1000 m^3/h	Jankowski et al. 2010
Nominal volume density	12 %	Jankowski et al. 2010
Instant min/max vol%	0/20 %	Jankowski et al. 2010

The suggested solution is to make the riser a bundled free standing riser. This is recommended to decouple the riser from the ship's motions. This also provides the opportunity to disconnect the production vessel from the riser when the environmental conditions become extreme. This suggestion is a modification of the Nautilus system, where the concept for lifting is similar to a subsea slurry lift pump driven by the pressurized return water, but the riser configuration is adopted to handle more relative motions of the surface vessel and the riser. The riser tower is a rigid steel pipe with buoyancy elements in the top and is anchored to the seabed with a taut mooring. The connection to the subsea production unit and the floating production vessel is by flexible jumpers because the rigid pipe's upper end is at 100-200m depth, where the wave loads have dissipated significantly. To reduce operations in the splash zone and to reduce offshore installation time it is suggested to assemble the riser onshore and transport it using controlled depth tow, then turn the riser underwater and moor it to a pre-installed anchor. This riser will be welded onshore and no connections are needed in the riser tower. An argument to choose a free standing riser versus a flexible riser system is that there are no bends in the rigid riser, leading to less resistance for the slurry pumping. Also, the riser is capable of carrying the SSLP. This concept also frees the surface production vessel from the riser, and makes the area around the riser more accessible for subsea interventions. Because the SPV is not carrying the pipe, means that the rigid riser section will not affect the carrying capacity of the SPV.

The mobility of such a layout will depend on the anchoring solution, the ability to control the buoyancy and the ability to tow the riser assembly. For shorter distances it might not be necessary to flip the riser horizontally during moving.

Figure 15 shows a concept drawing of the suggested system

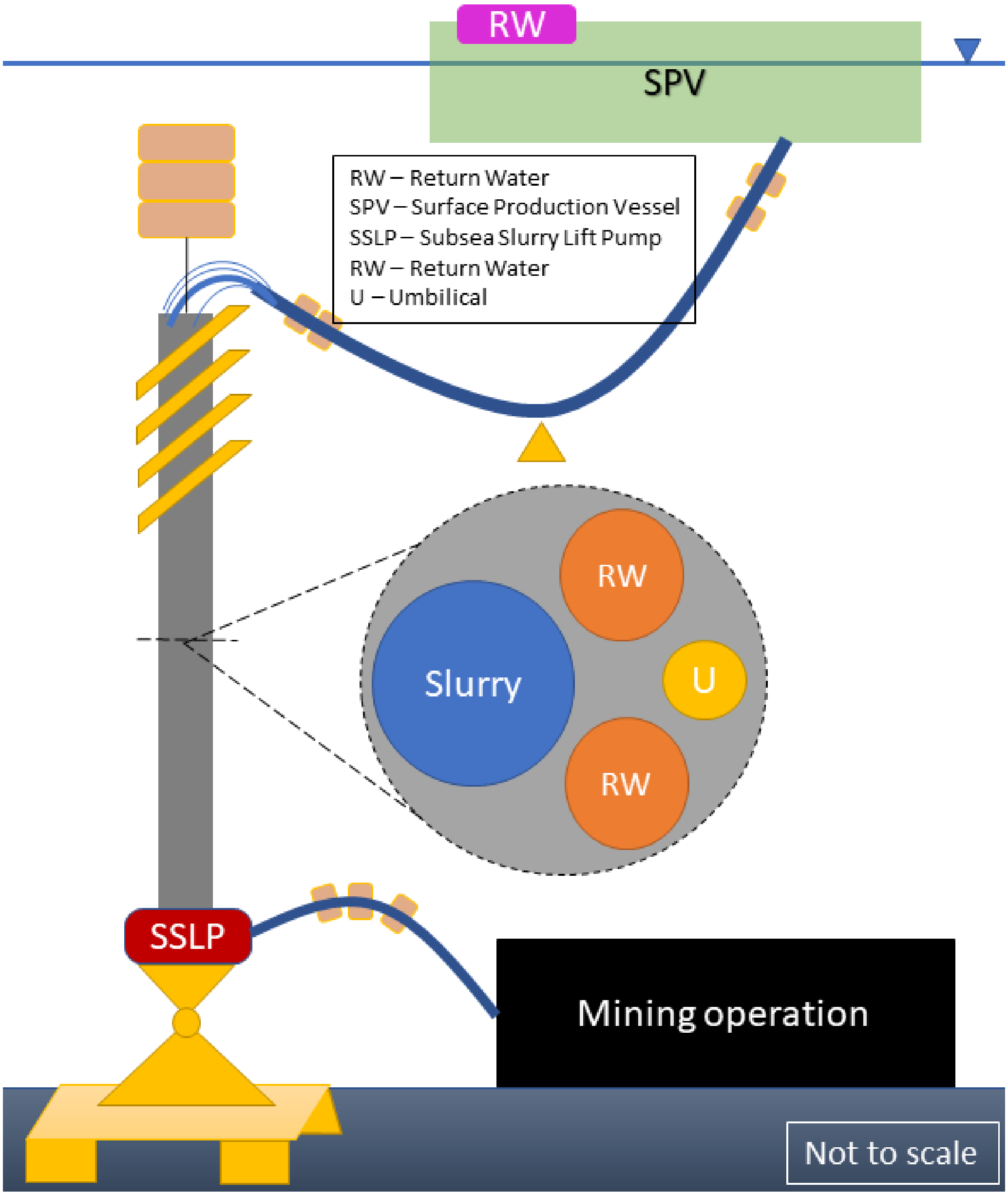


Figure 15: The suggested riser and lift system

6.2.3 Component descriptions

The components are grouped into the following groups: Surface equipment, equipment in the water column and subsea pumping. The equipment needed for mooring including the components needed for the towing are neglected from the following FMECA analysis. The reason for this division is to introduce the system and make the analysis more manageable and readable. The components and their groups are listed in Table 11. Since this is at an early design phase where specific components are not chosen, some components will have greater details in selection than other components. The subsystem's and component's function is written in *italic.*

Table 11: Specification of components in FMECA analysis, The sub system's function and the component's functions are written in *italic.*

[1] **Surface equipment**

Safe surface interaction and connection with lifting equipment
Return the water from the slurry with enough pressure to run the SSLP

NO	Component	Specifications
1.1	Jumper bundle [2] to SPV	*Connection of riser tower to SPV, with a safe and complete transfer of slurry, RW, power and control signals* All lines to the riser tower gathered in a carry pipe to ease connection and disconnection, while protecting the individual pipes An unbounded jumper for flexibility Extra wear in bends of slurry/RW jumper
1.2	Buoyancy [1.1] jumpers	*Provide correct shape to [1.1] jumper bundle* Buoyancy on [1.1] jumper to create the correct shape to [1.1] Solid buoyancy elements adjusted to the jumper length and desired shape.
1.3	Weight [1.1] jumpers	*Provide correct shape to [1.1] jumper bundle* Solid weight elements adjusted to the jumper length and desired shape.
1.4	Connections to jumpers	*Create a tight seal that is re-connectable* Standard jumper connections must be leak proof and capable of connection/disconnection Sealed when not connected
1.5	RW Pressure pump	*Provide pressurised RW at desired rate and pressure* Mounted on the SPV Sufficient power to run SSLP (enough pressure at desired volume flow Runs on mix of filtered water from the lifted slurry and seawater form the surface

[2] **Water column**

Connect signals and transport slurry and RW trough the water column
in a safe and environmental sound way

NO	Component	Specifications
2.1	Carry pipe	*Support the bundle* Onshore welded connections
2.2	Slurry pipe	*Contain the pumped slurry at the correct pressure* Uncertain wear rates
2.3	RW pipe	*Return seawater in the slurry at correct pressure and rate to power the SSLP* Onshore welded connections

2.4	Umbilical to [3] (SSLP)	*Send control signals between SPV, SSLP and sensors*
2.5	Guides for riser bundle	*Hold the pipes inside [2.1] in place*
2.6	Buoyancy element	*Tension the riser in the water column*
2.7	Strakes	*Reduce VIV* Mostly needed on upper part of riser

[3] **Subsea pump**

Pump the slurry to the surface vessel

NO	Component	Specifications
3.1	Pump casing	*Contain, hold and protect the pump assembly*
3.2	RW connection	*Tight pressurised connection* Connect to [2.2]
3.3	Slurry connection	*Connection to riser [2.2]* Needs sufficient diameter to not slow down the flow
3.4	Pressure chambers	*Contain and pressurise the slurry* withstand several internal pressure cycles
3.5	Hydraulic act. valves	*Flow control* Must be able to cut the sediments to ensure a proper seal
3.6	Control system	*Control the flow* reduce pules in the flow
3.7	Jumper to collector ROV	*Transport slurry from mining site to riser* Length depends on distance to deposit Flexible jumper

6.2.4 Different life phases for the riser system

Through the life time of a riser system it will have different functions and require several support functions. For the FMECA analysis only the operational phase has been considered, which includes startup, running, shutdown and standby. Initially the towing phase and decommissioning phase were considered, but there were discarded from the FMECA to reduce the scope of the FMECA and keep the focus on the operational phase.

Since a controlled depth tow is suggested for the transportation out to the field, the entire riser assembly can be assembled onshore with the pump and jumpers connected to the riser. This will reduce the riser assembly time offshore to the turning and connection of the riser.

When the tow of the riser has arrived at the site the anchoring has already been installed and ready for connection. Before the riser is ready for the connection it has to be flipped 90 degrees. This can either be done by pumping seawater in or out of ballasting compartments or by installing buoyancy elements. As this is an underwater operation, the ballasting solution is considered the most practical. But one has to ensure that environmental regulations are complied with and this might be done by leaving the tanks open during the tow, allowing circulation of sea water. Alternatively one has to actively change the water during towing. The mooring is connected with lower buoyancy than during operation mode and tensions the assembly by increasing its buoyancy. The weight of the riser will vary depending on if it is filled with seawater or slurry. This has to be accounted for when sizing the buoyancy and the moorings. After the riser is anchored one can start to connect the jumpers, piping, cables, umbilical, etc. to the riser from the SPV and connect the jumpers to the gathering device. The riser is to be filled with water during the tow and during standby, hence the problem of buckling due to external pressure is not of concern. There should be a visual inspection before and after the towing operation and after the installation to make sure that the system is in good condition.

When the riser is installed it is ready to start lifting the slurry. It is likely that there will be several standby periods between lifting periods, this will depend on the production rate at the mining site and the environmental conditions at the surface.

Deep sea mining at any specific location is expected to be of a relatively short duration as the equipment is transported to new sites. For the riser to be transported it needs to be released from the mooring and towed to a new location. It could be sufficient to tow the riser in a vertical position for shorter distances, but if it is moved longer distances it has to be flipped back in to a horizontal configuration for a controlled depth tow. During the tow the riser can vertices, which can lead to significant fatigue loads. The riser base has to be retrieved and installed at the new site before the arrival of the riser. Regulations for how to leave a site are still uncertain, but it is assumed that no equipment may be left behind and when the lifetime of the riser has ended the riser can be disconnected from the equipment on the site, flipped in to the towing position and towed to shore for refurbishment and re-use or recycling.

After the system has been installed it is ready for operation. There may be uncertainty around whether or not the mining rate matches the lifting rate of the system. The production rate of mined material will vary from site to site due to local variations in the deposits. But it is expected that the lifting solution lifts said volume faster than it is mined and the lifting system will have standby time, hence one might consider to gather ore in to piles for better utilisation of the lifting system when it is running.

The maintenance regime of the riser is expected to be seasonal given the harsh winter conditions in arctic waters. In addition one has the challenges of deep water operations and the remoteness of the sites. Worst case scenario of a breakdown can be that no slurry is lifted for a longer period, risking a long downtime period with corresponding financial losses. Opportunities for repairs are somewhat more difficult, harsh weather winter months and therefore it is advised to consider regular maintenance in the fall if winter operations are planned on the Riser And Lift System (RALS). It is recommended to design the system in such a manner that it allows for maintenance by a permanent residing ROV with available components to the RALS and is able to install the component without the need for surface operations. Thus only limited surface repair operations should be needed for the most common failures. The broken component(s) can be lifted to the surface when the conditions permit. This is an important issue to plan, because downtime is expensive and the potential number of breakdowns during the systems lifetime could be considerable. Accumulated downtime could be significant if one also has long periods of waiting on weather.

6.2.5 Potential costs of the operation

There are several uncertainties and parameters that can affect the costs of the operation. For downtime costs one has to consider what expenses are fixed and which depend on production volume, - again these will depend on the layout and structure of the operation and this will be site specific.

Comparing with the expenses that were predicted with the Solwara 1 project in Jankowski et al. 2010 one day of operating costs (OPEX) was 11,000 US$ Using the exchange rates from Norges Bank 2022 for the year 2010. This is equivalent to 66,550 NOK, and when accounting for Norwegian consumption price index this will equates to 84000 NOK for 2022 (Statistisk Sentral Byrå 2022). For the cost of downtime this cost has been assumed as the cost of one hour of down time, and the OPEX was with a contingency. The conversion to NOK is this regarded as a conservative estimate. There are a few reasons for choosing to use the Solwara 1 projects as baseline for the costs;

1. the layout of this operation is assumed to use the same mining equipment
2. transport barges are used to transport the ore to land
3. while the RALS and SPV needs to be adapted to arctic conditions, the SPV's power source will also have a significant impact on operating costs

Because of several unknown parameters the operating costs for Solwara 1 has been used. Not all costs are accumulated during downtime. Some costs will be "extra costs" during downtime and this is considered as the best estimate. Examples of these costs can be distance to shore, choice of fuel and environmental conditions.

6.2.6 Choice of logistic harbour

A brief discussion on where to ship the ore and land base is made. This was not considered a vital part of the design, but approximate sailing distances were required to make assumptions about the operation. Four sites were selected for consideration: Longyearbyen, Kirkenes, Hammerfest and Narvik. All of these towns are under Norwegian jurisdiction. Suggested sailing routes are shown in Figure 16 The gray points show the sites where hydrothermal activity has been recorded, and the black lines are the suggested sailing routes. The Geomapp App was used to find the total distance of each route. Route A is from Loki's Castle to Longyearbyen, route B is to Kirkenes, route C is to Hammerfest and route D is to Narvik. The tracks are plotted by hand and the true sailing distance might deviate slightly, but is considered negligible at this stage. Some qualities for the harbours are summarised in Table 12.

Table 12: Location and distances to alternative logistics harbours

	Longyearbyen	Kirkenes	Hammerfest	Navik
Location (dateandtime 2022)	78°13'N 15°38'E	69°43'N 30°02'E	70°39'N 23°40'E	68°26'N 17°25'E
Sailing distance [km]	582	941	616	850
Sailing time at 12 kn [h]	26.5	42.5	28	38.5

All the points used and the distances between them in Table 12 are included in appendix B. From the results in Table 12 Hammerfest was selected as the land base, due:

(a) to sailing distance

(b) its location on the mainland of Norway

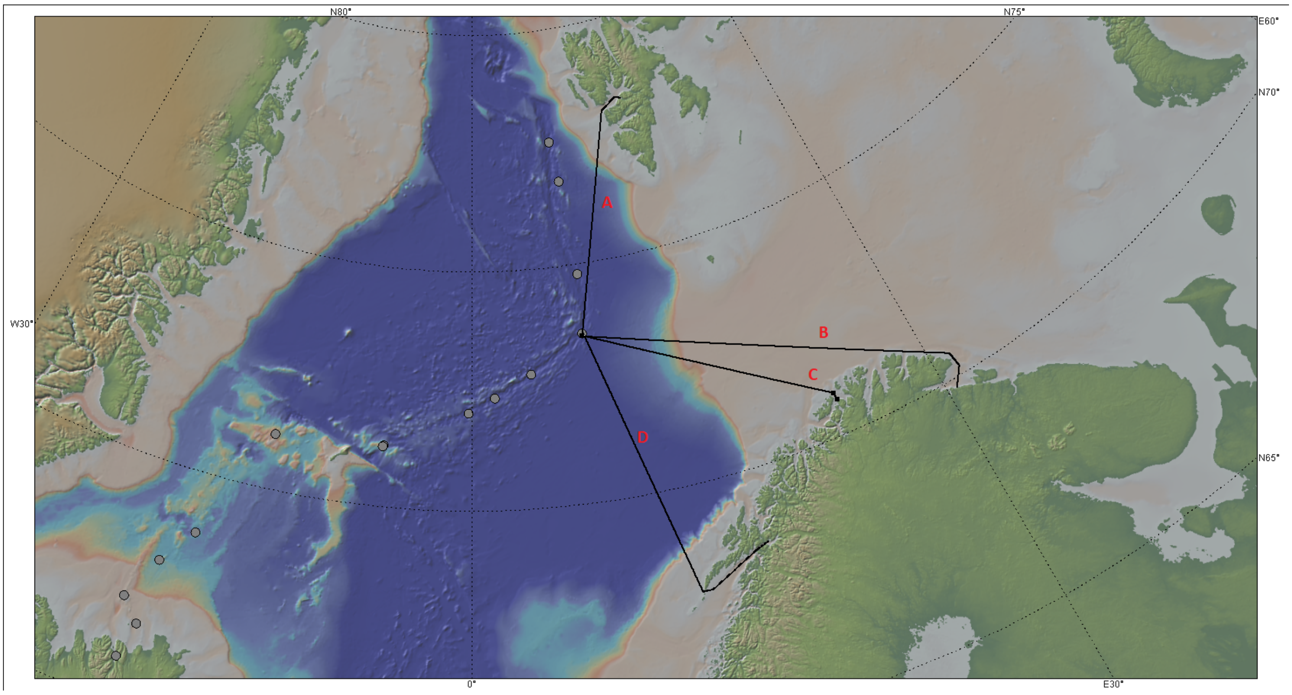


Figure 16: The suggested sailing routes to the selected cities considered as land base. Figure adapted from GeoMapApp (www.geomapapp.org) / CC BY (Ryan et al. 2009).

(c) the fact that logistics are simplified compared to a location on Spitsbergen.

For an unplanned mobilisation of a vessel it is assumed that it will take at least five days to deliver supplies to the mining site at Loki's Castle, 1 day in mobilisation, 1 day for loading, 2 days in transit (including contingency) and 1 day in unloading.

6.3 FMECA

Summaries of the downtime estimates are shown in Table 13. In the FMECA usually the shortest was used, the top one, except if it was assumed that the spares are stored onshore. Hence there are no additions from winter uses in the FMECA. The top entry marked "No surface operation" is the sum of the sub-operations needed for every repair without any delay, and is the value used in the FMECA unless the comments say otherwise. These are only generic estimates as the true repair times can deviate significantly from these estimates.

Figure 17 is a histogram of number of recorded RPN values. This shows the distribution of the RPN values. RPN = 9 was recorded the most, RPN = 6 the second most. No distribution is expected from a FMECA, due to its random nature, but Figure 17 shows the range of the resulting RPN values.

Figure 18 is a bar plot with all recorded RPN (in blue) and RPN2 (in orange). Note that the components are listed from the bottom up and only the component title is given, not the failure mode or cause. This plot is included to provide an overview of the results and to visualise any component requiring additional attention. In Figure 18 one can see that the RW pressure pump and the hydraulic acting valves has an overall low score, while in general, the pipes in the riser and connections are the most critical elements. The highest RPN score of 12 goes to the RW pipe and is the failure of fatigue due to density waves.

Table 13: Total added time used for repairs

Failure type	Operation	Duration
Sensor reading	No surface operation	5 hours
	Rare failure	8.5 hours
	Spare stored on SPV	5.5 hours
	New spare from land	125 hours
	Winter time	173 hours
Detection by inspection	No surface operation	736.5 h
	Rare failure	740 hours
	Spare stored on SPV	737 hours
	New spare from land	856.5 hours
	Winter time	904.5 hours
Instant detection	Spares at site	0-4.5 hours
	Rare failure	8 hours
	Spare stored on SPV	5 hours
	New spare from land	124.5 hours
	Winter time	172.5 hours
Equipment on SPV	Spare stored on SPV	2 hours
	Rare failure	8 hours
	New spare from land	122 hours
	Winter time (2 days)	50 hours

In total 106 failure modes were recorded from the FMECA analysis. Because of space considerations and readability only a few selected results are reported here in this section, whereas the full listing of results is attached in appendix C. The selected results from the FMECA worksheet are presented in Figure 19. Columns (2) and (3) have been left out and columns (14) and (15) merged. These failures will be commented in section 7.3 of the discussion. The numbering of the failures in column (1), named “NO”, is set in the following system:

1. The sub system the component belongs to
2. The component number
3. The failure number of the component

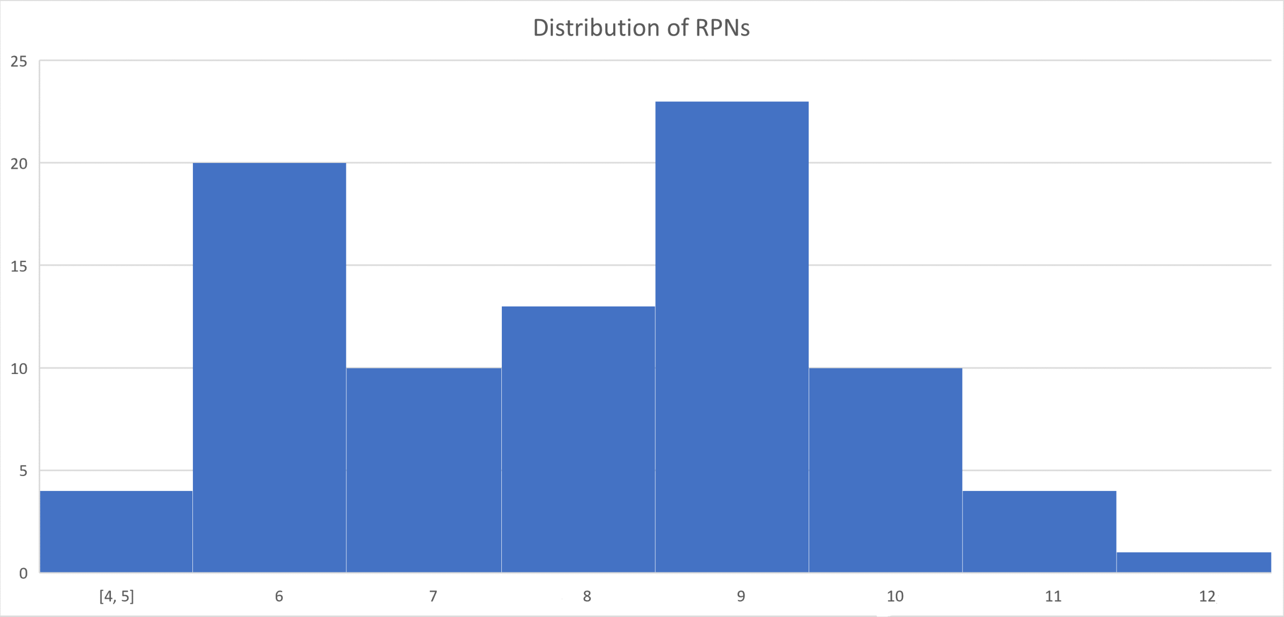


Figure 17: Histogram of recorded RPN values

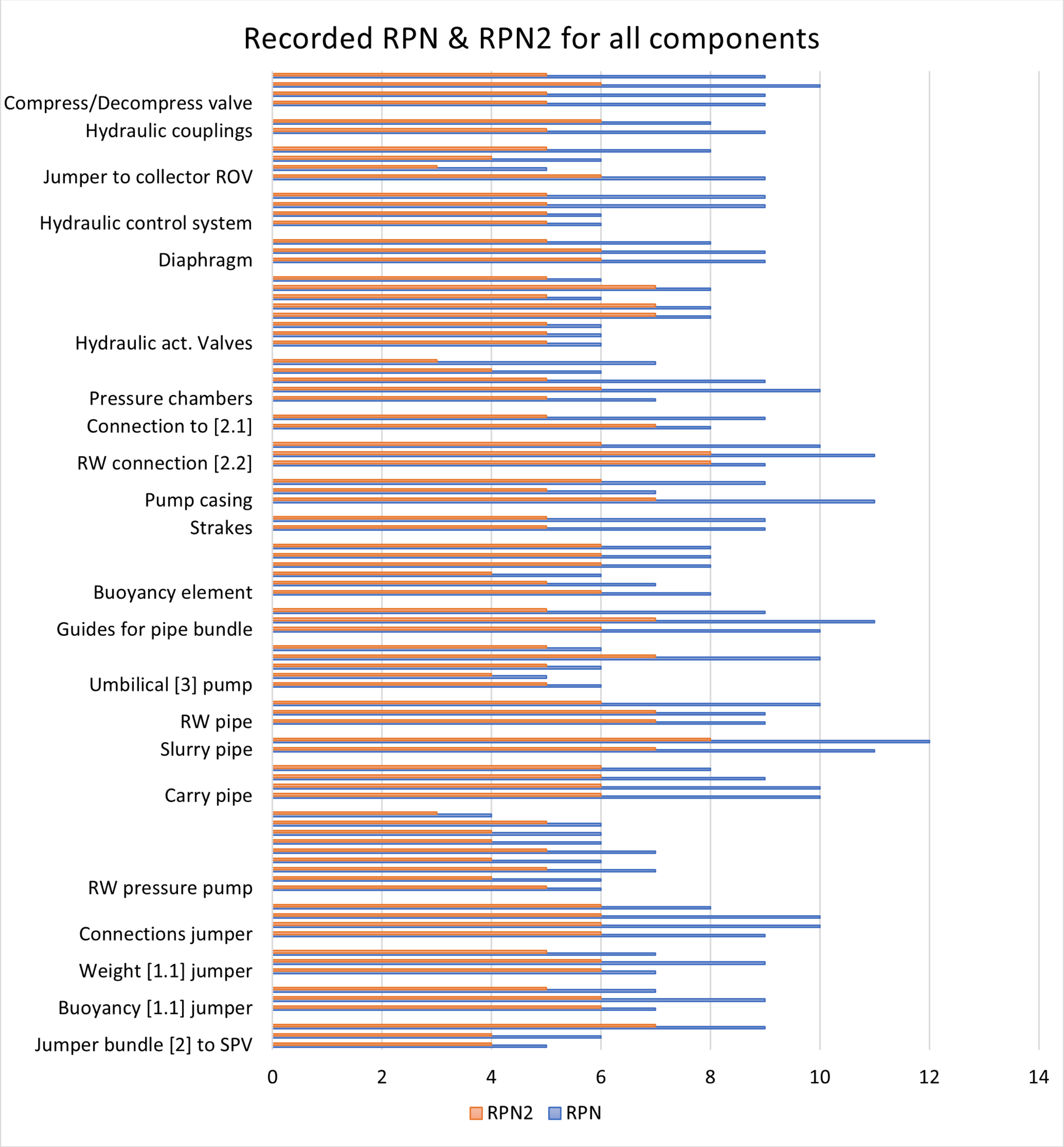
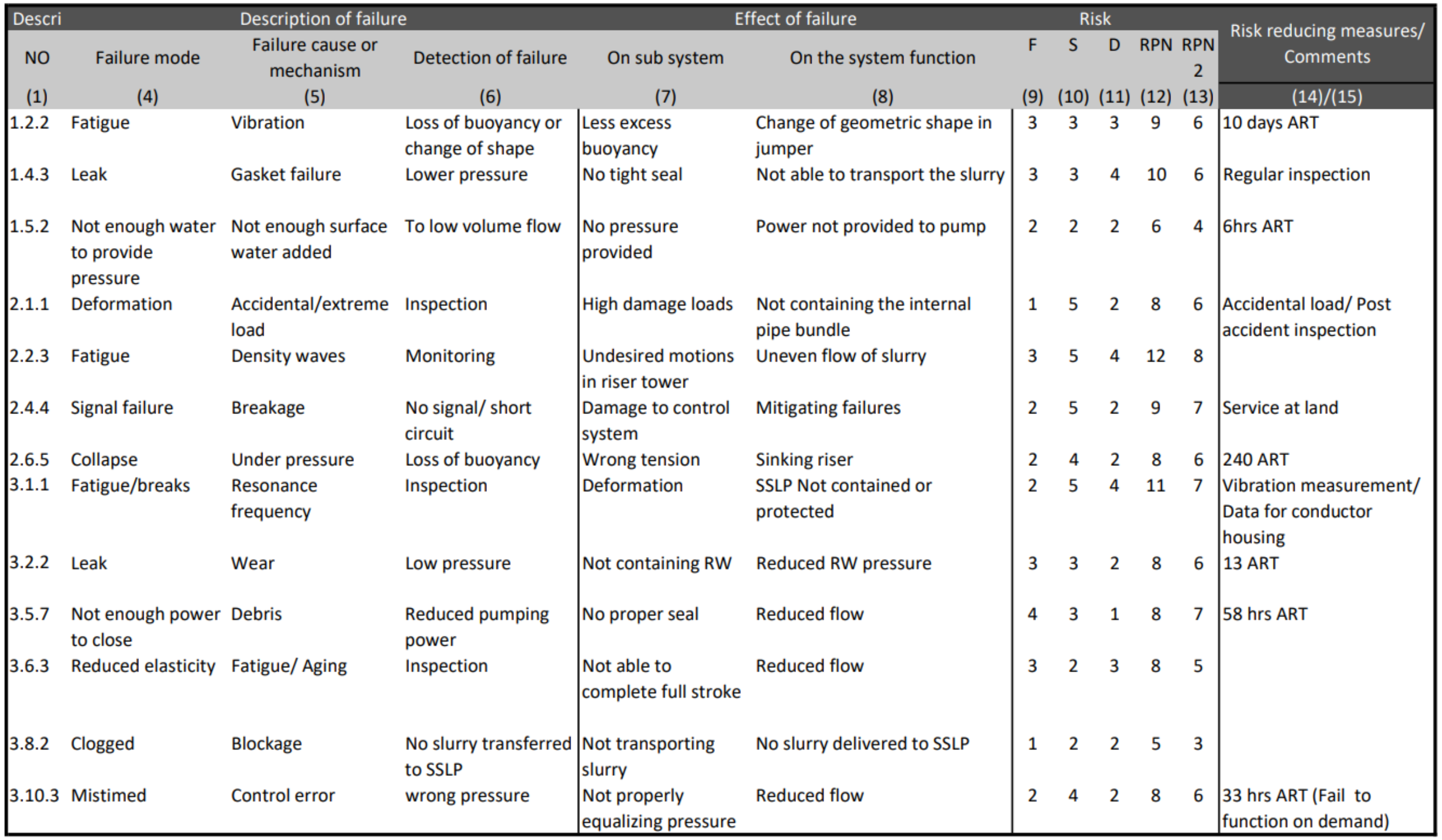


Figure 18: Bar plot of all recorded RPN values. Note that the components are listed from the bottom up, only the component title is given.



Descri	Description of failure			Effect of failure		Risk					Risk reducing measures/ Comments
NO	Failure mode	Failure cause or mechanism	Detection of failure	On sub system	On the system function	F	S	D	RPN	RPN 2	
(1)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)/(15)
1.2.2	Fatigue	Vibration	Loss of buoyancy or change of shape	Less excess buoyancy	Change of geometric shape in jumper	3	3	3	9	6	10 days ART
1.4.3	Leak	Gasket failure	Lower pressure	No tight seal	Not able to transport the slurry	3	3	4	10	6	Regular inspection
1.5.2	Not enough water to provide pressure	Not enough surface water added	To low volume flow	No pressure provided	Power not provided to pump	2	2	2	6	4	6hrs ART
2.1.1	Deformation	Accidental/extreme load	Inspection	High damage loads	Not containing the internal pipe bundle	1	5	2	8	6	Accidental load/ Post accident inspection
2.2.3	Fatigue	Density waves	Monitoring	Undesired motions in riser tower	Uneven flow of slurry	3	5	4	12	8	
2.4.4	Signal failure	Breakage	No signal/ short circuit	Damage to control system	Mitigating failures	2	5	2	9	7	Service at land
2.6.5	Collapse	Under pressure	Loss of buoyancy	Wrong tension	Sinking riser	2	4	2	8	6	240 ART
3.1.1	Fatigue/breaks	Resonance frequency	Inspection	Deformation	SSLP Not contained or protected	2	5	4	11	7	Vibration measurement/ Data for conductor housing
3.2.2	Leak	Wear	Low pressure	Not containing RW	Reduced RW pressure	3	3	2	8	6	13 ART
3.5.7	Not enough power to close	Debris	Reduced pumping power	No proper seal	Reduced flow	4	3	1	8	7	58 hrs ART
3.6.3	Reduced elasticity	Fatigue/ Aging	Inspection	Not able to complete full stroke	Reduced flow	3	2	3	8	5	
3.8.2	Clogged	Blockage	No slurry transferred to SSLP	Not transporting slurry	No slurry delivered to SSLP	1	2	2	5	3	
3.10.3	Mistimed	Control error	wrong pressure	Not properly equalizing pressure	Reduced flow	2	4	2	8	6	33 hrs ART (Fail to function on demand)

Figure 19: Chosen failures from the FMECA analysis for further discussion

7 Discussion

7.1 Discussions about design

The design process used in this thesis and suggested in Pahl et al. 2007 is a systematic approach for engineering systems design. The design should be performed in groups to explore more ideas and limitations to suggested solutions, but the entire design is performed by one person only. This will limit the solutions explored and it makes it difficult to eliminate personal preferences from the chosen design. But the design suggested here is consistent with the established requirements list.

For the process of lifting there are several possible designs that can provide good solutions. Several of the suggested lifting concepts can be good solutions and there are several possible configurations for the riser, lifting system and mooring. This thesis consists only of a qualitative analysis. There are several quantitative aspects to consider before selecting a final design for an operation, such as basic cost estimates, lifetime calculations and environmental loading. The hybrid riser solution is compatible with the several lifting concepts and the potential for technology development and adaptations of other lifting systems are possible and might be proven to be more feasible.

It is suggested to tow the whole assembled riser from shore to the selected site and to flip the riser to a vertical position when it arrives at site. Towing can impose severe loading on the riser due to VIV and the total fatigue damage depends on the towing speed and duration. It is important to include these fatigue estimates when designing the riser system. To reduce the fatigue damage one might consider to tow at very low speeds, which could add several days to the tow. It was also suggested to mount the pump and jumpers at shore and then tow it to the site assembled. With jumper connections made for subsea connection and disconnection, it may be better to connect the jumper after the riser has been installed to ease the tow and to add the possibility for changing the jumper cables. With regards to maintainability of the pump, it is wise to have the option of retrieving the pump to the surface vessel if extensive maintenance is required. In this case the pump must be detachable by an ROV.

Given the rapid changes in arctic weather one has to have the possibility to disconnect the SPV over a short time frame, and with regards to polar lows is it advisable to have a 30 min time frame for disconnection. Since the slurry is lifted by a pump it is easy to shut down production, but to avoid clogging in the riser it should be flushed of slurry before shutdown. If the SPV provides the power to the mining equipment too, a disengagement of these connections is also required. Hence several connections and disconnections from the sub sea equipment should be expected during its lifetime if one is producing during harsh winter weather conditions. The installation of the lifting equipment will leave a footprint in the seafloor, the size depends on the riser base and if the jumpers are laying on the seafloor. The total environmental impact from this is uncertain, but one should try and keep the affected area to an minimum. The surface impact will be the SPV, with light pollution, exhaust emissions and the different discharges from the vessel. It remains uncertain if light will have any affect to the local fauna. The exhaust emissions will depend on how the power is produced on the SPV, and the type of fuel used will have an impact on the total carbon footprint of the mined material. Discharges from the vessel must comply with the MARPOL convention and the requirements that govern deep sea mining.

Since the riser is free standing it is stationary and not able to follow the surface vessel or the collector. Therefore, the surface vessel becomes stationary and one might need to extend the length of the bottom jumper to be able to gather the ore if the field area is extended. On the other hand, this can motivate the operator to start mining several smaller deposits in the vicinity around the riser and then pumping ore material through the riser for lifting.

The SSLP is a vital part of the operation and any unexpected down time on the pump can cause significant reduction of retrieved ore and therefore it should be continuously monitored. The pressures in the slurry line, return water line and the pump chambers are monitored and help diagnose the condition of the pump. One should consider implementing vibration monitoring, because it can identify degradation of state at an early stage and provide more information about degradation in several components of the pump. Furthermore, it can often diagnose which component might be failing, and why. With this knowledge one can stop the pump before the failure and thus reduce possible spreading effects of a failure.

This thesis has considered one pump only. As mentioned in the theory section, it is possible to arrange several pumps in series or parallel. This possibility has not been considered during the design. There are a few reasons for this: (a) to limit the scope of the design analysis, (b) the challenges of uneven flow in to the pumps in a series configuration and (c) the infrastructure needed to transport the required power to the pumps locations complicates the design. For parallel configuration one should include bypass valves so the the system can be operated without running all the pumps. This can add redundancy to the system, but only if there is an overcapacity on the installed pumps.

The transition from the rigid riser to the flexible jumper to the SPV has several bends which increase flow resistance. Whether or not the pump can provide enough power to overcome this resistance or if a booster station is needed in the transition between the rigid and the flexible riser, needs to evaluated in the next design steps. A consequence of the asymmetric cross-section suggested for the rigid riser is that the equilibrium angle of the riser tower is non-zero. The effects of this are usually of low significance, but should be considered when designing the riser base and the transition to the flexible jumpers at the top.

If several ore deposits are located in close proximity to each other, then one can consider pumping ore from several mining sites to one shared riser tower. This would, however, require extra infrastructure on the seabed with pumping stations to transport the slurry to the riser. The benefit is that only one riser may be needed and also the benefit of achieving a higher utilisation rate on the riser. This will also affect the need for surface vessels. The SPV has to be stationary with the riser, but the satellite mining sites might need the support of a surface vessel. Smaller deposits might also become of interest for mining if several mining sites can be connected to one riser. As a field expands it might also be interesting to leave the riser in its original position and install a pump station close to the new site. This requires a cost/benefit analysis and will depend on parameters such as: distance, volume, and age of equipment. This type of operational design will naturally have to be on a case by case basis.

During operation it is important to know the state of the lifting system. A common concern for marine installations are the fatigue loads. During the design phase it is required by class (DNV-ST-F201 2021) to calculate fatigue estimates, but one will not know the true loading before the system is installed. Deep water systems are complex and difficult to maintain, therefore it is important to minimize the need for inspections and maintenance. Such mitigation can be achieved by installing several sensors to monitor the system, both the riser and the pump. For condition monitoring of the riser one should mount accelerometers to track motions and to calculate the total fatigue damage on the riser. It is uncertain how abrasive and corrosive the slurry will be, but one can track the inside conditions of the pipes by camera inspections or one can install wear tags for inspection. Due to poor accessibility, it will be challenging to service the pipes inside the casing pipe when it is installed, - therefore the pipe might have to be returned to shore for more extensive services.

To reduce the need of retrieving components or segments to the surface for maintenance, stopping production - possibly with waiting on weather time - one can design for more routine procedures that can be performed by an underwater resident ROV. To further reduce the need to WOW and the hoisting time of the ROV, it might be possible to store some spares on the seafloor. The option of a resident ROV might be a more compelling case for larger mining sites or a mining operation that consists of several smaller mining sites.

To make a design one has to make several choices, and some choices have a better basis than others. Sometimes one can have several options that are equally suited for its task. An example of this was the choice of lifting concept in this study. Four concepts were identified as suitable for lifting the slurry in a hybrid riser. By further analysis the SSLP was chosen because of its technological readiness and its utilisation of the return water. In this analysis most of the components were reviewed at a general level, mostly due to the earliness of the design. For more detailed design one would have to specify the components in more detail and more sub-parts would need to be included for analysis. Material selection is important for marine installations, both due to the issue of corrosion and high fatigue loads. Weight is always an issue for mobile installations. The material selected for the build will greatly affect the total cost of the system. Several alloys have been used for riser pipes and components. For the rigid part of the hybrid riser a steel pipe is typically suitable. There are many qualities to chose from because the compliant jumper will decouple the motions from the floater.

The deep sea mining industry is still a novice industry and no general standard has been established, hence there are many suggestions for how to lift and transport the ore. If this industry forms a standard it is likely this will be the most attractive solution, given that it can handle site specific challenges. Currently is arctic deep sea mining operations not a part of the more typical areas considered and need site specific adaptations. With this said, this solution is influenced by existing projects, with pumps being used for slurry lifting in a partly rigid riser. Several aspects in this design are modifications to lifting systems designed for more benign waters so that these can meet the demands for use in harsher arctic waters.

A desired trait for this system was for it to be mobile and to have the ability to follow the active mining site to avoid establishing an extensive infrastructure on the seabed, and to decouple the riser from the SPV motions. Some early design choices might be sub-optimal for the suggested design, but have followed to this stage. For a continuation and further specification of the design one might discover these vestiges and make improvements. This is a standard process of designing systems, where one has to iterate over all segments of the design to create a new, whole solution.

Because this hybrid riser solution is stationary, the range of the connected surface vessel be limited by the length of the flexible jumper. Hence the surface vessel receiving the slurry will not need to be very mobile, but must be able to hold its position. Vessels residing at the mining site during winter need to be equipped for arctic winters. This includes: ability to handle snow and sea spray freezing on the topside of the vessel, sub zero air temperatures, and harsh winter storms. The operation also needs robust search and rescue planning - and practice drills for such events, due to the remoteness of location, needs the operation to be self-reliant for several hours in case of emergency events.

7.2 Discussions about the FMECA

Often the severity of a failure is evaluated toward economical loss, but due to the lack of economical estimates around the operation and uncertainties of the final layout it was found that the best accuracy would be to estimate hours of downtime due to failure, then on a later stage this will allow for estimates of the total downtime cost. To make an estimate of the potential downtime of a failure some summations were made based on where the components are located, how the failure is discovered and other logistic additions. The accuracy of this is uncertain, but might on average give good estimates. A challenge in this analysis was knowing what spares are stored on site an what had to be shipped from a supply site onshore. An observation from these estimates was that if one has to bring components, equipment or personnel from shore this will take a lot of time, and the downtime will be extended.

Non failures were recorded with hazards towards human health. Within the boundary of the analysed system, is it only the RW pump that is located onboard the SPV and has the opportunity to directly harm humans onboard the ship. Hence has human safety been disregarded in the analysis and was performed with a technical focus, which the results reflects. A few failures record consequences towards environmental damage. The true damage from a potential leak of mining slurry is unknown, and the affected area and duration of the disturbance depends on several local factors (e.g. current speed and direction). Knowledge about spillage from mining slurry in the deep sea is limited.

The estimated frequencies was taken from the mean failure rates in the OREDA database. These are mean failures over several similar components, but not identical and not identically installed. The ORDEA database is for oil and gas installations, both offshore and onshore equipment, so the degree to which this failure data is transferable for use in deep sea mining assessments may have some limitations, but this is one of the few available open databases concerned with offshore installations. There are a few similarities between the oil and gas and the deep sea mining installations; both are offshore and some of the data in OREDA are from deep sea installations, but this data is merged with the data from more shallow water installations. Similar technical equipment is used so it is reasonable to expect that experiences made from the offshore oil and gas industry can be used for some deep sea mining scenarios. But how well the equipment matches and if the usage and wear rates are compatible carries some uncertainty. Also, values were used for components in the database with active repair time data. As above, how well the repair times match is another possible source of error, since maintenance planning and execution will likely not be be done in the same manner. Some of the equipment is specifically for deep sea mining only, and for such equipment there is no data in the ORDEA database. For equipment that is similar between the two types of ocean exploration sectors a reasonable assumption can be made about its function. The mined ore is expected to be more abrasive than the sand particles that in some oil and gas fields follows the production flow until separation.

A majority of the failures was recorded in the frequency class 2 and is a rate one can often expect from technical equipment. In addition, class 1-3 is on a logarithmic scale, hence the sensitivity of the classes will be lower for the failures with the lower failure rates. With regards to frequency, the failures of the highest rates most important to consider, but it is also important to pay attention to the failures with the highest severity. When considering design one should plan for easy maintenance of failures that is expected to occur often and equipment that would require frequent maintenance.

Again due to the uncertainties of the lay out and how the day to day operation will be, was the way of detection used to class the detectability of the failures. For inspection based failures is this a good estimate and for constant failure rates will on average the failure remain undetected for half of the inspection interval. Here was is the whole system to be inspected every 2 months inspection, for some components might this be too often, while other components might be inspected more frequently, but for simplicity was the same inspection interval set for the whole system. It is worth noting that in a pilot phase it is expected that the inspections will be more frequent.

The FMECA analysis was only performed by one person, not in a team which is the common practise in the industry, hence the focus of the analysis is limited by the knowledge and experiences by the author alone. Generic failures from the buzzwords are included, but the possible failures and mitigation of a failure may be limited.

The RPN values from the FMECA is presented in a bar plot in Figure 18. This is an unconventional presentation of the numerical results in a FMECA, but this plot was included to give a general view of the recorded results. This plot discloses if any components stands out with high or low RPN values, both the RPN and RPN2 values are included to disclose how great an impact the detectability has on the final RPN value. The top RPN value of 12 is an 8 without the detectability, and two other components has an RPN2 value of 8, but are deemed less critical because a failure is easier to detect. A histogram of the recorded RPN values was included too, this shows the distribution of the recorded values. It is worth noting that this histogram is not to be used later for finding a analytical distribution for predictions of RPNs, which does not follow any statistical distributions. This plot only shows the values that were recorded the most.

7.3 Discussion of selected failures

It is considered somewhat excessive to comment on all 106 failures, thus 13 failures have been selected for discussion and is presented in Figure 19, all 106 failures are found in appendix C. This aims to indicate what has been done and clarify the vocabulary used. The failures are referred to by failure number. The process of selecting failures for discussion was done by dividing the failures in to the failures with the top RPN values, RPN = {10, 11, 12}, and selecting one failure from each component, - this resulted in 15 + 23 failures. From these a total of 13 were selected for further discussion. Some failures were selected because further clarification was needed or seemed noteworthy, while other failures were set aside from the discussion as they were too similar with other failures.

1.2.2 The buoyancy device in the flexible jumper failing due to fatigue loads. Every time the jumper changes shape the depth of the buoyancy device is changed. This is a load cycle due to pressure changes, but the main contribution to the fatigue load is vibration from either an uneven internal flow or a the load from the external current. Due to several load modes contributing to fatigue this failure received a frequency of 3. The failure is fixed by replacing the buoyancy device and the failure is detected by a change in the shape of the jumper and received frequency and detectability scores of 3.

1.4.3 Leak in the gasket seal in the connections to the jumpers. It is assumed that the jumper connections have a gasket seal, and that these can get damaged during the connection/disconnection process or start leaking due to aging/wear. The result is a leak of the fluid inside the jumper and associated pressure loss. The size of the rupture in the gasket governs if particles from the slurry will leak out to the environment. The main reason this failure scores so high on the RPN value is that it is considered hard to detect; one has to inspect the connection with a pressurised flow to detect potential leaks. It is worth noting that a severe leak can be detected by reduction in pressure.

1.5.2 To have enough water to power the SSLP needs additional seawater from the surface to be added to the return water from the slurry. If this mix is wrong, the return flow will not be ideal and this will affect the pumping of the slurry. Since all the technical equipment is located on the SPV this failure can be resolved quickly with resources already onboard the SPV, and has a short downtime.

2.1.1 The carry pipe protects the internal pipes to some extent and will take the hit for all accidental load, but larger loads might also damage the internal bundle. This depends on the type of accidental load. The accidental nature gives a frequency score of 1, but there is a potential for a complete loss of the riser, hence it has a severity score of 5. It is assumed that there will be a post incident inspection, and receives a detectability score of 2, in total the RPN value is 8.

2.2.2 A positive displacement pump creates a pulsating flow, but there are several mitigating measures one can implement to reduce this pulsation. The SSLP has several chambers that are not at peak pressure at the same time and valve control and a pressure relief valves to reduce some pulsations. Nonetheless, there could be slight variations in the flow. In addition, the slurry mix may not be uniform and exert a force on the riser. Over time these potential issues can sum up to significant fatigue damage. This failure scores high on severity because the riser has to be serviced at shore, which will halt production for a longer period. Detectability is rated as a class 4 because it is found by inspection. Since this loading is during operation of the riser this failure has received a class 3 on frequency in total results this with a RPN of 12 and has the highest RPN score in the whole FMECA analysis.

2.4.4 A failure in the umbilical can result in either complete loss of signals or a transmission of corrupted signals to connected equipment. Inability to communicate with the subsurface equipment can lead to mitigating failures in other parts of the system. From the failure rate in the OREDA database the breakage of an umbilical did get the frequency class of 2. It is assumed that the riser has to be shipped back to shore for replacement of the umbilical and this failure received a severity of 5. The loss of signal and power is picked up by sensors and the detectability received a score of 2; ending with a RPN value of 9.

2.6.5 The main buoyancy element holds the riser upright and is a critical element in a hybrid riser. A collapse can come from fatigue due to depth changes, but the failure referred to here is if the tank sinks too deep where it can collapse by the high surrounding pressure. This is only rated as a 4 in severity because it is assumed that if the riser survives the tilting, then one can reattach a new buoyancy tank and restore the riser. It is likely that several minor damages befall the riser, but can be repaired. If the risers integrity is compromised, then the riser must be towed to shore for maintenance. It is also possible that the riser base will take damage from the tilt and must be replaced. Detectablilty is set to 2 because it can take some time for the riser to tilt enough for it to be noticeable. To avoid the event of the buoyancy tank collapsing it is important to design for a higher collapse pressure than the depth at which the buoyancy tank is installed. Due to low frequency and detectability score the RPN value is 8, and one might consider this value not reflecting the criticality of a failure of this component.

3.1.1 The casing and frame for the pump breaking due to excessive vibrations. This is mainly a problem if the pump operates around its own resonant frequency, hence the pump should not have its operating point at these frequencies, but it might be the case that resonant frequencies are crossed during startup and shutdown. Worst case is that the pump falls apart and it is not repairable. If one takes this issue seriously during design, then one reduces the chance of it causing problems later. This failure got a severity of 5 because if the pump fails no pumping will be be possible and no ore is lifted. It got a detectability of 4 due it is detected by inspection, installing vibration sensors can help to monitor the state of the system, and will sooner detect if there is a problem.

3.2.2 Leak in the Return Water connection between the pump and the RW pipe due to wear. If particles follow the RW flow these can cause extra wear on components and bends in the piping. Furthermore, the high pressure increases the strain on the pipes and connections. This failure got a score of 3 for frequency and severity, because higher wear rates are anticipated, but it is assumed that the connections can be changed on site and will take less than a week to repair. It got a detectability of 2 since a leak can be detected by declining pressure, but an inspection might be needed to locate the leak.

3.5.7 The valves are hydraulically actuated to ensure closing and opening, but if the debris is to hard or the hydraulic power is to weak, then the valves may not close properly. This can result in internal leaks in the pump and reduced pumping power. If the debris is not stuck then this is typically only a problem for one cycle, but if the debris is jammed in the valve then the flow trough one of the chambers will be reduced and also reduce the exiting pressure from the pump. This failure got a frequency of 4 and is mainly referring to temporary jamming, and no action is needed for repair. If the blocking particles do not loosen by themselves then one might have to disassemble the valve for cleaning. This failure got a severity of 3. The detection is instant due to a position measurements on the valves connected to the chambers.

3.6.3 The diaphragm separates the RW flow from the slurry flow and is a vital part of the pump. It is elastic and to be able to fully empty the chamber it needs to be at full flexibility. Aging of the diaphragm can result in a less flexible barrier and it not being able to complete the stroke, resulting in a reduced flow trough the chamber. Due to an assumed lifetime of five years on the diaphragm this failure got a frequency of 3, but a severity of 2 because this is a gradual degradation and does not lead to an instant stop in production. Detectability is assigned a 3 because one has to read the trend of the measurements.

3.8.2 Clogging of the jumper from the collecting unit to the pump, leading to reduced or complete stop of the slurry transport in to the pump, and lifting of slurry. This is not considered a frequent event and got a score of 1. Often the material clogging the jumper can be purged by either pumping water in the jumper or reversing the flow. This failure received a severity score of 2, but if the material clogging the jumper does not come loose, is it likely that the jumper has to be retrieved for purging. This failure is detected by reading a reduced flow of slurry of the sensors installed, and received a detectability score of 2 resulting in a RPN score of 5. This failure is not considered very critical.

3.10.3 If the decompression valve in the pump chambers is opened or closed at the wrong time the pressure will not be equalised at the correct time, leading to an uneven flow and a potential reduction in pressure in the flow. By use of the OREDA database for a hydraulic valve this failure received a class 2 on the failure rate. It received a severity class of 4, because it is assumed that the valve needs to be changed. If a position sensor is installed then the failure gets a detectability if 2.

8 Conclusion

This thesis is concerned with a conceptual design of a hybrid riser system for deep water slurry lifting in arctic sea conditions. Critical components have been found by using a FMECA. The design was performed by: 1. setting up a requirements list, then 2. use this list to divide the problem in to sub-functions, and 3. followed by finding possible solutions for the defined sub-functions. The solutions for every sub-function were chosen based on qualitative aspects and if they were compatible with the whole system. Four sub-functions were defined: Contain slurry, move slurry, positioning, and connection to SPV.

The suggested solution is a bottom mounted hybrid riser that uses a SSLP (positive displacement pump) powered by pressurised return water of the slurry. The riser is connected to the SPV by the use of flexible jumpers. This allows the motion of the SPV to be disconnected from the riser, thus reducing the loads on the riser. However, this limits the range of mobility of the connected vessel and sets requirements for the station keeping of the vessel. The choice of design can be further evaluated by calculations and modelling. The design process is based on desired attributions and solutions that fulfill them. A slight change in priorities can have a severe impact on the concept of choice. Also, note that the results depend on the technical and operational expertise of the group performing the design.

Hammerfest (in northernmost Norway) was chosen as the logistics harbour. For the estimation of potential downtime the following scenario was used: a ship sailing at 12 knots needs 28 hours to get to the Loki's Castle vent site, and for an unplanned mobilisation it was assumed in the FMECA that it would take five days from the request of goods till delivery. The remoteness and environmental challenges makes the arctic a less attractive area for pilot phase projects and is considered unlikely to be the first area with a full scale commercial mining operation.

The most critical component from the FMECA is fatigue wear in the slurry pipe. This failure was assigned a 3 in frequency score, 5 in severity and 4 in detectability. The high severity is because the whole riser would have to be shipped to shore for repair. It got a high frequency because there are several high frequent loads on the pipe. There are several mitigating measures with regards to fatigue on can implement in design, but the pipes in the internal bundle are difficult to inspect given their location inside the casing pipe.

An observation from the way failures was quantified in FMECA is that the logistics around repairs are critical and can be time consuming if one has to get spare equipment or personnel from shore. Unexpected events and downtime can cause severe delays in the operation. Planning for self sufficiency - to as high a degree as practicable - can reduce the downtime significantly. Another measure to help this is close condition monitoring so that repairs can be planned and performed at planned maintenance intervals.

Some weaknesses in this FMECA are: (a) an insufficient focus towards human health, (b) limited data resources from suiting equipment and (c) that the analysis was performed by one person with somewhat limited experience from offshore operations. It is not possible to confirm the validity of the results of the FMECA because the system does not yet exist and there are very few comparable sources for the analysis. The frequency of failures being rated on classes with non-constant intervals gives a better resolution for failures that are likely to happen. More rare failures are grouped together. This reflects the need for priority (and the logarithmic scale makes the rarer failures less sensitive). The more frequent failures will be more sensitive to where they are located.

8.1 Further work

A feasibility study should be conducted to evaluate if this suggested design is competitive with existing designs and if an operation will be competitive with terrestrial mining. For this to be possible, exact design parameters are needed and for the parameters to be set the environmental loads must be found.

For the lifting, NAUTILUS found that the required pressure in the return water line needed to be 79 bar for 1600 meters in a rigid riser, and that the top jumper in the hybrid solution has several bends, increasing the resistance. An analysis should be performed to evaluate if the flow needs to be boosted in the transition between the rigid riser and the flexible jumper, or if there are more optimal placements of the booster station.

As mentioned in the discussion, one can use this concept as a collective lifting hub for several active mining sites. In such a case the ore is pumped from the sites to the riser as one common lifting hub to get a higher utilisation on the lifting system. However, there are several variables to be explored to see of this can be a beneficial configuration.

Other concepts for lifting include mobile lifting solutions which can be beneficial because there would be no need to establish bottom infrastructures, allowing for short duration operations as a more attractive alternative. A further study in to possible mobile lifting solutions in arctic environment is encouraged. Also, other studies should investigate the possibilities of only lifting ore during the summer season and storing the mined material during the winter season.

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Appendix

A Anchors

For some riser shapes and TTRs are the riser in need of anchoring in the seabed. One of the most common anchors are suction anchors, cylinders with an open bottom and a closed top, with a venting hole to pump out the water so the anchor will suck itself to the ground, how well the anchor sits depends on the type of seabottom. Another anchoring is to use gravity based anchors, where the weight of the anchor holds the moored installation in place. Some hybrid solutions exist where suctions anchors are combined with the gravity base and requires smaller suction anchors (Y. Bai and Q. Bai 2005). A third anchoring solution is torpedo piles, torpedo shaped arrows that are released a certain height above the seafloor, the impact velocity of the pile make the pile penetrate the ground and it is stuck. The effectiveness of the penetration and how well the pile penetrates and sits depends on the type of seafloor (Audibert et al. 2006).

For the mooring lines there are two main configurations: catenary lines and taut leg moorings. The catenary moorings has a line profile that lies on the seabed, this allows larger motions of the floater than a taut mooring, but the footprint on the seabed is greater and more material is needed than for the taut mooring. The taut leg mooring has a smaller footprint on the seabed and no lines are on the seabed. The motions responses from the floater is directly associated with the axial stretch of the mooring lines, hence this configuration might be less suitable for shallow waters (Kai-Tung et al. 2019).

The required strength of the mooring lines is set by designing for a combination of different environmental conditions with a return period, typically 100 years for permanent moorings and 5-20 years for temporary moorings. Fatigue and operability are other design factors to consider when designing and sizing the mooring (Kai-Tung et al. 2019).

Different risers and its configurations influence the loading on the mooring. A hybrid riser rely on the axial tension to resist horizontal deflection, and for the riser to have an acceptable response is typically the required axial tension in the area of 70-1000Te (metric ton), and the anchoring has to be reliable to provide the required tension over the life of the riser. The total loading in a hybrid riser is complex and in combination with the installation load, the mooring can become a significant cost element (Hatton et al. 2005).

Suction piles

Suction piles have a cylindrical shape and typically have a diameter of 4-6 meters and have a sealed top with a valve to attach a pump to evict seawater. The suction pressure holds the pile in place. These anchors can hold direct vertical loads, but are more commonly used for catenary and taut moorings. The piles are installed by by first penetrating the seabed under its own weight, while the valve at the top is open. When the pile stops sinking a ROV attaches to the valve and pumps out the remaining water and creates a negative pressure, sucking the remaining pile in to the soil. The strength of an installed anchor depends on the seabed surrounding it. Suction piles can be used for temporary moorings and be moved by reversing the installation process and start by pumping in water (Kai-Tung et al. 2019).

The resistance in a suction pile is provided by a combination of self-weight and skin friction to the soil. The anchors holding capacity can be increased by increasing the anchor length (if the maximum diameter of the production facility has been reached) and the suction piles has a high resistance to lateral loads. The suction piles require high quality welds and are usually installed by drilling vessels, providing some logistic challenges. The soil around the pile is disturbed and its holding capacity might be affected. In deep water and soft sediments the stability of the hole can be affected, resulting in coning and collapse (Hatton et al. 2005).

Gravity Base

A gravity base anchor consists of a steel or concrete structure that can be weighted with ballast. The structure's self-weight provides the resistance. Its properties are well understood, has no soil consolidation time, can be installed by several vessel types and is easily repositioned. But the anchor may walk due to dynamic lateral loads, has a limited tension capacity and is not very well suited for softer bottom conditions (Hatton et al. 2005).

Driven Piles

Driven piles are pipes that are open in both ends and have a typical diameter of 1 to 3 meters and are driven in to the soil by the use of a hydraulic hammer. The piles can be driven more than 100 meters in to the soil, this can provide a grand axial resistance, and are suited for tensioned systems (Kai-Tung et al. 2019).

The fatigue performance of the anchor has to be considered given the anticipated depth and anticipated number of blow counts. The piles are typically used for template foundations. The installation process degrades the surrounding soil to a minimum and provides a high skin friction due to the internal soil plug, in addition provides the internal plug extra weight to the pile. Some of the qualities of a driven pile are: short soil consolidation time, good control of vertical position, low-tech fabrication and transportation requirements. Hard soils might be a hinder for the piling and one has to mobilise an underwater hammer (Hatton et al. 2005).

Jetted Pile

Jetting is an alternative method of lowering the pile in to the soil, there is no drilling, but the soil is removed by water jets as the pile is lowered, vertical reciprocation is often required. Jetting is considered an quick and cost effective practice for deepwater applications. The jetted piles have a good tension capacity, that can be increased by length, control of vertical position and the anchors are easy to transport. But hard soils and rocks might hinder the jetting, the soil needs to settle after the installation for the skin friction to be optimal and excessive jetting might wet the soil, reducing its holding capacity. Good quality welds are required to resist lateral loads and bending moments.

Drag embedment anchors

A Drag Embedment Anchor (DEA) consists of a fluke and a shank that is attached to the anchor line. A DEA can have a holding capacity of 20-90 times its own weight and is easy to install, but the position, hence its strength, is uncertain. Therefore the strength of the anchor can be proof tested after installation by a vessel with a significant bollard pull. The anchor will move downward when it is dragged at the correct angle, this angle depends on the soiltype. DEAs are fast to install and was designed for mobile moorings, but with more experience it has become a viable option for permanent moorings as well. Due to the anchors design it only provides resistance to horizontal loads, only the moorings dead weight resists vertical loads, but in some soils with deep penetration can the anchor hold both catenary and taut moorings. These anchors are relatively easy to recover (Kai-Tung et al. 2019).

Vertically loaded anchors

Vertically Loaded Anchors (VLA) was developed to improve the pullout resistance of DEAs in soft clays. The anchors are installed in the same manner, but a releasable shank can be opened after the dragging operation and the load angle during operation is different than during installation, for permanent moorings this angle can be 90 degrees. This means that the anchor will pull out of the sediments if it is overloaded. This anchor can handle reverse loading, but one should pay attention to the resulting angle of the anchor after. There are also temporary versions of the VLA, where pulling in reverse will trigger a release mechanism and one can recover the anchor by the mooring line (Kai-Tung et al. 2019).

Torpedo anchors

Torpedo anchors is gravity based anchor with a torpedo shape and three or four guiding vanes. A typical size is 20 meters length, 1 meter diameter and a dry weight of approximately 100 metric tons. These anchors are installed by its own gravity, the torpedo is dropped about 100 meters above the seabed with the mooring line attached and before the seabed the pile has reached its terminal velocity, in the range of 30 to 50 m/s. The torpedo anchor penetrates the seabed by its own kinetic energy. The main advantages of the torpedo piles is that they are quick and accurate to install. They are mainly used in soft to medium soft clay and penetrates the clay deeply. Because of this deep penetration the anchors can resist both horizontal and vertical loads. These anchors has mainly been used for permanent moorings (Kai-Tung et al. 2019).

B Points used for route calculation

Below is a composition of the printouts from GeoMap App when lining the sailing routes.

```
Longyearbyen
Longitude Latitude Elevation (m) Cumulative distance (km) Distance between points (km)
Digitized points
8202 73527 -2 6392 0 0
13409 78077 -3413 525 525
15061 78292 -2443 570 45
15578 78246 -761 582 13

Kirkenes
Longitude Latitude Elevation (m) Cumulative distance (km) Distance between points (km)
Digitized points
8122 73481 -2 6923 0 0
31269 70501 -2290 855 855
31400 70177 -2596 891 36
30612 69820 -240 941 50

Hammerfest
Longitude Latitude Elevation (m) Cumulative distance (km) Distance between points (km)
Digitized points
8130 73497 -2 7053 0 0
23624 70883 -1051 599 599
23690 70734 1817 616 17

Narvik
Longitude Latitude Elevation (m) Cumulative distance (km) Distance between points (km)
Digitized points
8266 73540 -2 7163 0 0
12722 67794 -760 659 659
13278 67794 -1666 683 23
16059 68338 94 813 130
16916 68459 -1516 850 38
```

C FMECA

Description of unit			Description of failure			Effect of failure		Risk						
NO	Component	Function	Failure mode	Failure cause or mechanism	Detection of failure	On sub system	On the system function	F	S	D	RPN	RPN 2	Risk reducing measures	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1.1.1	Jumper bundle [2] to SPV	Transport slurry from rigid riser to SPV	External leakage/burst	Wear	Loss of pressure	Leak	Not transporting from riser to SPV	2	2	1	5	4		
1.1.2			Clogged	Object in line or build up of silt	Reduced flow	Obstructed flow	Not transporting from riser to SPV	2	2	2	6	4	Flush jumper of slurry before standby	
1.1.3			Breakage	Structural deficiency/Environmental load	Loss of pressure	Leak	Not transporting slurry from riser to SPV	3	4	2	9	7		Environmental, Spare transported from land
1.2.1	Buoyancy [1.1] jumper	Correct shape to [1.1] jumper	Wrong shape on jumper	Change of weight in jumper	Change of tension in jumper connection to SPV	Change in buoyancy	Change of geometric shape in jumper	5	1	1	7	6		
1.2.2			Fatigue	Vibration	Loss of buoyancy or change of shape	Less excess buoyancy	Change of geometric shape in jumper	3	3	3	9	6		10 days ART
1.2.3			Deformation	Change of buoyancy in jumper	Change tension in jumper connection	Reduced excess buoyancy	Change of geometric shape in jumper	2	3	2	7	5		10 days ART
1.3.1	Weight [1.1] jumper	Correct shape to [1.1] jumper	Wrong shape on jumper	Increased weight in jumper	Increased tension in jumper connection to SPV	Less excess buoyancy	Change of geometric shape in jumper	5	1	1	7	6		Assumed same rates as for buoyancy device
1.3.2			Fatigue	Vibration	Loss change of shape	Increased excess buoyancy	Change of geometric shape in jumper	3	3	3	9	6		
1.3.3			Deformation	Change of weight in jumper	Change tension in jumper connection	Increased excess buoyancy	Change of geometric shape in jumper	2	3	2	7	5		
1.4.1	Connections jumper	Connect/disconnect with a tight seal	Miss of connection	Deformation	Failure to connect	No tight seal	Not able to lift the slurry	3	3	3	9	6		
1.4.2			Leak	Deformation	Lower pressure	No tight seal	Not able to transport the slurry	3	3	4	10	6	Regular inspection	
1.4.3				Gasket failure	Lower pressure	No tight seal	Not able to transport the slurry	3	3	4	10	6	Regular inspection	
1.4.4			Clogged	Velocity reduction	Lower slurry output	Reduced inner pipe diameter	No/reduced throughput	3	3	2	8	6		
1.5.1	RW pressure pump	Provide pressure to run the SSLP	No start	Bad contact	On demand	No pressurised water to run SSLP	No Pumping commenced	3	2	1	6	5		3hrs ART

1.5.2			Not enough water to provide pressure	Not enough surface water added	To low volume flow	No pressure provided	Power not provided to pump	2	2	2	6	4		6hrs ART
1.5.3			Insufficient power	Not provided from SPV	Input power gauge	Not enough pressure	Not lifting slurry to surface	2	3	2	7	5		23hrs ART
1.5.4			External leakage	Gasket failure	Water under the pump unit	Not sending pressurised water to the SSLP	Not lifting slurry to surface	2	2	2	6	4		4hrs ART
1.5.5				Pipe leak	Water under the pump unit	Not sending pressurised water to the SSLP	Not lifting slurry to surface	3	2	2	7	5		4hrs ART
1.5.6			Fluctuating flow	unstable water supply	Uneven power input to SSLP	Extra wear/ fatigue load	Not providing correct pressure to SSLP	2	2	2	6	4		Density waves
1.5.7				Uneven pump speed	Pump speed/power indicator	Extra wear	Not providing correct pressure to SSLP	2	2	2	6	4		
1.5.8			Spurious stop	miscellaneous	Stop observed	Not providing pressure to the SSLP	Not lifting slurry to surface	2	3	1	6	5		
1.5.9			not stopping	miscellaneous	No stop observed	Providing pressure without demand	Power supplied to SSLP without demand	1	2	1	4	3		
2.2.1	Carry pipe	Support the riser bundle	Fatigue	Density waves	Monitoring/ Inspection	Bundle not properly supported	Not safe to transport slurry	2	4	4	10	6	Inspection/vibration monitoring	
2.1.1			Deformation	Accidental/extreme load	Inspection	High damage loads	Not enough pressure delivered to SSLP	1	5	2	10	6	Accidental load/ Post accident inspection	
2.1.2			Fatigue	Vibrations	Monitoring/ Inspection	Fatigue damage	Not supporting the riser bundle	2	4	4	10	6	Vibration sensor	
2.1.3			Fatigue	VIV	Accelerometers	Fatigue damage	Not able to support bundle	2	4	3	9	6		
2.1.4			Breakage	Accidental/ Extreme load	Recording of accidental state	Damage	Not able to support bundle	2	4	2	8	6		
2.2.1	Carry pipe	Support the riser bundle	Fatigue	Density waves	Monitoring/ Inspection	Bundle not properly supported	Not safe to transport slurry	2	4	4	10	6	Inspection/vibration monitoring	
2.2.2	Slurry pipe	contain the slurry during lifting	Leak	Wear	Loss of pressure	Not containing the slurry	Slurry not lifted to surface	2	5	4	11	7		The inside pipes of the riser has to be serviced at shore
2.2.3			Fatigue	Density waves	Monitoring	Undesired motions in riser tower	Uneven flow of slurry	3	5	4	12	8		
2.3.1	RW pipe	Provide pressure to run the SSLP	Crack	Fatigue	No pressure	Not enough pressure provided to SSLP	Not transporting pressurised water to SSLP	2	5	2	9	7		Assumption: The inside pipes of the riser has to be serviced at shore
2.3.2			Low pressure	Leak	Not enough power to SSLP	Reduced pressure	Not enough pressure delivered to SSLP	2	5	2	9	7	Inspection	
2.4.1	Umbilical [3] pump	Send control signals to SSLP	No start signal received	Interrupted on the way	No Start	No control signal sent	No pumping commenced	2	3	1	6	5		Less than one week DT

2.4.2			Signal failure	Isolation fault/short circuit	No output	Erratic signals sent	No pumping	2	2	1	5	4		Fuse blown
2.4.3				No power	No output	No signals transmitted	No pumping	2	3	1	6	5		
2.4.4				Breakage	No signal/ short circuit	Damage to control system	Mitigating failures	2	5	2	9	7		Service at land
2.4.5			No shutdown signal sent	Interrupted on the way	No stop	Not stopping on demand	Mitigating failures	2	3	1	6	5		
2.5.1	Guides for pipe bundle	Contain pipe bundle	Slack in fastening	Fatigue	Inspection	Earlier fatigue	Early cracking	1	5	4	10	6		
2.5.2			Loose pipes in bundle	Corrosion	Inspection	Earlier fatigue	Early cracking	2	5	4	11	7		Carry pipe filled with seawater
2.5.3			Shifted position	Forces during operation	Inspection	Bundle not stable	System not safe for transport	1	4	4	9	5		
2.6.1	Buoyancy element	Tension the pipe in the water column	Sinking	Not enough buoyancy	Grounding of riser	Sinking	Riser hanging off jumper or lying on seabed	2	4	2	8	6		240 ART
2.6.2			Connection failure (to ballasting pump)	Weak links or bolts	Sinking riser bundle	Wrong tension	Riser hanging off jumper or lying on seabed	2	3	2	7	5		
2.6.3			Floating up	Reduced weight in riser	riser observed in surface	Wrong tension	not operable	2	2	2	6	4		
2.6.4					Wrong tension in jumper	Wrong tension	not operable	2	4	2	8	6		
2.6.5			Collapse	Fatigue	Buoyancy elements falls off and floats up	Wrong tension	Sinking riser	2	4	2	8	6		
2.6.6				Under pressure	Loss of buoyancy	Wrong tension	Sinking riser	2	4	2	8	6		
2.7.1	Strakes	Reduce VIV loads	Deformation	Corrosion	Inspection	Wrong shape	Less reduction in VIV	1	4	4	9	5		
2.7.2				Accidental load	Inspection	Wrong shape	Less reduction in VIV	1	4	4	9	5		
3.1.1	Pump casing	Protect and carry the SSLP	Fatigue/breaks	Resonance frequency	Inspection	Deformation	SSLP Not contained or protected	2	5	4	11	7	Vibration measurement	Data for conductor housing
3.1.2			Loose parts	Vibrations	Pump vibrations	Deformation	SSLP not contained or protected	2	3	2	7	5		
3.1.3			Deformation	Accidental load	pump vibrations/ inspection	Deformation	SSLP not contained or protected	2	4	3	9	6		
3.2.1	RW connection [2.2]	High pressure connection	Burst	Overload	Slurry not sufficiently pump	Not containing RW	No high pressure	3	3	1	7	6		
3.2.2			Leak	Wear	Low pressure	Not containing RW	Reduced RW pressure	3	3	2	8	6		13 ART
3.2.3			Corrosion	Seawater	Inspection	Not containing RW	Reduced RW pressure	1	3	4	8	4		Material choice

3.3.1	Connection to [2.1]	Carry the SSLP	Falling off	Vibration	No slurry pumped	SSLP not attached to riser	No pump connected	2	5	1	8	7	Vibrations assumed to accelerate failure
3.3.2			Loose connection	Corrosion	Inspection	Not firmly carried	Vibration	2	3	4	9	5	
3.4.1	Pressure chambers	Contain the flow at fluctuating pressures	Burst	Overpressure	No pressure from chamber	Fluids not contained	No flow from chamber	2	3	2	7	5	
3.4.2			Leak	Erosion	Inspection	Leak	Flow not contained or pressurized	3	3	4	10	6	Unknown wear rate from slurry
3.4.3				Fatigue	Inspection	Not containing the flow	Flow not contained or pressurized	2	3	4	9	5	
3.4.4			Clogged	To large chunks or accumulation of particles	Start up	No flow	Flow stops	2	2	2	6	4	
3.4.5			Pitting	Corrosion	Inspection	Increased flow resistance	Reduced flow	2	1	4	7	3	
3.5.1	Hydraulic act. Valves	Control RW/slurry flow	Not starting to move	Stuck	Not starting up	No control of flow	No flow	2	3	1	6	5	
3.5.2			Hang up	Stuck/ misaligned	Flow stops	No control of flow	No flow	2	3	1	6	5	
3.5.3			Leak	Wear	Reduced flow	No proper seal	Reduced flow	2	3	1	6	5	Possible position measurements
3.5.4			Not fully closed	Slurry components in valve	Reduced flow	No proper seal	Reduced flow	4	3	1	8	7	
3.5.5			Not fully opened	Hydraulics not able to open	Reduced flow	Obstruction in flow	Reduced flow	4	3	1	8	7	
3.5.6			Hole	Erosion	Inspection	Leak	Reduced flow	2	3	1	6	5	
3.5.7			Not enough power to close	Debris	Reduced pumping power	No proper seal	Reduced flow	4	3	1	8	7	
3.5.8			Leak	Corrosion	Reduced pumping power	No proper seal	Reduced flow	2	3	1	6	5	
3.6.1	Diaphragm	Separate RW and slurry flow	Leak	Erosion	Reduced amount of slurry pumped	Mixing of RW and slurry	Diluted slurry flow/Discharge if particles in RW	3	3	3	9	6	Assumed lifetime of 5 years
3.6.2			Tear	Fatigue	Reduced amount of slurry pumped	Mixing of RW and slurry	Diluted slurry flow/Discharge if particles in RW	3	3	3	9	6	
3.6.3			Reduced elasticity	Fatigue/ Aging	Inspection	Not able to complete full stroke	Reduced flow	3	2	3	8	5	
3.7.1	Hydraulic control system	Control the actuated valves	Not starting	Wrong actuation of valves	No flow	Not controlling the valves	Limited control of pumping	2	3	1	6	5	58 hrs ART
3.7.2			To low speed/To high speed	Control error	Low/high volume flow	Out of sync with the other chambers	Limited control of pumping	2	3	1	6	5	24 hrs ART
3.7.3			Bad contact	Corrosion	Inspection	Spurious signals sent	Limited control of pumping	2	3	4	9	5	98 hrs ART

3.7.4			Breakdown of sensors	Aging	Erratic output	Spurious signals sent	Limited control of pumping	2	3	4	9	5	
3.8.1	Jumper to collector ROV	Transport slurry from mining site to Riser system	Burst	Over pressure	No slurry transferred to SSLP	Not transporting slurry	Environmental spill	2	4	3	9	6	
3.8.2			Clogged	Blockage	No slurry transferred to SSLP	Not transporting slurry	No slurry delivered to SSLP	1	2	2	5	3	7 hrs ART
3.8.3			External leakage	Erosion/fatigue/ wear	Reduced slurry flow to SSLP	Not transporting all slurry to SSLP	Environmental spill	1	3	2	6	4	14 hrs ART
3.8.4			Breakage	Fatigue	Reduced slurry flow to SSLP	Not transporting all slurry to SSLP	Environmental spill	1	4	3	8	5	
3.9.1	Hydraulic couplings	Tight seal of hydraulic connections	External leakage	Deformation	Reduced pressure/power	No tight seal	Environmental spill	2	3	4	9	5	14 hrs ART
3.9.2			Obstruction	Alignment failure	Reduced flow	Reduced open cross section for flow	Reduced flow	3	3	2	8	6	
3.10.1	Compress/Decompress valve	Adjust pressure in chamber at top/bottom	Leak	Leak when closed	Pressure not equal to flow pressure	Reduced pumping power	Reduced flow	2	3	4	9	5	17 hrs ART
3.10.2			Clogged	Reduced clearance	Pressure not equal to flow pressure	Reduced pumping power	Reduced flow	2	3	4	9	5	14 hrs ART
3.10.3			Mistimed	Control error	wrong pressure	Not properly equalizing pressure	Reduced flow	2	4	2	8	6	33 hrs ART (Fail to function on demand)
3.10.4			Stuck	Obstruction/ Corrosion	Pulsating flow/ chamber pressure	No equalization of pressure between filling/emptying stroke	Pulsating flow	2	3	2	7	5	

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