Astrid Vamråk Solheim

Transportation for deep sea mining using underwater vehicle

Conceptual design using a systematic approach

Masteroppgave i Marin teknikk
Veileder: Bjørn Egil Asbjørnslett
Desember 2019

Masteroppgave

NTNU
Norges teknisk-naturvitenskapelige universitet
Fakultet for ingeniørvitenskap
Institutt for marin teknikk

NTNU
Kunnskap for en bedre verden

Astrid Vamråk Solheim

Transportation for deep sea mining using underwater vehicle

Conceptual design using a systematic approach

Masteroppgave i Marin teknikk
Veileder: Bjørn Egil Asbjørnslett
Desember 2019

Norges teknisk-naturvitenskapelige universitet
Fakultet for ingeniørvitenskap
Institutt for marin teknikk

NTNU
Kunnskap for en bedre verden

SUMMARY

The purpose of this thesis is to propose design solution(s) at the conceptual level for underwater transportation of ore from seabed to port for deep sea mining. The essence of deep sea mining operations is to extract minerals from a marine deposit and make them available for further processing and refining in order to obtain a sellable product. However, the retrieval of abyssal mineral resources is demanding due to the remote presence at several thousand meters water depth.

The methodology to answer this issue was based on systematic conceptual design by Pahl, Beitz, Feldhusen, & Grote (2007). Fundamental problems were identified through abstraction and establishment of function structure. Moreover, the solution field was explored by discovering working principles (design parameters) and categorised based on physical principles. Design tools such as classification schemes and morphological chart we used. The principles were combined and compatibility between principles was reviewed. This led to the identification of working structures (i.e. a combination of design parameters). These were firmed up into solution variants by introducing an example case for operation at the Atlantic Mid-Ocean Ridge (AMOR).

The resulting promising solutions were:

1. An AUV with a spreader for collecting a container inside cargo hold. Marine railway used at port.
2. An AUV for towing of a container using a rope. Marine railway used at port.

Other important contributions include:

- A systems design focus and implementation of marine technology principles to a renowned conceptual engineering design approach: bringing the external environment of the solution into the evaluation in a marine technology context
- A matrix containing design parameters that can be utilised for designing an (underwater) transportation system for deep sea mining, but also other transportation of similar character
- A way of using working structure sets for combability check and selection of large solution field: narrowing the solution space more slowly in order to not lose any good solutions
- An update of the value chain with respect to the decoupling of excavation and transportation

Promising paths for further work were to take the results into embodiment design where layout and auxiliary functions, such as energy supply and control, are studied closer. Also, any working structure can be made from the morphological matrix presented in this thesis for design of different solutions.

SAMMENDRAG

Hensikten med denne oppgaven er å foreslå designløsning (er) på konseptuelt nivå for undervannstransport av malm fra havbunn til havn for gruvedrift. Essensen av dyphavs gruvedrift er å utvinne mineraler fra en marin forekomst og gjøre dem tilgjengelige for videre bearbeiding og raffinering for å få et salgbart produkt. Innhenting av dypthavs mineralressurser er imidlertid krevende på grunn av den fjerne tilstedeværelsen på flere tusen meters vanndybde.

Metodikken for å svare på denne problemstillingen var basert på systematisk konseptuell design av Pahl, Beitz, Feldhusen, & Grote (2007). Grunnleggende problemer ble identifisert gjennom abstraksjon og etablering av funksjonsstruktur. Videre ble løsningsfeltet utforsket ved å oppdage arbeidsprinsipper (designparametere) og kategorisert basert på fysiske prinsipper. Designverktøy som klassifiseringsordninger og morfologiske diagram vi brukte. Prinsippene ble kombinert og kompatibiliteten mellom prinsippene ble gjennomgått. Dette førte til identifisering av arbeidskonstruksjoner (dvs. en kombinasjon av designparametere). Disse ble laget til løsningsvarianter ved å introdusere en lokasjon ved Atlantic Mid-Ocean Ridge (AMOR).

De resulterende lovende løsningene var:

1. En AUV med en spreader for å samle en container inni lasterom. Marine railway brukt ved havn.

2. En AUV for tauing av en container. Marin railway brukt ved havn.

Andre viktige bidrag inkluderer:

- Et systemdesignfokus og implementering av marinteknologiprinsipper til kjent konseptuell ingeniørdesigntilnærming: bringe det ytre miljøet til løsningen inn i evalueringen i en marin teknologisk kontekst
- En matrise som inneholder designparametere som kan brukes til å designe et (undervanns) transportsystem for gruvedrift, men også annen transport av lignende karakter
- En måte å bruke arbeidsstruktursett for kompabilitetssjekk og valg ved stort løsningsfelt: begrense løsningsrommet saktere for ikke å miste noen gode løsninger
- En oppdatering av verdikjeden med hensyn til avkobling av utgraving og transport

Lovende veier for videre arbeid var å ta resultatene inn i embodimentdesign for layout og hjelpefunksjoner, for eksempel energiforsyning og kontroll. Enhver arbeidsstruktur kan også lages av den morfologiske matrisen som presenteres i denne oppgaven for design av forskjellige løsninger.

PREFACE

This master thesis has been written at the end of my master studies in Marine Technology at The Norwegian University of Science and Technology (NTNU) in 2019. It was combined with a position as integrated PhD candidate.

The work has involved a wide literature search to find solutions performing missions throughout the water column. Moreover, the method is built along the way and reiterated in order to maintain the integrity of the methodology. It has been time-consuming, but also extremely rewarding.

There are several that should be acknowledged for their contribution. I would like to thank the Department of Marine Technology at NTNU for providing funding for me to do additional research during the writing of the thesis.

I wish to express my sincerest appreciation to my main supervisor, Professor Bjørn Egil Asbjørnslett, for sharing knowledge and advice on marine systems design and scientific writing. I have learned a lot when discussing ideas and Friday emails during our weekly supervisions.

This thesis also had two co-supervisors that should be thanked. First, Professor Stein Ove Erikstad for lively discussions and for inspiring me to choose a research path, for which I am grateful. Second, I want to thank PhD candidate Maxime Lesage for helpful contributions on systems design applied to deep sea mining problems and for challenging me to think outside the box.

Lastly, thank you, David, for discussions, proof-reading and support along the way.

The work has now come to an end, and I hope that it may serve as a helpful supplement to others that are undertaking development of conceptual design for marine technology problems.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AMOR	Atlantic Mid-Ocean Ridge
CCZ	Clarion-Clipperton Fracture Zone
CP	Classification parameter (physical principle)
FR	Functional requirement
ISA	International Seabed Authority
O&G	Oil and gas
PSV	Production support vessel
ROV	Remotely operated vehicle
M&R	Maintenance and repair
SMS	Seafloor massive sulphides
WP	Working principle
WS	Working structure

1. INTRODUCTION

1.1. Background and motivation

Metals such as copper, lithium, cobalt, nickel and rare earth elements are essential components in a wide range of products, such as cell phones, computers, electric cars, wind turbines (James R. Hein, Mizell, Koschinsky, & Conrad, 2013; OECD, 2015). Demand for these metals is expected to increase in the future due to global population growth, increasing economies and a growing renewables industry (Bloodworth & Gunn, 2012; IEA, 2019; OECD, 2019). The principal source of such metals has been land-based deposits. However, it is expected that the land-based mineral production will at some point not keep up with demand (*Blue Mining*, 2018; Prior, Giurco, Mudd, Mason, & Behrisch, 2012). Recycling of metals might aid in metal supply, but today's inefficient collection of waste electrical and electronic equipment is an obstacle for ensuring mineral availability (Ali et al., 2017; Zhang, Ding, Liu, & Chang, 2017). This raises the question of investigating other sources of minerals. With its immense resources, the seafloor is of interest both scientifically and due to its potential economic value (Peter A. Rona, 2003). Some subsea areas contain more precious metals than the entire terrestrial reserve for key metals (James R. Hein et al., 2013). Thus, the deep ocean floor might be the next frontier for mining of minerals (Amdahl et al., 2014; Bloodworth & Gunn, 2012; James R. Hein, Conrad, & Staudigel, 2010; James R. Hein et al., 2013; OECD, 2015).

The essence of deep sea mining operations is to extract minerals from a marine deposit and make them available for further processing and refining in order to obtain a sellable product. Deep sea is here defined as deeper than 400 metres water depth. Prototype testing on deep sea mining has been carried out since the 1980's, see for instance Welling (1981) or Deepak et al. (2007). Moreover, various deep sea mining concepts have been proposed for decades (Sharma, 2017). Despite the continuous investigation of deep sea mining there is no known full-scale production yet. A company that has been successful with mining operations in more shallow waters is DeBeers Group, who mine diamond ore at approximately 120-140 meters water depth outside Namibia. For exploration and sampling they are using a highly advanced production support vessel (De Beers, 2019). The company that has been closest to a commercial realisation of a full-scale deep sea mining operation is Nautilus Minerals. They intend to start production of sulphides in Papua New-Guinea at 1,600 meters water depth. The concept consists of seafloor machines for excavation and riser and slurry pump for lifting to a production support vessel at water surface level (Nautilus Minerals, 2019a). Furthermore, several countries have entered into one or more contracts for exploration of minerals in abyssal, international waters, such as China, India, France, Korea, Russia, and Germany (ISA, 2019a).

However, the retrieval of abyssal mineral resources is demanding due to the remote presence at several thousand meters water depth. The ores must first be removed from the seabed and further brought from seabed to shore – all the while being in a perilous environment. The transportation during a deep sea mining operation has been identified as critical and challenging regarding the efficiency (Amann, 1982; Sharma, 2017). The term *transportation* is here defined as *changing position of payload*, with position being any point in space and payload being what should be carried. The current proposed concepts have in common the use of a vessel as a mother station at the ocean surface. This involves extraction with costly, advanced equipment submerged on the deep seabed – followed by an extensive ore lift through several kilometres towards the ocean surface. Already in Amann (1982), "free moving transport shuttles" was suggested as an alternative for transporting ore. The book points out some of the problems by having a conventional pipeline or riser for deep sea mining, such as weight, seabed pumping system, and high energy transfer over large distances. The weight is of concern due to drag resistance of pipelines and the seabed pumping system from corrosion. The new proposal was however deemed "too exotic" at the time. More recently, autonomous vehicles was suggested for better operability and maintenance options due to the high-risk nature of lifting through water column (Sharma, 2011). By high risk, they mean the relation between high investment and high-risk nature of the task. The book further suggests several nodule collectors operated from a mining platform as a possible solution. The rationale is that the mining platform, or mother station, and the collecting devices are independent of one another, and as such increase evacuation opportunities in case of emergency situations by abandoning seafloor devices. According to Jenkins & D'Spain (2016), the ability to move large payloads or cargo over long distances would be a logical function for a category of underwater vehicles known as gliders. The justification of this is their high endurance, i.e. the ability to remain under water for a long period of time by low energy consumption. For the future, they suggest bigger gliders and buoyancy engines as future measures in glider technology due to the economies of scale in packing efficiency and increased weight which permits higher speed. However, underwater transportation at high depths is not a novel endeavour. Since the mid-20th century, a wide variety of underwater vessels and diving systems have been developed for scientific, commercial and military interests (Hawley, Nuckols, Reader, & Potter, 1996). Lesage, Juliani, & Ellefmo (2018) identified the asset availability factor, meaning the uptime in production duration, as having the greatest influence on economic value for a case at the Arctic Mid-Ocean Ridge (AMOR). This might indicate that it may be valuable to find concepts that give a high asset availability factor, i.e. developing concepts that minimise interruption due to for instance harsh weather conditions, scheduled and unscheduled maintenance, or crew-changes. Concept development on deep sea mining using design methodology has been researched to some extent in the past. Systematic design was used to assess different technological solutions for extraction and transportation of ore and propose alternative mining system concepts (Lesage, 2019). The work is based on existing concepts in deep sea mining. Cho et al. (2019) deal with design optimisation for a seabed mining vehicle using axiomatic design. Design theory was applied to a manganese nodule extraction system in order to determine the level of coupled relations. They mention that an alternative function structure where transportation is treated as one 'diagonal' phase would require an update of the design catalogue, i.e. the design choices.

1.2. Problem formulation

The lack of any viable deep sea mining operation and the identification of the transportation being critical calls for an exploration of new concept designs. The objective is of this thesis to propose a novel conceptual design for the underwater transportation of minerals from a deep sea deposit to a shore location. This is done by exploring the research gap of "use of a coupled form for vertical and horizontal transportation". Figure 1 shows an overview of the conventional transportation route and an alternative transportation route addressed in this thesis.

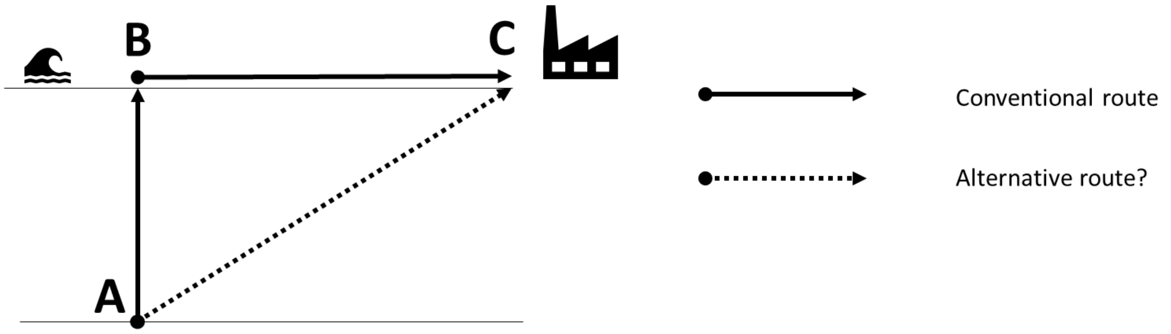


Figure 1: An overview of transportation route. Solid lines: Conventional transportation route. Dotted line: Alternative transportation route?

The conventional solution transports ore vertically from the seabed (A), to a standby mother station (B), and further transports horizontally to port (C). This thesis will investigate whether transportation can happen directly from A to C without going through B. The reader is informed that the diagonal arrow is not meant in literal terms. Its purpose is to illustrate the combination of vertical and horizontal transportation simultaneously as opposed to a two-step process. If an alternative transportation solution under water can be found, it may help solve some of the issues presented above. Thus, the hypothesis of this research is:

Underwater transportation can be an alternative transportation solution for deep sea mining.

The research objectives that are performed to confront this hypothesis are to:

i. Find the essential entities of problem by abstraction
ii. Identify the functions that the overall solution needs to fulfil in order to meet the problem
iii. Search for solutions that may meet with these functions
iv. Find promising combinations of solutions that meet the functions and overall problem
v. Firm up solution variants by applying results to Arctic Mid-Ocean Ridge location

1.3. Scope of work

The thesis will only concentrate on the transportation itself, not other activities such as excavation or processing. An important assumption that the thesis is based on is that the ore must be moved by some sort of vehicle, i.e. it cannot move on its own. This leaves out subsea transportation solutions such as extensive pipeline infrastructure, tracks, etc. The methodology applied is conceptual design methodology by Pahl et al. (2007, Chapter 6), see Figure 2.

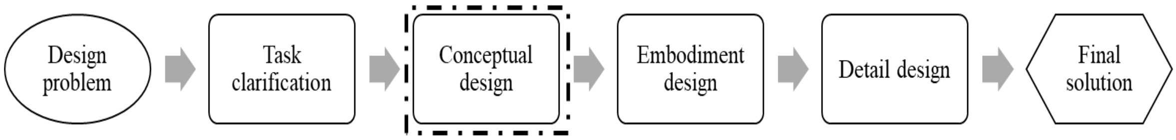


Figure 2: The activities in engineering design, adapted from (Pahl et al., 2007, p. 130). The scope of this thesis is shown with a dash-dotted line

The design process is limited to conceptual design, i.e. embodiment design and detailed design will not be covered in this thesis. This means that a validation in terms of production, experimental and computational testing of concepts is not included.

1.4. Structure of thesis

Chapter 2 reviews relevant literature laying the foundation of the thesis. Chapter 3 presents the methodology used in this thesis. Chapter 4 shows the results of the thesis after applying the methodology from the previous chapter. Discussion of results, methodology, and recommendations for further work is found in Chapter 5. Lastly, Chapter 6 is conclusion of thesis work.

2. LITERATURE REVIEW

The literature review will study mineral resources, relevant system concepts for mining and transportation, and the surrounding environment where a transportation system will be present. The resources vary in their geographic location, consistency, depth and more. This may influence a mining system and its operation, and therefore the characteristics of these mineral resources is investigated further in the following. Existing deep sea mining concepts and transportation systems are reviewed in order to gain more knowledge about an ore transportation system at deep seas. However, the design also needs to be able to operate in the marine environment. Hence, essential marine principles are presented. Lastly, systems design and conceptual design are studied, and what the current literature can tell about how to approach this early part of the design process.

2.1. An introduction to deep sea mining

2.1.1. Marine mineral resources

The literature distinguishes between *resources* and *reserves* when speaking of mineral deposits. The difference is that the former is only seen as exploitable in the foreseeable future given certain conditions such as technology, financing, legal framework, etc., while the latter is available (UNOET, 1987). Marine mineral resources can be categorised into three main groups: Polymetallic nodules, ferro-manganese crusts and seafloor massive sulphides.

Polymetallic (manganese) nodules are independent dark-coloured, potato-shaped rocks found at 3,500-6,500 m water depth lying on the seabed or buried in the sediment. They contain manganese, but also nickel, copper, cobalt, and iron in addition to traces of many other metallic elements – hence polymetallic. Fields containing such nodules are vast and common, but the economic potential varies greatly because of the variation in size, metal content and density. The regions expected to have greatest abundance of nodules are the abyssal Pacific Ocean and Central Indian Oceans, where the coverage is as much as 50% (J. R. Hein & Koschinsky, 2013; Kuhn, Wegorzewski, Rühlemann, & Vink, 2017; Mizell & Hein, 2018; Peter A. Rona, 2008). An area of high concentration and commercial interest is the Clarion-Clipperton Zone (CCZ) in the NE Pacific Ocean, located approximately between Hawaii and Mexico. According to the International Seabed Authority (ISA), a number of countries have entered into contracts for exploration of polymetallic nodules (ISA, 2019b). They wish to explore the economic benefits of the metals in the nodules.

Ferro-manganese (Fe-Mn) crusts are large dark layers covering the hard-rock substrate on the seabed at 1,000-5,000 m water depth. The formation contains mostly manganese and iron, but also cobalt, nickel, titanium, copper, and rare earth elements – in addition to interesting trace elements. The crusts can be found throughout the entire abyssal waters of the earth – including the Pacific, Atlantic, and Indian Oceans (Halbach, Jahn, & Cherkashov, 2017; Peter A. Rona, 2008).

Seafloor massive sulphides (SMS), or hydrothermal sulphides, are chimney-like formations found at 1,200-3,500 metres (Hannington, Jamieson, Monecke, Petersen, & Beaulieu, 2011). They consist of mostly iron, copper, zinc and lead, and some deposits exhibit gold and silver as well. SMS are found at the Atlantic Mid-Ocean Ridge (AMOR), but also in back-arc basins in the western Pacific (Hoagland et al., 2010; Peter A. Rona, 2003).

The type of resource to be mined are will affect the mining system. Manganese nodules are black, round “chunks” that are available to be picked up without any separation from the seabed – in other words, laying loose on the seabed. Crusts and sulphides however, are fixed to the seabed, and must be physically separated (broken) from the substrate. This may indicate that the former resource demands less effort than the two latter ones during excavation. Nodules are found on much greater depths than SMS, and somewhat greater than crusts.

2.1.2. Deep sea mining value chain

The mineral resources that have here been presented are difficult to both find, estimate and reach due to their great depths and variation in areal density and mineral content (Earney, 1990). It is important to know what activities that must be completed in order to generate value during the life cycle of a deep sea mining operation. A deep sea mining operation consists of many stages, from exploring possibly mineral-rich areas to distribution and sales of the product (Abramowski, 2016; ECORYS, 2014). The value chain containing these activities and their subsequent deliverables is presented in Figure 3.

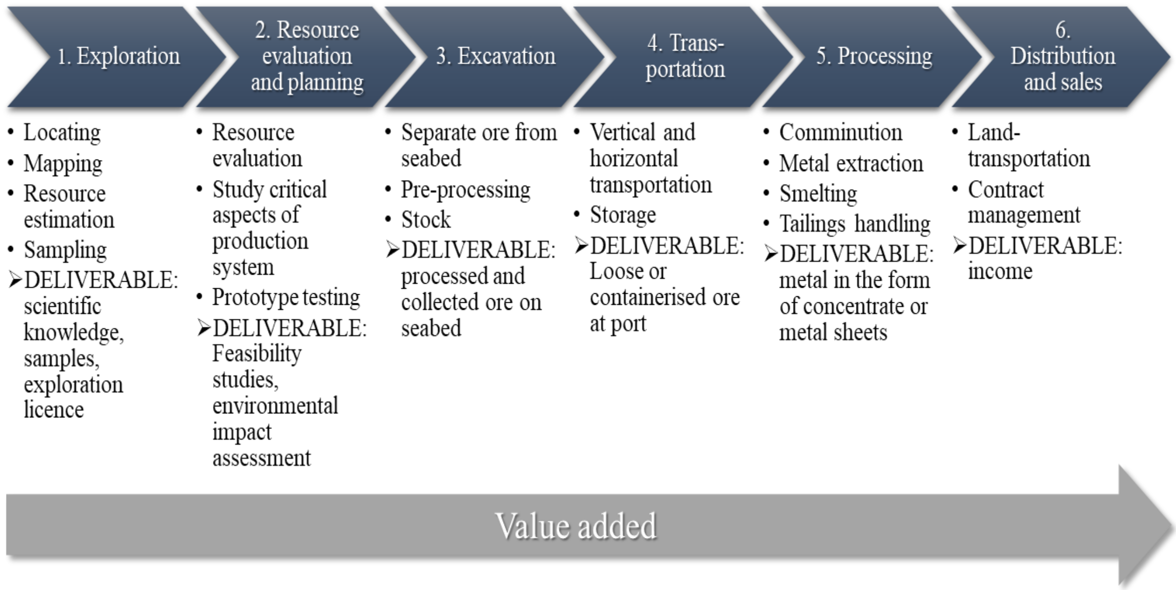


Figure 3: Deep sea mining value chain activities

A value chain is known as a company’s set of activities where each stage gets resource input which results in output generating value to the firm (Porter, 1985). One may think of value as something that fulfils someone’s need – whether it be a product, a service, or information or knowledge. The value chain presented here consists of six stages: exploration, resource evaluation and planning, excavation, transportation, processing, and distribution and sales. In the following, I will elaborate on the purpose of the activities seen in Figure 3.

A deep sea mining operation starts with **exploration** in order to gain information about the location and topography of a potentially mineral-rich site. Exploration here means locating and mapping the features of the earth’s core and its processes that lead to mineral-rich ore formation. Literature has previously addressed discovering field characteristics and geological processes that were previously unknown (Connelly et al., 2012). This may include crust thickness, hydrothermal venting and mantle upwelling. Furthermore, research has been conducted on imaging the earth crust and mantle in order to gain knowledge these conditions (Edmonds et al., 2003; Pedersen et al., 2010). The recency of some of this literature tells that the inside of the earth and the resources present on the seabed from the processes taking place here are still being explored. Further, estimating the metal content is important for the economic value.

Resource assessment means increasing knowledge about the resource abundance and development potential of deposits. Samples are important in order to determine the grade of mineral and metal value of resources. One sample may not be representative for an entire area, and thus many samples should be analysed to ascertain the potential of a deposit site. In addition, the obtained ore will provide information on processing and extractability. The evaluation of resources should also include an estimate on processing and how to achieve a successful venture (Roonwal, 2018).

Excavation is when mineral resources are separated and collected from the seabed. Some pre-processing of the rock, such as crushing and dewatering, may take place. The product is then stocked, either loose (in piles) or in containers on the seabed, awaiting further transportation. Unlike adjacent industries such as the oil and gas industry, the resources do not have be accessed by drilling far into the "ground" because the resources are present in the open at the seabed.

Transportation refers to the moving of ore from seabed to an onshore location. This step is essential in the value chain. The product must be moved up from the depth and towards shore in order to become available to a customer. While being moved the ore will need storage space of some kind. How much that needs to be transported and how heavy it will be, may vary from case to case. Compared to the oil and gas industry however, the process may be more difficult. When oil or gas is being transported from a deep reservoir to a platform facility, the pressure of the reservoir drives the hydrocarbons upwards – providing lift. This feature is not present for the mineral resources, as they are lying out in the open on the seabed. Traditionally, cargo can be shipped in different classes, depending on the form and packaging of the commodity, for instance as loose, containerized, palletized, liquid, and refrigerated (Stopford, 2009). For ore transportation it can be assumed that the class would be either loose (bulk) or containerized. A form of liquid is also obtainable, and that would involve pre-processing on the seabed, i.e. comminution of ore into slurry.

The aim of **processing** is to extract the desired metals from a sample of mineral deposit. For this, extensive equipment is needed. Only fractions of the ore contain metals that can be exploited, and the processing produces tailings which is the undesired residue. The ore may be crushed and mixed with seawater to obtain a slurry that can be transported through pipes. If this is the case, the slurry will also have to be dewatered, which adds another function to the processing. The degree of processing may vary, and the recovery rate of metals inside the ore is very dependent on the equipment available. Many scientists are welcoming more research into processing in order to increase the economic value. This would mean that more input resources would have to be moved to the seabed (from shore) in order to produce a more refined output (ore).

Distribution and sales is where the economic value added of the previous stages of the value chain is realised. The product has been located, excavated, transported to shore and processed, and is ready to be shipped to a customer. Who the potential customer is depends on the degree of processing of the ore and the type of metal extracted. The income accrued is most influenced by the price of metals, which traditionally has fluctuated (Abramowski & Stoyanova, 2012).

2.1.3. Example study at AMOR

The example location used for this thesis is Mohn's Ridge at the Atlantic Mid-Ocean Ridge (AMOR). Here lies a vent site called Loki's Castle, roughly between Svalbard and Jan Mayen, see Figure 4. The vent site is located at about 2,330 meters water depth on the Mid-Atlantic Ridge (Pedersen, Thorseth, Nygård, Lilley, & Kelley, 2013). The Mohn's Ridge is of great interest to the scientific and governmental communities due to the presence of seafloor massive sulphides (Juliani & Ellefmo, 2018; Martin Ludvigsen, Kurt Aasly, Steinar Ellefmo, Ana Hilario, Eva Ramirez-Llodra, Søreide, Ismael Falcon- Suarez, Cyril Juliani, Amanda Kieswetter, Anna Lim, & Malmquist, Stein M. Nornes, Emil Paulsen, Hauke Reimers, 2016; Pedersen et al., 2010; Regjeringen.no, 2019; P. A. Rona, Klinkhammer, Nelsen, Trefry, & Elderfield, 1986; Schander et al., 2010).

Figure 4: Map of Mohn's Ridge. Loki’s Castle with red dot and Svalbard port with yellow dot. Image courtesy: Google Maps, 2019.

SMS have a chimney-like appearance rising from the seabed. It must be physically torn from the seabed before transportation and possibly pre-processing. In 2016, exploration and collection of rock samples was performed during the MarMine exploration cruise project. The team obtained samples, tested technology for exploration and further explored the area to gain knowledge about resource potential, benthic fauna, and active and in-active hydrothermal vents. The samples were collected using ROVs with a manipulator arm and subsea baskets, and they contained copper and zinc, in addition to traces of gold and silver (Martin Ludvigsen, Kurt Aasly, Steinar Ellefmo, Ana Hilario, Eva Ramirez-Llodra et al., 2016).

The choice of port where ore is being shipped to is an important constraint. For this thesis, Svalbard was chosen further in this study because it is the closest to site (i.e. less travel distance) compared to other available ports, and they also have prior experience in mining (Ellefmo, Ludvigsen, & Frimanslund, 2017). However, the port may be covered in ice during winter time. This might be problematic when vehicle arrives at port. This implies that it might be difficult to move the ore (or unloading) from under water to the quayside. Therefore, production must either be avoided during winter, the ice must be broken, or the ore left under water without any damage being done to the vehicle. A solution should take this into consideration.

2.2. Deep sea mining concepts

Although there are no full-scale deep sea mining operations running yet, concepts have been developed. A particular focus has previously been on mining of nodules. There has been less research on crusts and SMS deposits. However, with the growing commercial interest and information on SMS, this has recently been a resource getting more focus (Yamazaki, 2017). This section will present the state of the art in deep sea mining engineering approaches.

The only industrial endeavour within deep sea mining is by Nautilus Minerals, a company aiming to commence production in Papua New Guinea (SRK Consulting, 2010). Nautilus Minerals intends to utilise technologies from offshore industries within dredging, oil and gas and offshore mining for mining minerals at high depths (Nautilus Minerals, 2019b). One of their most promising projects is the Solwara 1 project containing SMS. The deposit is located in the Bismarck Sea, Papua New Guinea, at approximately 1,600 metres below the ocean surface (Nautilus Minerals, 2019a). Their proposed solution consists of three seafloor production tools, a riser and lifting system (RALS), a production support vessel (PSV), and ore transportation using shuttle barges in addition to onshore processing activities (SRK Consulting, 2010). The crawlers on the seafloor will excavate, gather and comminute ore. For further transportation a vertical riser system will carry slurry to the PSV using a large subsea slurry lift pump. Onboard the PSV the slurry will be dewatered, stored, and later transferred to a barge using conveyor belt ship-to-ship transfer. The effluent will be returned to the water column using the riser. The dewatered ore will further be sent to shore for processing, and further shipped for smelting (Coffey Natural Systems, 2008). A schematic view of the production can be found in Figure 5.

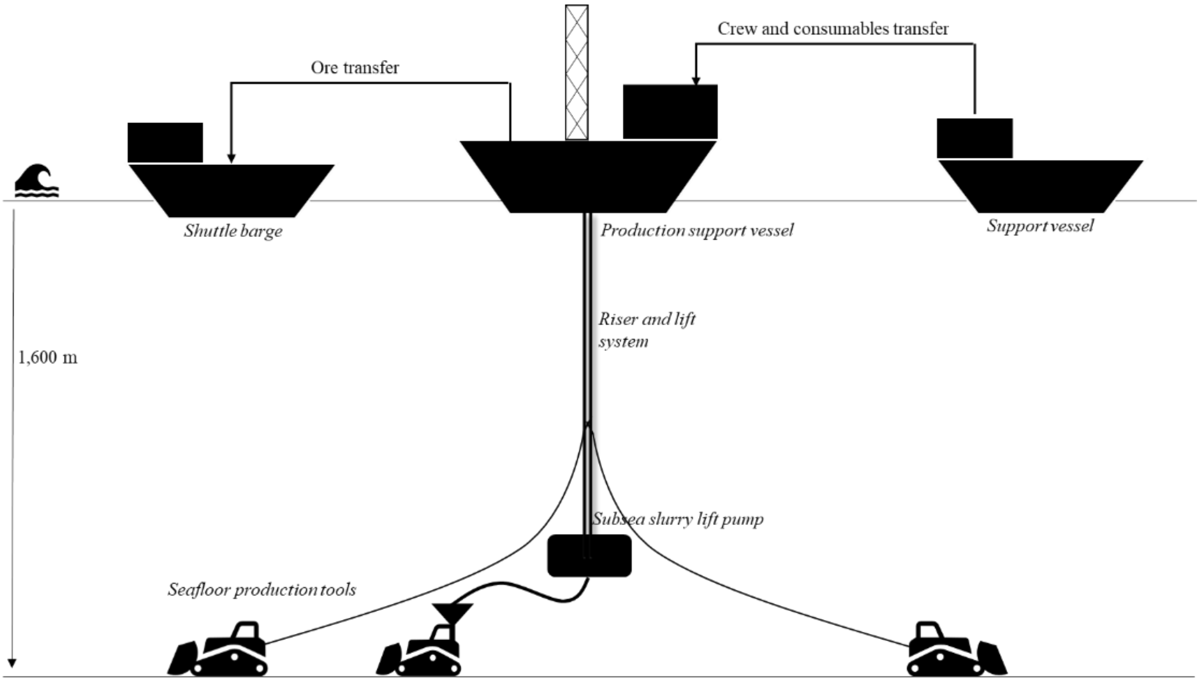


Figure 5: Schematic view of Nautilus Minerals intended production

Krypton Ocean Group is a company developing underwater vehicles for deep sea mining at depths up to 6,000 m. They have also made a proposal for a mining system using the vehicles. The resource for mining is polymetallic nodules. However, they also explore other mineral resources. Krypton Ocean have developed three different types of vehicles: the remote-controlled underwater mining apparatus (RCUMA), an autonomous underwater vehicle (AUV), and a manned underwater vehicle (MUV). The RCUMA is a vehicle for mining of polymetallic nodules with remote-control from the mother vessel.

It uses a ballast system to submerge to the seabed, where it collects nodules by scooping the seabed with its rotating chain collection device. The chain collecting device harvests nodules mechanically, and the nodules are then unloaded into an onboard tank. The nodules are then pre-processed inside an own chamber by crushing. When the crushed nodules have the necessary grain size, the resulting slurry can be lifted using a flexible riser and high-pressure pump (Krypton Ocean, 2019c). The Krypton AUV 1 is an autonomous vehicle for sampling and transporting nodules. It immerses towards the seabed using buoyancy at a rate of 4.5 km/h. When it is positioned a sampling tool grabs nodules using a vertical conveyor. It can carry up to 1 ton of nodules, and it has a 110 kW unit powered by hydrogen fuel cells with reserves for up to 8 hours operation (Krypton Ocean, 2019a). The Krypton MUV 1 is an autonomous/manned underwater vehicle for exploration and underwater operations. The vehicle resembles the AUV in its characteristics, but it also has a grabbing tool in the front for gathering samples. The manned version has room for 3 crew members, and it can supply oxygen for 1 hour (Krypton Ocean, 2019b). Considering the oxygen supply and the immersion rate, it is reasonable to believe that the manned version is designed for operations at lower depths, although this is not specified.

The mining system proposed by Krypton Ocean consists of three AUVs, one semi-submersible vessel with a deck frame structure, two handy size ore carriers, and two pusher tugs, see Figure 6. The AUVs are as described above, and they are located on the deck of the semi-submersible vessel together with the tugs. A semi-submersible vessel is a ship that can adjust the draught using ballast tanks in order to change the immersion of the ship, making the ship semi-submerged. This vessel immersion feature is practical when wanting to load and unload the tugs and AUVs.

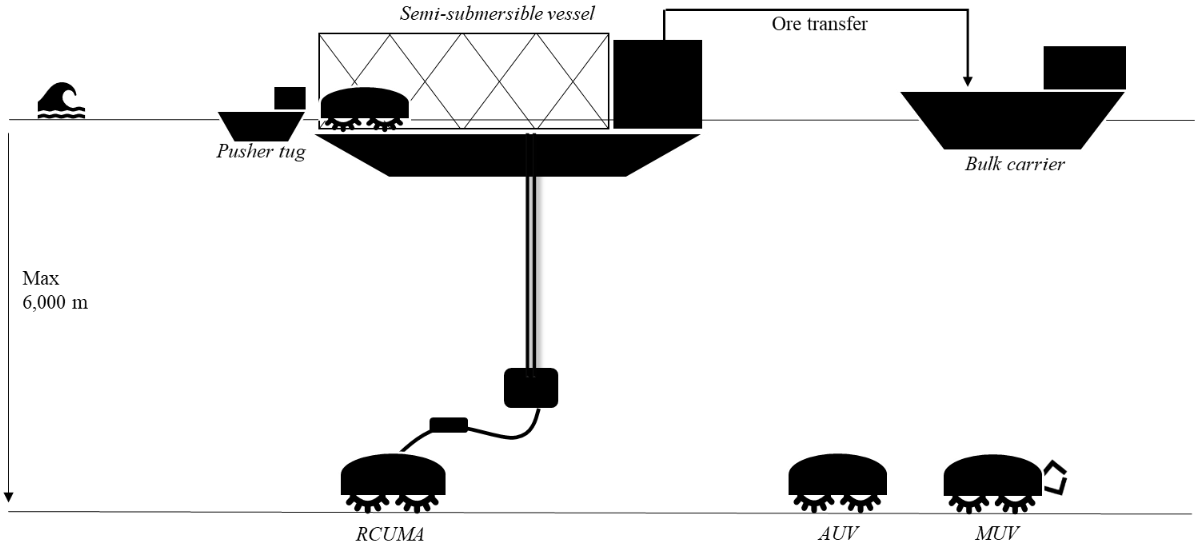


Figure 6: Schematic view of Krypton Ocean concepts and mining system

A successful ore excavation and lifting pilot test was conducted for seafloor polymetallic sulphides at 1,600 m by The Ministry of Economy, Trade and Industry and The Japan Oil, Gas and Metals National Corporation (METI & JOGMEC, 2017). The aim was to study production technologies for ocean areas surrounding Japan in order to potentially develop resources for domestic supply of minerals. Once the ore was excavated, it was collected using a submersible seafloor pump. Further, it was lifted towards surface support vessel through a riser pipe.

2.3. Underwater transportation vehicles

This section will address literature on underwater vehicles that have (payload) transportation function.

Brown & Clark (2010) have studied a large, long-range UUV (LRUUV) with payload-carrying capabilities. The paper uses a computer program for conceptual design of UUVs. The tool takes payload size, power consumption and other requirements as input, and gives out vehicle sizes and weights. The LRUUV is designed to pick up, carry, and drop off a large weight payload. They present three different concepts: 1) Internal Payload Vehicle, 2) Expandable Internal Payload Vehicle, and 3) External Payload Vehicle. As the names imply, the difference between them is whether the payload is stored inside the vehicle itself or carried beneath the hull, see Figure 7. The first and second concepts have payload inside the vehicle while the third concept have the payload outside the vehicle. The second concept has a payload expansion option when deployed, which limits the space when stowed. The carrying capabilities must be of a “large-volume, variable payload of unspecified weight”. The vehicles are designed to carry up to 4.5 tons at a water depth of maximum 450 m. The transit range is between 20 and 300 nmi (~40 to 550km).

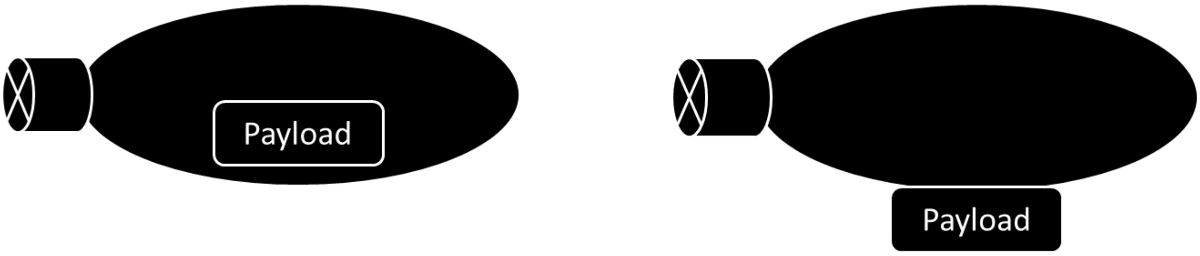


Figure 7: View of LRUUV with internal and external payload integration

Malinetsky & Smolin (2019) investigate the opportunity of using Cargo Autonomous Underwater Vehicles (CAUV) for underwater transportation of cargo under ice cover through the Arctic Ocean. A challenge of surface transportation in this area is the ice cover, which may limit the use of surface vessels. The need for specialised underwater vehicles was demonstrated after experiments with military submarines revealed that although this type of operation is possible, there were several economic challenges: the low payload-carrying capabilities of the submarines, the complexity of load/unload-operation, and the inability to enter shallow ports.

The concept consists of lighters carrying 1-2,000 20 ft containers, CAUVs, and a seafloor train system. Lighters (i.e. simplistic barges) are used for parts of the route that are without ice formation. When the lighter arrives at ice border, the CAUV sends up robotic devices with giant latches weighing more than 10,000 tons that clasp the lighter. The latches and the AUV are connected by hawsers, and the lighter is lowered into the water by AUV winding the hawsers. The lighter and CAUV then travel underwater as one unit using the seafloor train system. When the ice formation has ended the lighter is detached by releasing the hatches, and it floats up for further surface shipping. See Figure 8 for an overview of transportation.

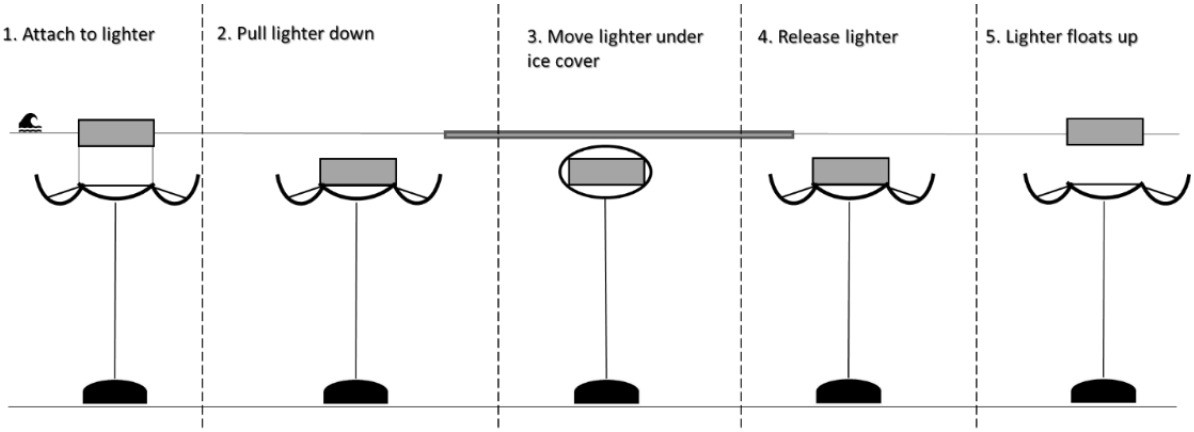


Figure 8: Transportation under ice cover using CAUV

2.4. Design for the marine environment

Any structure or vehicle in the marine environment must adapt to its surroundings in order to not succumb to its forces. The difficulties of a deep seabed exploration is related to the presence of total darkness, great hydrostatic pressure, resistance created by viscosity in seawater, and irregular topography (Earney, 1990). This section will investigate forces present in the physical environment. By the physical environment, we mean the seabed, the ocean column, and the ocean surface. The basic requirements of a vehicle's operation in the marine environment are flotation and stability. The principle of flotation in water for any vehicle is Archimedes' principle: Any solid body immersed in liquid will experience an upthrust equal to the weight of the fluid displaced. The weight of the fluid displaced is the volume of the solid body times the density of the liquid it is immersed in – i.e. buoyancy (Rawson & Tupper, 2001). Both an immersed vehicle and a surface vehicle will experience hydrostatic forces from the water onto the wet surface. Flotation is possible due to inflicting water pressure. A submerged vessel will experience pressure increasing with weight according to the following formula

$$p = \mathrm{p}_0 + \rho g h \ ,$$

where p_0 is the atmospheric pressure, ρ is the water density, g is the gravitational acceleration and h is the immersion depth (Amdahl et al., 2014). The relation above shows that the more an object is submerged, the more the outer walls will feel compressive forces. For a surface vessel the weight is made up of the weight of the ship (including any cargo). The weight can be intentionally altered by adding or rejecting weight, known as ballast (Hawley et al., 1996). Also, most underwater vehicles have ballast tanks to allow this adjustment of weight. For submarines in particular, the weight is also altered because of consumables and discharge of weapons (Renilson, 2015). Another quality of ballast tanks is the possibility to adjust trim. Trim is an imbalance in the angle of the vehicle which makes the vehicle tilt towards one side more than another. For a surface vessel (longitudinal) trim is often undesired because it can give increased wave resistance or an open propeller issue, which both increase power consumption. For a vehicle under water, trim does not need to be an undesired factor – in fact, trim is used by gliders to move in a so-called "saw-tooth pattern", meaning that it dives and climbs when moving forward using buoyancy in order to save energy (Jenkins & D'Spain, 2016).

Forces of fluctuant and stochastic nature that marine vehicles are subjected to are waves, currents and winds. Unlike for wind, waves and currents excitations are found throughout the whole water column and surface level. These metocean forces must not exceed acceptable limits. Hence, another important requirement of a vessel becomes stability. Stability is the ability for an object to regain its original state after suffering a minor disturbance (Rawson & Tupper, 2001). The responses of a marine structure after being subjected to the above-mentioned excitation effects are important. A vessel or structure will gain a response from the excitation and added mass depending on factors like size and mass. The excitation responses are due to incoming forces while added mass responses are due to the forced oscillations of water. The added mass effect may be a significant contribution to the motions that the marine vehicle must withstand (Pettersen, 2004).

A vehicle moving in water will experience drag, or water resistance, see Hawley et al. (1996) for an overview of hydrodynamic estimates. It is important to estimate the magnitude of the total resistance because it indicates the required amount of force – and subsequently power – for moving the vehicle. The total resistance is made up of the bare hull resistance, R_{BH}, and the appendage resistance, R_{APP}:

$$R_T = R_{BH} + R_{APP} \ .$$

The first term constitutes approximately 60-70% of the total resistance. The bare hull resistance has been predicted as

$$R_{BH} = \frac{1}{2}\rho A V^2 C_t \ ,$$

where A is the reference area depending on the type of vehicle, V is the speed of the vehicle and C_t is the drag coefficient. The drag coefficient is made up of

$$C_t = C_f + \Delta C_f + C_r + C_w \ ,$$

where C_f denotes the resistance due to friction between water and hull, ΔC_f represents the resistance due to surface roughness due to for instance rough surface or venting holes. The residual resistance, or drag, coefficient, C_r, is the resistance arising from the physical shape of the vehicle. The physics behind relates to where separation of flow occurs. Empirical estimates have been made to propose values depending on shape. The wave making resistance coefficient, C_W, denotes resistance due to wave making when resurfacing. If the vehicle is only operating under water this may be neglected. Summarised, the bare hull resistance is made up of the vehicle speed squared and the drag coefficient accounting for water resistance due to the hull. The second resistance term, appendage resistance, is resistance due to any apparatus causing a deviation from the main hull shape:

$$R_{APP} = \frac{1}{2}\rho A V^2 C_{t-app}$$

Examples are submarine sail and manipulator arms. The appendage coefficient, C_{t-app} is estimated empirically (Hawley et al., 1996). The required (effective) power for vessel propulsion is found by the same means for both surface vessels and submerged vessels. It is defined as the product of the total resistance and vessel speed (Carlton, 2007):

$$P_E = R_T \cdot V$$

The required power is essential because it determines how much energy needs to be stored onboard and how effective the vessel is. Effective here means the endurance under water versus energy used. The energy stored onboard for propulsion is commonly diesel engines for surface vessels, while for underwater vessels there is a distinction between nuclear and secondary battery systems, where the former is used only for military submarines. The difference in endurance between the two energy supply systems is immense – the nuclear is almost unlimited in energy supply while batteries are limited to hours and days (Hawley et al., 1996).

2.5. Design of systems by mapping between domains

A system is a set of interrelated entities, whose functionality is greater than the sum of the individual entities (Blanchard & Fabrycky, 1998; Crawley, Cameron, & Selva, 2016; NASA, 2007; Suh, 2001). It is comprised of the entities inside the system boundary and the outside of the system boundary is known as the environment (Pahl et al., 2007). Entities may be components or subsystems that are dependent on or influencing each other each other. Design of systems is a top-down approach (Suh, 2001). It is a process executed in order to achieve a desired state (Coyne, Rosenman, Radford, Balachandran, & Gero, 1990). A desire, or need, may be an attribute, product or system that is necessary or wanted. The needs domain represents the space where these needs are identified and expressed. The next step is to find which actions must be undertaken to meet these needs. The main action that we want to be executed is the overall function – the intended benefit produced by the system. The overall function may be divided into smaller subtasks. After identifying these actions, it is necessary to find the physical solution that perform this action – the form (Crawley et al., 2016).. The journey between needs, functions and form is called mapping, see Figure 9.

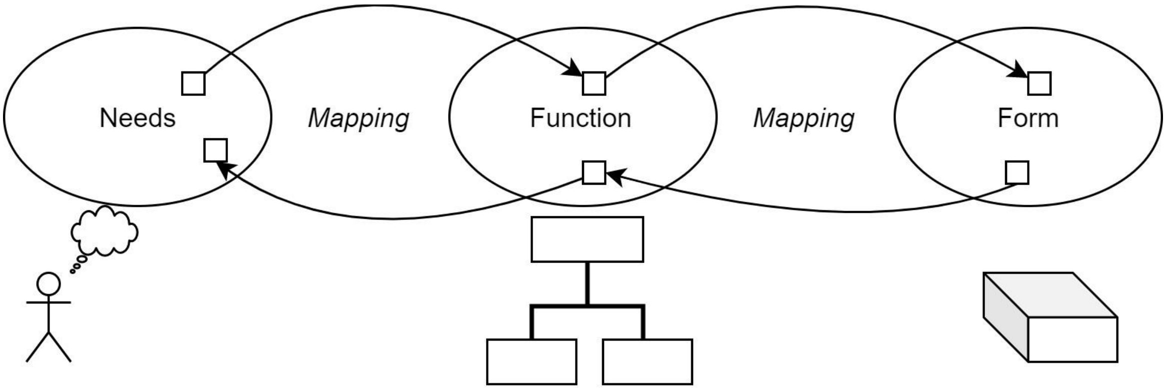


Figure 9: Mapping between needs, function and form domains

Mapping means that new information is gathered throughout the process. Hence, the solution must be continuously refined in order to obtain improvement (Pahl et al., 2007, p. 53). Mapping from function domain to form domain finds forms to the functions which together give a combination producing a new effect. This is called synthesis. When mapping from form domain to function domain the designer analyses whether the form yields the function it intended to (Pahl et al., 2007). After the functions have been identified, an evaluation is made between the intended functions and produced functions, see Figure 10.

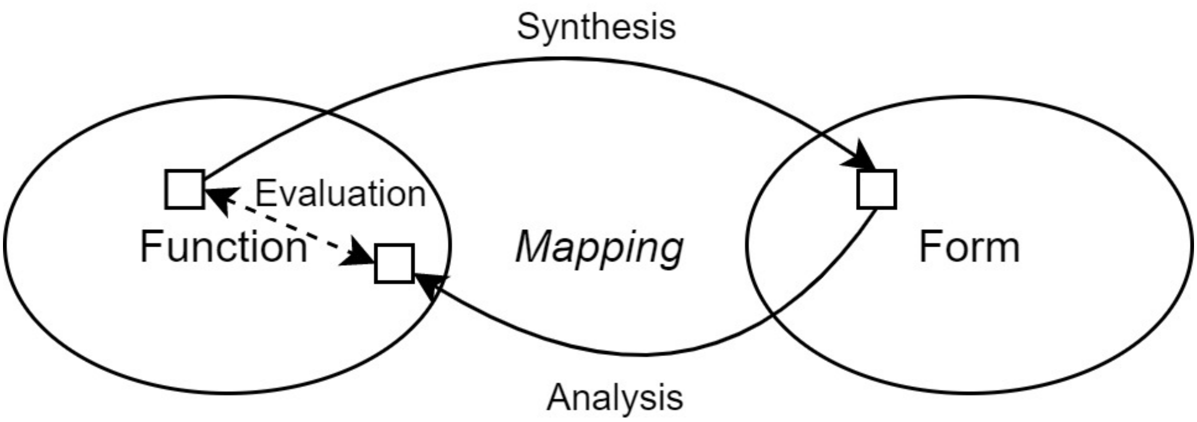


Figure 10: Synthesis, analysis and evaluation when mapping between domains

During evaluation the functionality is studied. Functionality means what the system achieves: an action which in turn produces an output and an impact. The output is the immediate result of the action, while the impact is a result seen from or on the environment, not necessarily immediately apparent (Crawley et al., 2016; Hubka & Eder, 2002). The rationale behind having a system is that the system achieves an output and an impact not possible with the entities alone. However, some impacts, or outcomes, may not always be desirable. A ship, for instance, has subsystems such as a propulsion system while being in an environment with waves, winds, and other metocean conditions. Its main function (or purpose or mission) may be "(safe) transportation of payload from port A to port B", where payload could be containers, cars, people, etc. (Levander, 2012). The desired and intended output may therefore be the transportation of payload, while undesired outcomes may be emissions from burning fuel. The analysis of physical solution and its functionality is important in order to become aware of, and try to avoid, developing unwanted functions or features.

2.6. The stages of conceptual design

Conceptual design is the first part of the overall design process. This section will investigate conceptual design approaches in the literature. Elements that will be addressed are: the steps of conceptual design and the primary focus of the book in question.

Ulrich & Eppinger (2012) find the first stage of concept development to be identification of needs and establishing specifications, generating product concepts and selecting product concepts. The primary focus is on product development; more specifically marketing, design and manufacturing. In other words, it is suited for designers wanting to create a product as a business opportunity. Understanding the market and potential customer is important, but they also present design methods and procedures, such as concept selection methods.

According to Blanchard & Fabrycky (1998), a well-known handbook in systems engineering, conceptual system design starts with an identification of a need. They have a solid focus on requirements not being only related to customer needs and technical feasibility, but also operational requirements and lastly maintenance and repair. This is justified by stating that it is not only necessary to know *what* functions that a system will perform, but also *where*, *when* and *how* the system will perform these functions. This step is then followed by a functional analysis where system requirements are translated into actions that is necessary to achieve the given objective. Functional block diagrams are used to structure the system requirements. The final product of the conceptual design phase according to Blanchard & Fabrycky (1998) is a system specification that is either approved for further design process or rejected.

The book that constitutes the framework of this thesis, Pahl et al. (2007), has the following steps of the conceptual design are: abstraction to identify essential problems, function structures, searching for solutions (called working principles), combining solutions (into working structures) and selection and evaluation of concepts. The final product of the process is a principle solution, which may be taken into embodiment (layout) design and further into detail design. The process is systematic with a strong focus on charts and architecture as a way of structuring the problem. The book is more product-oriented than system-oriented, and they offer many solution-finding methods with subsequent examples. Although the procedure is structured, it is not strict – the designer is requested to choose the methods and path that suits the problem best, and even intuition used for finding ideas is acknowledged. There is a strong focus on the creative and innovative part of concept development, and it highly recognizes the design process is an iterative process. The rationale behind this is that decisions and information are needed in order to obtain knowledge.

Literature has also tackled the science of system architecture. Crawley et al. (2016) provide methodologies of system architecture and focus more on the principles and how they work together than the design itself. Many of the topics treated is interesting to a design engineer, such as stakeholder analysis and decision-making. Summarized, the literature agrees that the conceptual design process involves the following stages: Identifying needs, abstract the essential objectives, functional analysis, solution-searching and concept selection, see Figure 11. The next sections will treat these steps in more detail by using the literature presented and other relevant literature.

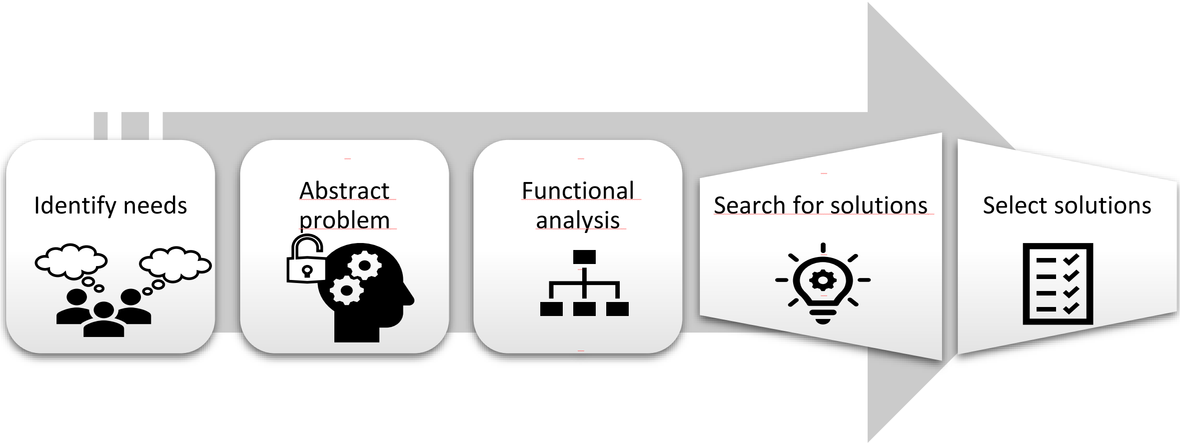


Figure 11: The steps of the conceptual design process

2.6.1. Identifying needs and opportunities

From NASA (2007, p. 19) it says that "All systems start with the recognition of a need or the discovery of an opportunity". A need is an attribute desired by the customer, while opportunity can be thought of as a hypothesis of how value can be created (Ulrich & Eppinger, 2012). More generally, a need is a desire for one or more entities, or for new or improved capability (Blanchard & Fabrycky, 1998). The stakeholder's needs are important throughout the whole design process to achieve success of the project. However, the literature is divided as to what a stakeholder is. Crawley et al. (2016) find that a stakeholder is someone who has a stake in a project – they are important to the project owner's needs because they might influence it. NASA (2007) however find a stakeholder to be any "customer or interested party", i.e. a stakeholder is someone who has both interest and influence on the project. These needs can be identified by performing a stakeholder analysis. In order to perform a stakeholder analysis, data and feedback from stakeholders are needed. The analysis will take the needs and transform them into goals or requirements. The needs are not specific for a project while requirements are. However, a stakeholder analysis is not always performed because it is not possible or not needed. For instance, in the case where a company only wants to do minor adjustments to a product or a contract specification is present, requirements are often available in advance (Pahl et al., 2007).

The number of stakeholders may be vast and their needs may be difficult to characterise and even conflicting. Pahl et al. (2007) emphasise the importance of a requirements list and propose discussion about different needs of stakeholders. Further, they also propose other methods for determining a new need for a product – including within the company itself. It starts with the importance of analysing the current situation. This could be an investigation of the current status of technology, the company's competence, market trends and product diversification in life cycle phases. After one or several of these aspects have been studied, the next is search strategies for gaps that can be exploited. These are an identification of strategic opportunities, needs and trends, and considering company aims which will lead to a limited number of search fields. Strategic opportunities have to do with finding gaps within aspects from the situational analysis, such as the product range or market. A company may choose to i) introduce new products in current market, ii) develop existing products into new markets, or even iii) create new products for new markets. Different reasoning may be behind such strategic decisions. The company may make changes to product line or market if expecting increased profits or increased market shares from making the changes. As stated, the company may also try to identify needs and trends that can be exploited. This may be found in the change of customer behaviour, for instance the current increased environmental awareness. Customer needs can also be found by gathering raw data from customers (Ulrich & Eppinger, 2012). This may come from interviews, focus groups, or observing the product in use. Statements from end-users or others may further be used to identify needs and their subsequent importance.

2.6.2. Abstraction to find essential entities

A central part of system architecture is finding the essential entities of the real world (Crawley et al., 2016). Developing a perfect model of physical phenomena is not possible and as such a model will always be a distortion. A scientist may choose idealization or abstraction to develop concepts, see (Woods & Rosales, 2010). They explain that idealization is a way of over-representing the physical phenomenon by basing a model on assumptions that are not true, while abstraction is under-representing the physical phenomenon by only extracting some of what is true. To a design engineer, abstraction is useful when needing to analyse a system and extract only the parts of a phenomenon that are essential to shed light on. Pahl et al. (2007) define abstraction as "ignoring what is particular and incidental and emphasising what is general and essential". This corresponds well with other literature, such as Chakravartty (2001, p. 328) that find abstraction as choosing some relevant parameters to be represented in a model and leaving out other parameters that are relevant to the phenomenon. Crawley, Cameron, & Selva (2016) distinguish between abstraction as "an expression of quality or as a representation having only the intrinsic nature rather than detail".

The literature has different views on why abstraction is necessary. Chakravartty (2001) find two reasons: First, the number of factors representing some phenomenon may be too high for modelling them in a practical manner. Second, we might not be interested in all the factors related to the phenomenon because it might be irrelevant or outside our scope. Pahl et al. (2007) however see abstraction as a way of finding the *crux of the task*, i.e. identifying the essential problem of the design process. The rationale behind is that designers are influenced by previous experience and mental blocks, and abstraction is a way of opening up the path to other ideas that was not initially clear or apparent to the designer. In conclusion, the literature distinguishes between abstraction as either *expressing essential problems* about the physical phenomenon or *representing essential parameters* about the physical phenomenon.

When choosing method for abstraction the *degree of novelty of the product* will be the most defining. Differentiation in degree of novelty can be made between three types of designs: Original designs, adaptive designs and variant designs. Original designs involve development of new tasks and problems, either entirely new or creating new functions and properties. Adaptive designs mean making changes to the embodiment of a design but keeping the solution principle. Variant design involves changes in size, parts or assemblies of a product, but the functions and layout remains the same (Pahl et al., 2007, p. 64). To know this differentiation is important with regards to the extent the design team can or aim to utilise knowledge, experience and existing solutions when making a new design.

2.6.3. Establishing functions

The aim of function analysis is to establish the functions required and the system boundary of a new design (Cross, 2000). It is important that the design synthesis process leads to a design that fulfils the *overall function*. This is a functional statement of the overall task of the design problem (Pahl et al., 2007). The overall function can be divided into *main functions* which are (sub)processes that have been divided from the overall function. See Figure 12 for an exemplification of the first three levels.

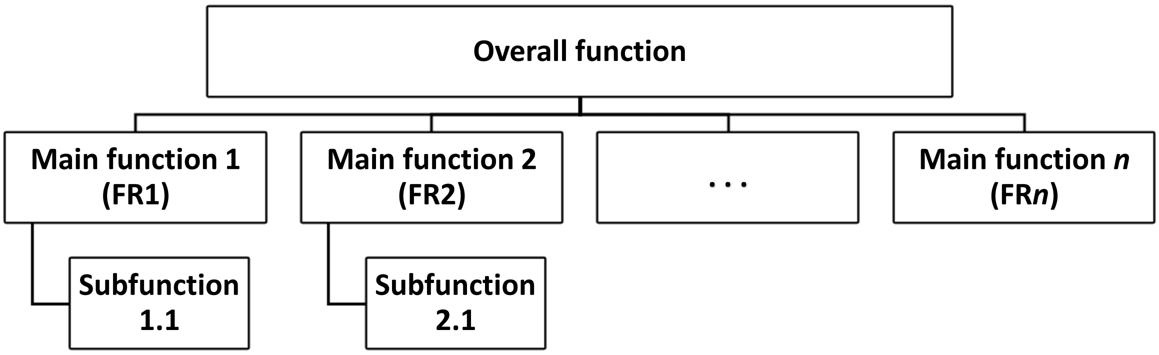


Figure 12: The first three levels of a functional hierarchy

The written formulation of the function often consists of a verb and a noun, which describe the flow conversion of input to output. All technical systems have flow conversion of energy, material and signals (Pahl et al., 2007). Type of energy may be mechanical, thermal, electrical, chemical conversion, but also force, heat and current. The type of material may be raw material, sample, component, but it can also refer to the physical state of a product, such as gas, liquid or solid. The type of signals can for instance be data, information, impulse, magnitude. Using block diagrams is helpful when wanting to express solution-neutral relationships between input and output, see Figure 13.

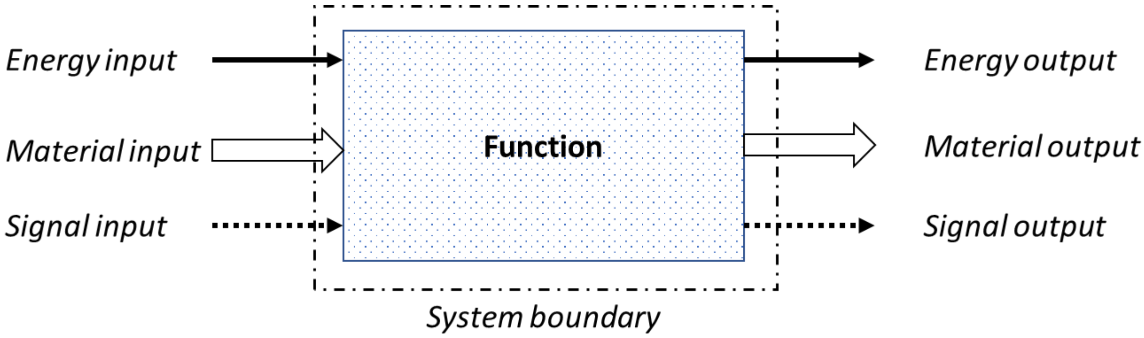


Figure 13: Block diagram of energy, material and signal flow input and output. Adapted from Pahl et al. (2007), p. 30.

The system's boundary is shown with dash-dotted lines. The block diagram shows the flows and the corresponding overall function representing the conversion of flow input to flow output. The different types of flow conversion are energy, material, and signal conversion respectively. Energy conversion is related to conversion of power, currents, forces, etc., such as for instance changing energy from chemical to mechanical energy in a combustion engine. Material conversion has to do with conversion of gas, liquids, solids, etc., for instance the transportation, packing or coating of a component. Signal conversion is related to the processing of information, for instance connecting and displaying data. All the conversions can the connect, store, channel or vary flow (Pahl et al., 2007).

2.6.4. Searching for new ideas and solutions

There are many ways of generating ideas and finding solutions. Pahl et al. (2007) divide them into conventional methods, intuitive methods and discursive methods. Conventional methods is the use of state-of-the-art information, such as literature studies, analysis of processes in the nature, analysis of existing technical systems, using analogies and measurement and model tests. Intuitive methods include brainstorming and other group creativity methods. Lastly, discursive methods include studies of physical processes (relationships between input and output of functions and their variables), systematic search with classification schemes and the use of design catalogues. Classification schemes are a way of structuring information into rows and columns. They are also known as morphological charts (Jones, 1992; Zwicky, 1967). The method searches for interrelations between physical objects and phenomena in order to systematically explore the entire solution field – making sure nothing is overlooked. The book further states that ideally, a combination of solution-finding methods should be applied to extend the solution space.

2.6.5. Selecting suitable combinations

When a satisfactory solution space is present, the designer may start the selection process. The aim of this is to find the optimal solutions of the many possible solutions available. The literature distinguishes here between tools providing an overview of options, and tools aiding in the decision-making. Basic decision support tools such as the morphological matrix from above and design structure matrix are useful, straightforward methods for representing decisions and options (Crawley et al., 2016). The design structure matrix is a study of entities and concurrent systems, and how they interrelate. The entities of the matrices may be components, decisions, functions, and more which a project or system is made up od. This is used for getting an overview and identifying connections and different systems which may be used to make decisions about sets.

Although a good overview of the alternatives are given through these methods, they do not give an adequate representation of the results and outcome of decisions. The exception is perhaps the decision trees, where performance factors, such as profit, can be included in the tree. Concept selection can also be viewed as where solutions are evaluated against criteria, such as customer needs and other criteria, and comparing relative strengths and weaknesses between concepts (Ulrich & Eppinger, 2012). According to Pahl et al. (2007) narrowing the solution space should happen in two stages in a systematic approach: first eliminating all theoretically possible, but practically unattainable solutions. This is called elimination, and four criteria are stated. The solution should be: 1) compatible with overall task and one another, 2) fulfil demands of requirements list, 3) be realisable with respect to performance and layout, and 4) be within permissible costs. If the solution space is still too large, preference should be given to solutions that: 5) incorporate safety measures or favourable ergonomic conditions, and 6) are preferable by designer’s company. Such selecting criteria are also proposed by Jones (1992), suggesting ranking and weighting as a way of comparing solutions. This type of method may vary as to how quantitative they are: numerical or divided into more subjective ranking such as “level of satisfaction”. They could also be somewhere in between, such as “number of complaints.”

To summarise, some think of this process as a decision-making process while others think of it as an evaluation (and preference) process. All the same, it concerns a passing of judgement on a situation with options.

3. METHODOLOGY

This chapter will present the methodology used for encountering the problem of this thesis: *Transportation of ore from seabed to shore.* Conceptual design methodology by Pahl et al. (2007) serves as the methodology framework. First, the essential problem(s) are found through abstraction. Then function structures are established, and further working principles fulfilling these functions are found. Moreover, these working principles are combined into working structures, and suitable selection of combinations can be found. Furthermore, solution variants are found, see Figure 14 for a flow chart of method.

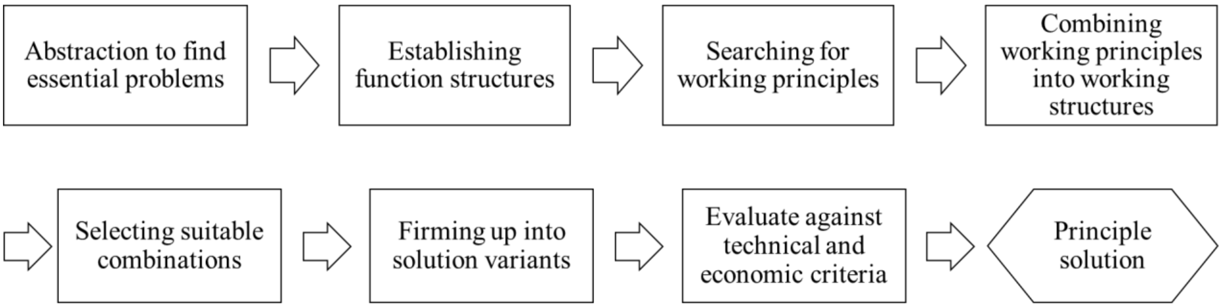


Figure 14: The steps of conceptual design by Pahl et al. (2007, p. 160)

The next sections will present the steps in more detail. The last step has been excluded because there is not adequate and satisfactory data available to make an appropriate evaluation of costs. Thus, the method will deal with the steps from abstraction to firming up promising solution variants. Upon the last step a product and location are specified in order to provide context and illustrate the findings. Thus, the result of the thesis will be one or more solution variant(s). The steps of conceptual design have been dealt with in the literature review, and examples will be provided in the results to increase understanding as the method is applied. Therefore, this chapter is kept concise.

3.1. Abstraction to find essential problem

Abstraction is a way of extracting the general and abstract information and ignoring the incidental information (Pahl et al., 2007, p. 161). It requires the designer's ability to unlock the mind from thinking in objects and visual images. By abstracting the true overall function and important constraints appear. Abstraction to find essential problems can be done either by systematically broadening the problem formulation or by analysing the requirements list. Broadening of problem formulation is a stepwise enquiry to discover extension of original task and bring it to a higher level. A requirements list is a list of demands provided by a customer or found through stakeholder analysis. The lack of a requirements list favours the method of abstraction through broadening the problem formulation. However, this method is also favourable due to the novelty of the task. It was seen in the literature review that the development of deep sea mining concepts is limited and no operation is up and running yet despite decades of research. It is therefore reasonable to say that we are dealing with a task of limited experience, i.e. an original design. When dealing with this type of novel design it is important to remove mental blocks in search of solutions, and this level of abstraction aids in that regard.

The problem formulation is extended through systematic study of the physical processes. This facilitates the acquisition of the goal formulated in the problem definition: transporting ore from seabed to quayside under water. The physical process of the transportation activity of the value chain is coherently studied to establish what state the material is in, and how it converts from one state to another. Illustrations with basic figures are provided to increase understanding, but all the while trying to keep it free of a designer's prejudice.

3.2. Establishing function structures

The division of the main physical process and their interrelationships lead us to the overall function. This is found by taking the goal of the task along with the first input and the last input of flow conversion and system boundary. Here, block diagrams as seen in Figure 13 are used. Once the overall function and its corresponding block diagram are found, it is time to proceed to the function structures. This is a systematic and discursive method that does not exclude intuition. The procedure starts with deriving a rough function structure based on the steps identified during abstraction. This is done by working from the system boundary and inwards and determining the inputs and outputs of functions. The output of one function, will be the input of the neighbouring function in terms of flow. Keeping a consistency in flow and aiming at solution-neutral formulation helps in creating the inputs and outputs. The relationship between functions must be logical, but also related to the physical process as identified through abstraction. Decomposition of the structure should be done until one cannot be solution-neutral anymore. This is a trial and error procedure, and it is easy to get stuck because abstracting is challenging to the mind. Making something more abstract is going against nature of human beings: visualising solutions in your head and concretizing (Pahl et al., 2007).

The practical application of function structures depends on the novelty of the task. For this thesis, the problem formulation and abstraction are crucial. In order to find the function structure, the subfunctions which it is made up of need to be found. The subfunctions are essential in obtaining the overall function and they are related through their flow conversions, as seen in Figure 12. When the main flow is found, the flow is analysed further by studying the flow conversion. The rationale here is that the flow might be converted in several sub-steps between the input and output of the overall function, and that this might lead to a clearer picture of generally valid subfunctions. After finding the stages of flow conversion, the subfunctions can be obtained by studying the input and output of flow. It is important to keep consistency between the inputs and outputs on all levels, and the function itself must represent the flow conversion.

The function structure is rarely free of a designer's prejudice. Hence, it is important to propose a preliminary solution as early as possible and abstract this. By abstracting in a function analysis context, it means finding the fundamental and solution-neutral functions and flow conversions so that no parameters in the designer's mind are given preference. To exemplify, think of the difference between "lifting" and "moving" something. Which is the most solution-neutral? The first verb indicates that something changes position vertically, while the last verb indicates that something simply changes position. The designer may proceed to the next steps without completing the function structure in its entirety. This is because the design process is subject to iteration, and knowledge gained along the way is at least as important as the knowledge from start.

3.3. Searching for working principles associated with functions

This section is were forms are found to the functions identified. The designer is here expected to aggressively seek solutions, and insight into the solutions, in order to explore and expand the solution field. Good ideas cannot be forced (Pahl et al., 2007, p. 83), and a systematic exploration is needed. This stage of the conceptual design process can be divided into three:

1. Searching for and listing working principles
2. Abstracting classification parameters from list of working principles
3. Placing the classification parameters and working principles into a design catalogue

First, there is an extensive search for *working principles (WP)* associated with the subfunctions. A working principle may be any physical solution (form) which fulfils what a function describes, see Figure 9. When searching for working principles several methods may be used, such as literature searches and intuition-based methods. For our case, it may be useful to look for similar solutions in the subsea and offshore industry, the mining industry and the dredging industry. However, only imagination sets boundaries on where to look for solutions that fulfil the function at hand. It is important to be careful about excluding any of the found working principles at this point. This is a time for widening the solution field – not assessment of suitability. The working principles are listed with a brief text, including any extra equipment or auxiliary functions needed in order to make it operable. Also, a complimentary sketch and possibly reference is added.

Next, the list is analysed for information about the solutions, their characteristics and principles, and any similarities in physical principles. This may require a lot of iteration, since there is no straight forward method for recognising principles – it requires training. These principles are called *classification parameters (CP)*. These classification parameters are derived through discursive methods, which do not exclude intuition. When the working principles have been listed, and appropriate classification parameters found, it is now time to create the design catalogue of the function in question. The design catalogue is a matrix containing the classification parameters in the columns and rows, and the working principles in the cells. Design catalogues give the full overview of possible solutions for one of the main functions. If there are more than two types of classification parameters, the design catalogue may be expanded into more pages.

Summarized, it is important for the designer to have a creative mindset and to not exclude solutions nor put unnecessary constraints to the solution space. This is the time to be inventive and imaginative – not to evaluate or disparage. This part of the design process illustrates why it is so important that the functions remain as abstract as possible. If we think about the example from the previous section, it can be seen that a possible working principle for "lifting" may be an elevator, while a possible working principle for "moving" may be both an elevator and a car.

3.4. Combining working principles into working structures

Once the working principles are found, and these have been combined into design catalogues, we may search for the overall solutions. The overall solutions are made from combining one working principle from each main function, also known as a *working structure (WS)*. Once one solution is found for each function, we have a working structure which – if able to be assembled together – fulfils the overall function. During this stage of the process it is important to not just consider the solutions individually, but also consider how the solutions put together perform together in an overall solution. This is done by creating a morphological matrix where the rows and columns are made up of the main functions, classification criteria and working principles. Here, we may put the design catalogues that have been created, and as such we get a full visual overview of our solution space. By adding the physical principles to the matrix as well, the designer gets more information about the physical process behind the solutions which might give indications about the subsequent effort and performance of the solution. The morphological matrix is not only useful to the designer alone – it can be used to create many working structures. Thus, this matrix is not merely a tool, but also a result which may be useful to others. A morphological chart is particularly suited for problems of novel nature, as the one in this thesis. This is because the method does not only rely on changing existing solutions, but exploring what is beyond existing solutions.

At this point all solutions to the main functions are available, and it is time to combine these in order to find an overall solution. From this stage of the design process the solution field will become narrower. The first step is to eliminate solution variants that are by no means suitable. The morphological matrix is very useful for getting an overview and picking working principles providing us with an overall solution. However, more guidance is still needed as to how to combine these working principles into a suitable working structure. The issue now is to pick combinations that are favourable from the large field of theoretically possible combinations. If the set of solutions is large, preselection is necessary to reduce effort as early as possible (Pahl et al., 2007, p. 215). Functions and their respective working principles have to this point been treated separately, i.e. there has not been an investigation of the relationship between functions and between forms. This calls for a proper study of the compatibility between functions and solution variants. Combability refers to two or more entities existing together without conflict. This examination can be performed with a *compatibility matrix*. It investigates the combination possibilities between classification parameters of subfunctions. The choice of which classification parameters to combine in the compatibility matrix is up to the designer. The ultimate goal of the compatibility matrix is to be a tool for ensuring smooth flow of energy, material and signals (Pahl et al., 2007, p. 103).

When the compatibility matrix is set up, a study of how the CPs work together is made. This may be done with a simple “yes/no” or more explanation. Only compatibility should be studied, and any further evaluation should be delayed for now. Combinations that are impossible are shown by a solid cross over the cell, and less compatible solutions are shown by a dashed cross over the cell. The compatibility matrix is essentially a matrix for information processing, and as such the possibilities are vast. The designer should utilise this to the benefit of the design process.

3.5. Selecting suitable combinations

During this stage it is time to select combinations based on the solutions found and the compatible solutions. This part of the design stage depends on the novelty of the task, and the actual process may vary largely between cases. In essence, it involves taking the knowledge from combining into working structure and select the suitable combinations for further study.

The compatibility matrices and morphological matrix from the previous section make up the framework for selecting suitable combinations – i.e. suitable working structures. Only promising solutions should be pursued. Decisions must be made about which classification parameters that are compatible together, and which working principles from the morphological matrix this applies to. The result may be one or more working structures. There should be a bigger focus on the classification parameters, and what they entail for the overall solution than the individual working principles. Further analysis of the resulting working structures and inherent working principles should be done, and observation should be made that may aid in the next process.

3.6. Firming up into solution variants using specific location

At this point it is necessary to select between the working structures by elimination and preference. The working structures will be analysed and evaluated for operation at AMOR, see Section 2.1.3. The elimination is where the theoretically possible, but practically infeasible working principles are removed. In other words, the totally unsuitable solutions are excluded from the solution space. This must be handled with caution because the strength of a working structure appears after combination of working principles. Further elimination and preference are given based on the following criteria:

A. Being compatible with the overall task and one another
B. Incorporate safety measures
C. Being attainable with respect to performance, layout, and costs

Criterion A means that the concept proposal should have working principles that are compatible together, and that they together achieve the overall task. This means that a fundamental requirement is that they fulfil the functions found. However, some working principles have additional requirements, and it should be evaluated to which extent these are acceptable or not. As stated in Section 2.5 the evaluation investigates whether the solution obtained in the form space can perform the actions previously stated in the function space. Moreover, the surrounding marine environment will be determining for the external compatibility.

Criterion B involve incorporating safety measures. A solution should not only be internally functional, but also consider the external conditions. The suitability of a solution depends on the characteristics of where the operation takes place, e.g. depth, distance to shore, weather, etc. This criterion needs a more qualitative approach, and review of the solutions available will be performed to assess their expected level of safety. Safety measures here means avoiding solutions that involve harm, danger, or risk to humans, equipment and environment.

Criterion C deals with the performance, layout, and costs of the working structures. The performance of the working structure may be qualitatively evaluated by using the information from Section 2.4 about the fundamental requirements of a marine structure subjected to the forces of the marine environment. The layout has an important influence on the resistance. This includes any appendage and sharp edges that hinder a smooth flow. The costs are not found in exact numbers, but the evaluation will be based on information about the working principle regarding transportation efficiency and costs. E.g. endurance, utilisation of cargo hold, carrying capacity, or solutions that are known to require extensive and/or costly equipment.

The criteria presented here are the ones that are in focus. Other criteria, such as the ones from Section 2.6.5, are not prioritised here. Criteria are sometimes difficult to establish due to lack of information, and preference or elimination may be done (Pahl et al., 2007, p. 107). ‘Fulfilling demands of requirements list’ is not relevant since such a list is not a part of the method, see Section 3.1. ‘Being within permissible costs’ is difficult to determine as what is ‘permissible’ may vary from project to project and the data to calculate in exact numbers is lacking. However, costs are an important constraint in any project, and therefore it is included in criterion B above. Lastly, ‘preferred by designer’s company’ is subjective and project-specific and cannot be decided here. Simple sketches of the resulting solution solution(s) are provided.

3.7. Summary of methodology

A designer using the systematic approach to engineering design is expected to complement the process by the ability to abstract, work systematically and to think logically and creatively. Figures, tables, lists, block diagrams and drawings will be widely used to assist in the process. This is convenient because some of the stages in conceptual design are quite abstract and the human mind comprehends more when subjected to visualisations than plain text. The methodology of this thesis can be summarised using a flow chart, see Figure 15.

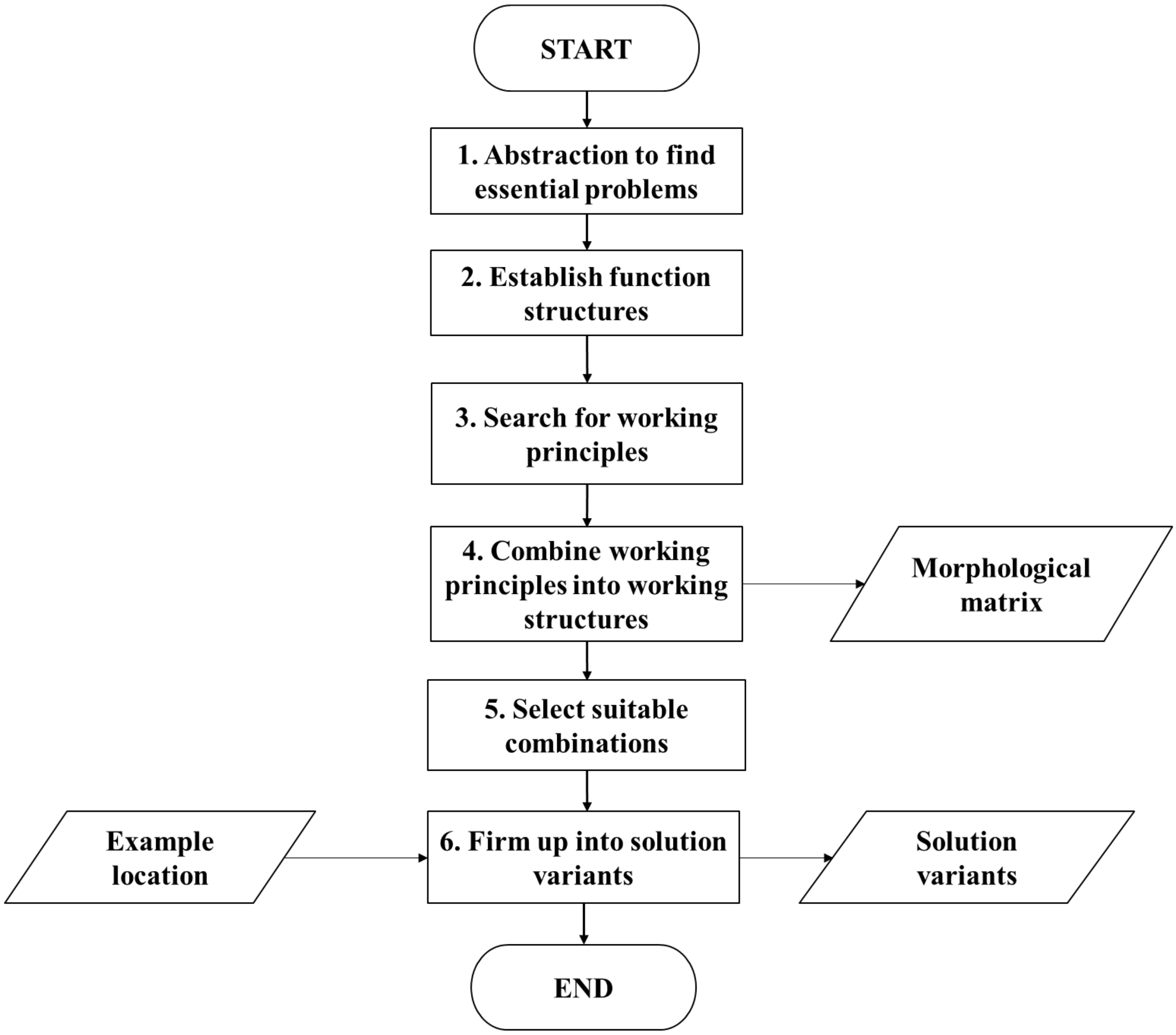


Figure 15: Methodology flow chart based on conceptual design by (Pahl et al., 2007)

4. RESULTS

This chapter will present the results from using the methodology presented in the previous chapter. It starts with abstraction and establishing function structures, which is where the foundation for the solution-space is created. Next, the mapping from function to form begins, i.e. finding physical solutions, or working principles, that fulfil the functions found. This is a comprehensive section because it involves a literature study to find the solutions, and an abstraction of the principles, or classification criteria, these are made up of. The working principles and classification criteria are then put into a joint catalogue. Further, the combinations of functions with respect to classification criteria and working principles are explored. Based on the compatibility between principles a selection of working structures is performed. Lastly, solution variants are firmed up using the example case from Section 2.1.3.

4.1. Abstraction by systematic broadening of problem formulation

The problem formulation is the basis of abstraction. The goal has been defined as “to transport ore from the deposit at seabed to the quayside”. This is the solution-neutral formulation of the goal – a goal that does not favour any particular design. We start by identifying the objects, or entities, that the problem is made up of. There is a product that we want to bring to the quayside – the ore. This product comes from a seabed deposit. Further, an assumption is to use an underwater vehicle. The objects that the task consist of are therefore the ore, the seabed deposit, the underwear vehicle and the quayside. The deposit and quayside are locations and therefore stationary, as opposed to the underwater vehicle and ore. This, in addition to the goal of the task, tell us that the main flow of this thesis is the *material flow of ore*.

Now it is time to go into detail on the physical processes. It is presupposed that the ore is present at the seabed in some form (either loose or contained – it is not known yet), and it is also assumed that the ore will be available at quayside once our mission is finished. This assumption is necessary in order to have a starting point and an end point for the material flow. It is not known about the state of the ore yet, but the input and the output of our system are known. Having defined the entities of the system, the boundaries and inputs and outputs, a simple sketch may be made of the high-level material flow shown using white arrow, see Figure 16.

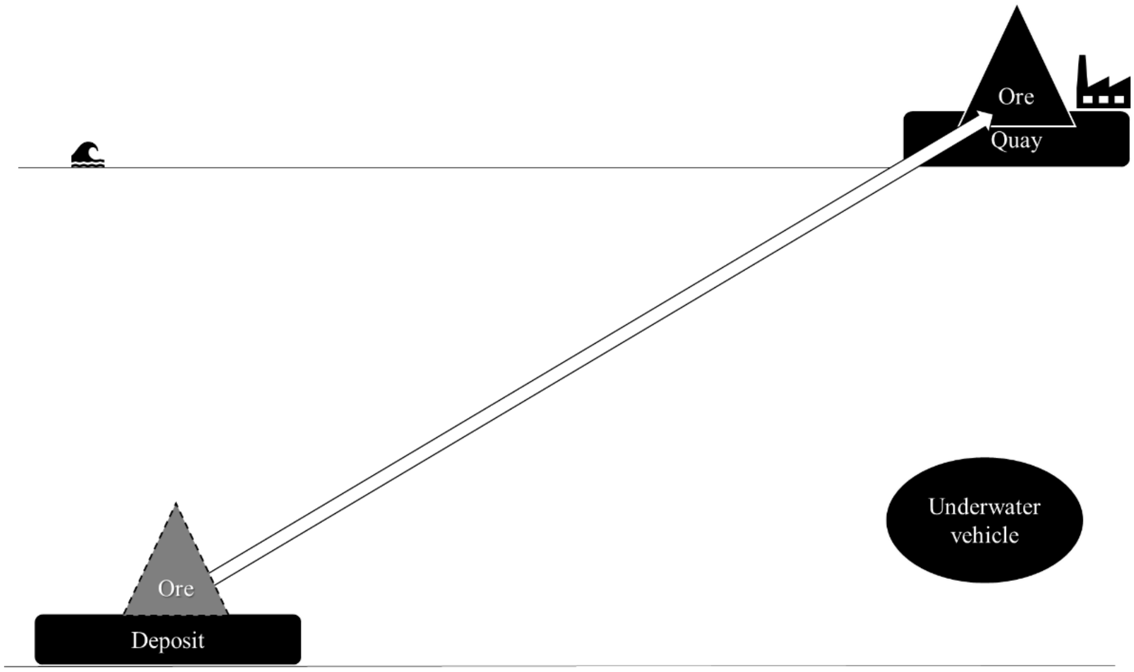


Figure 16: High-level material flow of underwater system

The figure shows the locations – deposit and quayside – as squares, the ore as a triangle and the underwater vehicle as an ellipsoid. We know that the flow conversion is related to material flow, but what type of conversion it is remains to be determined. The conversion is the action from or to a flow in order to achieve a certain goal. For our case the conversion of material flow is the *transfer* of ore, which is shown by a white arrow as seen in Figure 13. The figure and the goal of the concept generation given the scope of this thesis provide with the first and last state of the ore. The first state of the ore is being available at the seabed. By being available it is meant that any extraction from deposit and preparatory steps have taken place and that the ore is ready for shipment with regards to any processing. The last state concerns the ore being available at the quayside at the port's location – ready for any further processing, sales, and distribution.

The high-level material flow is the basis of the further study of physical processes. We are now ready to dive into detail on the process, i.e. to study the next level flow. The basis is the initial state of the ore. It is available on the seabed, lose or containerised, and awaits transportation. The underwater vehicle has positioned itself in proximity of the ore to be collected. The ore must now be transferred in proximity of the vehicle including some form of physical attachment, i.e. when the underwater vehicle decides to move, the ore will move with it. This transition from seabed towards vehicle is shown as a white arrow, see Figure 17. In conclusion, the first material flow concerns the collection of ore from seabed towards the underwater vehicle at the deposit's location.

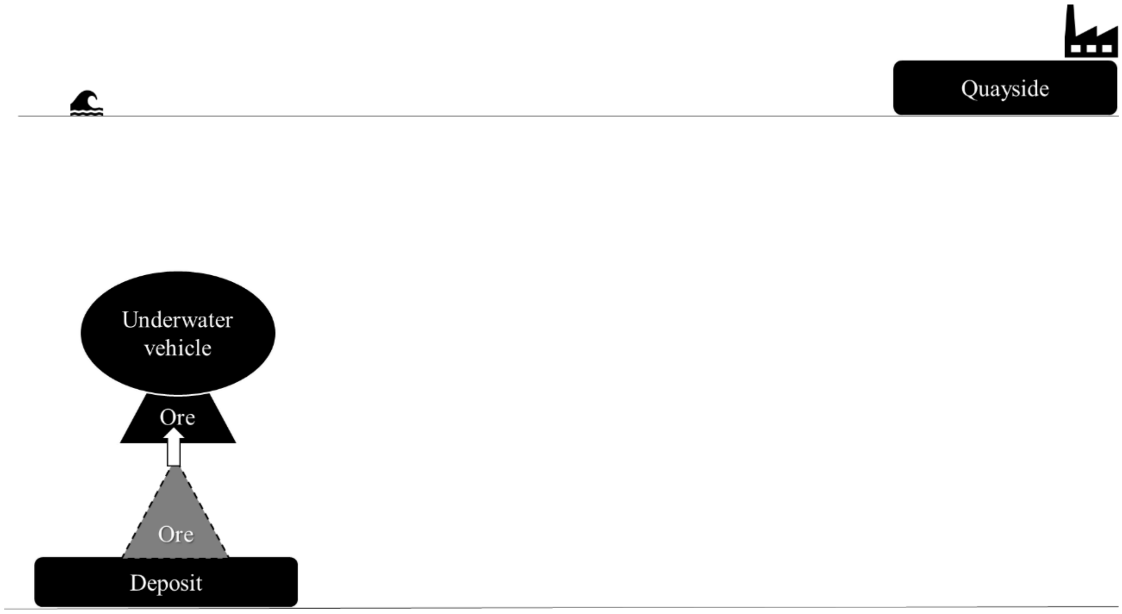


Figure 17: Ore flow from seabed deposit towards the underwater vehicle

The ore is now collected and somehow attached to the underwater system. We now want to study the next conversion of the ore. We have assumed that any necessary pre-processing has taken place upon collection, and the ore is therefore ready to move towards shore. The underwater vehicle will serve as the entity making this possible, see Figure 18.

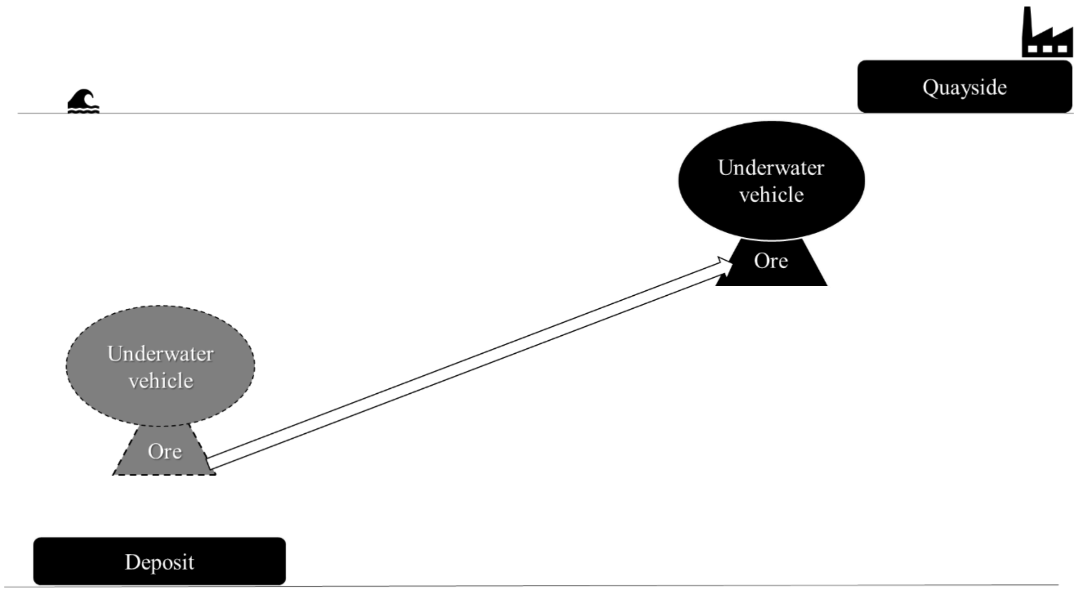


Figure 18: The flow of collected ore from deposit's location to port's location

The starting point is the deposit's location. Further we know that we want it to be at port after the conversion has taken place. This process happens under water. The port is located a good distance from the deposit in terms of water depth and horizontal distance. In other words, a vertical and horizontal movement is needed during the transfer.

Now the underwater vehicle and collected ore are at the port's location. By port's location, we mean that the vehicle and ore are still under water and close to the quayside. The ore is still attached to the vehicle, and we know want the ore to be available at quayside. Thus, the next flow of material is the moving of ore from port's location (underwater) to quay (above surface). This can happen in two different ways: 1) the collected ore is transferred to the quay alone, or 2) the underwater vehicle and collected ore are transferred to the quayside together as one unit, see Figure 19 and Figure 20.

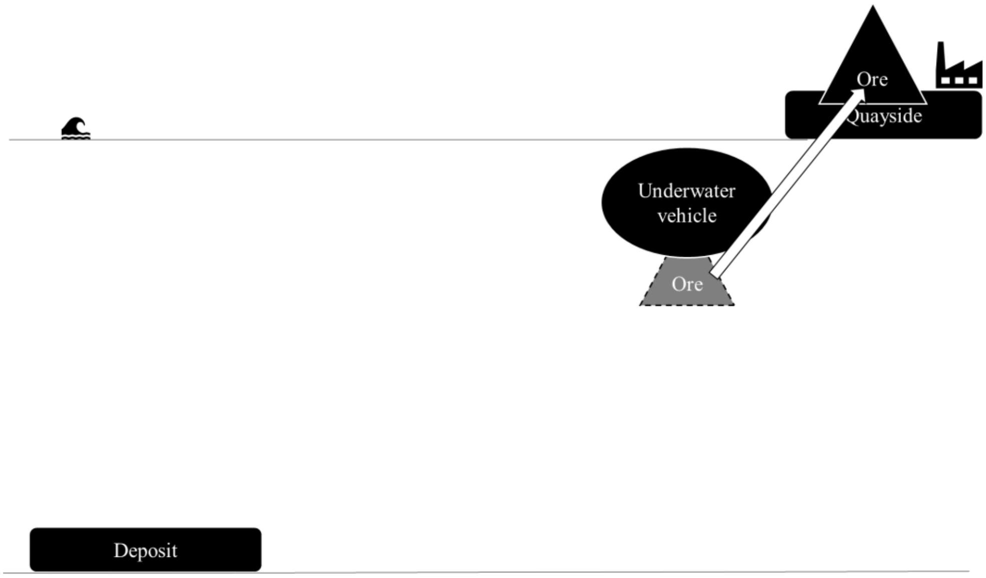


Figure 19: The flow of collected ore from port's location to quayside, alternative 1

Alternative 1 will now be explained further, and then alternative 2. The ore is either in loose form or containerised, and it will have to be separated from the underwater vehicle somehow since the vehicle will not go to the surface as well. If the ore is in loose form it may either be contained by the vehicle itself or be inside a container. It will then have to be moved from the underwater vehicle or container to the quayside by some form. Another alternative is that the underwater vehicle dumps the ore on the seabed next to the quayside. If the ore is containerised the separation between vehicle and container may look more straight forward.

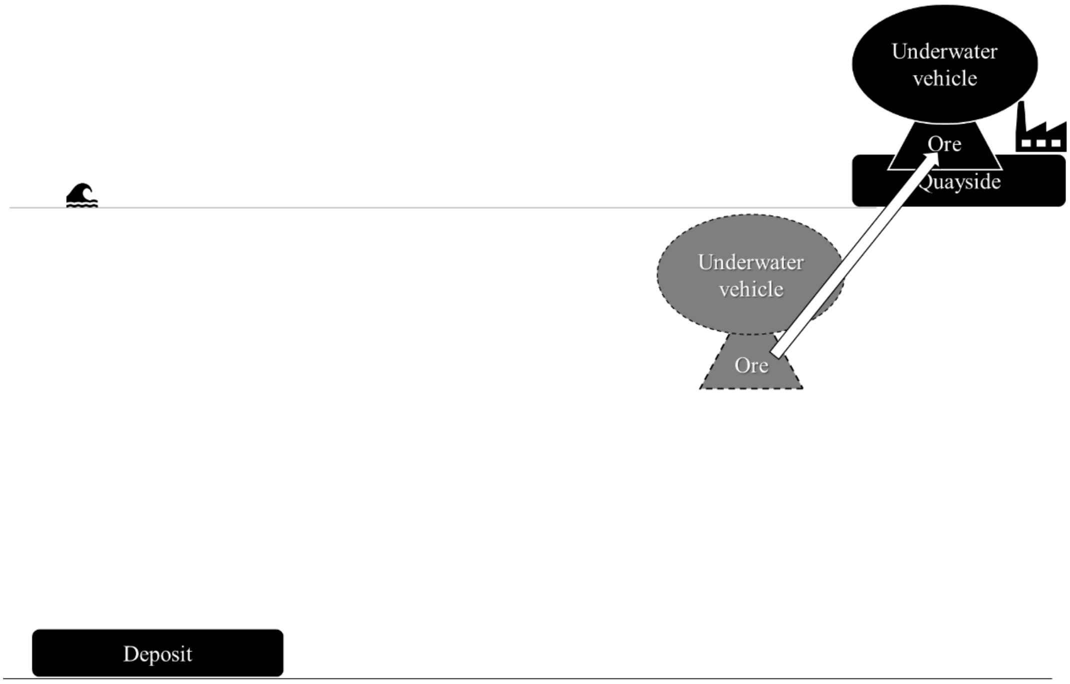


Figure 20: The flow of collected ore from port's location to quayside, alternative 2

The second alternative involves bringing the ore and vehicle together as one unit to the quayside. This initially seems like too much effort. We may wonder why we would move an entire vehicle with the ore to the quayside when we may only move the ore alone. It is almost certainly heavier, and it may seem to be purposeless to have the vehicle on the quayside where it has no function. Is this alternative even worth considering for further study? It is here argued that it is brought further into consideration because there may be needs that are unfamiliar today that suggests considering this option after all. Such needs may for instance be related to operation and maintenance and repair (M&R). Questions that may arise related to this are: Does the vehicle need refuelling? Does it need any M&R? These are all challenges where surfacing of vehicle may be an option. Refuelling, restocking and M&R are actions that may comprise of less effort to be performed on quayside – depending on factors such as fuel type, propulsion system, uptime of vehicle and components, etc. This may be particularly useful if the ore is contained inside a cargo hold of the vehicle.

4.2. Establishing function structures

We have now abstracted the problem at hand. The important characteristics of the transportation have been identified by studying the physical processes. From the material flow abstraction exercise, we can now see that the ore flows in three different stages: First from seabed deposit's location to the underwater system, then from deposit's location to the port's location and lastly from the port's location to the quayside. In order to find the main functions, a study of the work that is done for the flow to go from input to output. It is crucial to maintain consistency between input and output of flow at all levels.

4.2.1. Overall function

The material input and output of the overall function can be shown in a block diagram, see Figure 21.

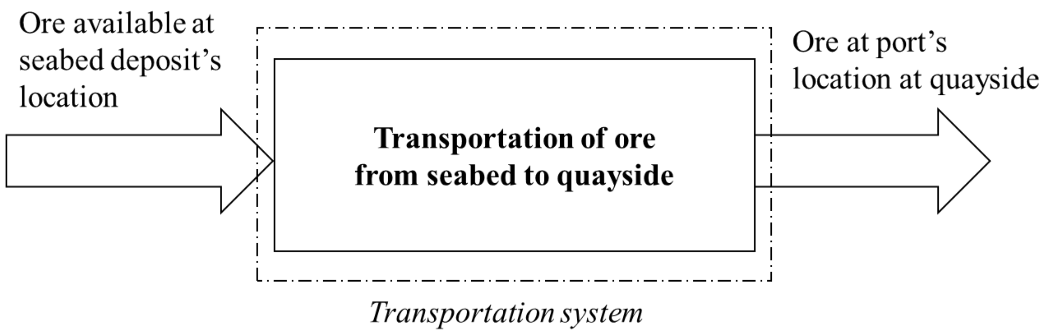


Figure 21: Block diagram of the material input and output for the overall function

The first input flow is the ore available on seabed at deposit's location. The final output is the ore available at quayside at port's location. The system boundary of transportation system by shown in dash-dotted lines. The overall function is shown in bold writing: "transportation of ore from seabed to quayside".

4.2.2. Material flow at deposit's location

It is seen from Figure 16 and Figure 21 that the first flow input is "ore available at seabed deposit's location". From Figure 17 the output of the first main function is that the ore is attached to the underwater vehicle at deposit site. More specifically, the output becomes "ore collected in the underwater vehicle at deposit's location". 'Collected' means that it is moved and stored in proximity of the vehicle. The system needed to convert the flow from “available” to “collected” is a collection system. Hence, the first main function (FR1) becomes: “Collecting the ore from deposit’s location to the underwater vehicle”. See Figure 22 for a material flow block diagram for FR1.

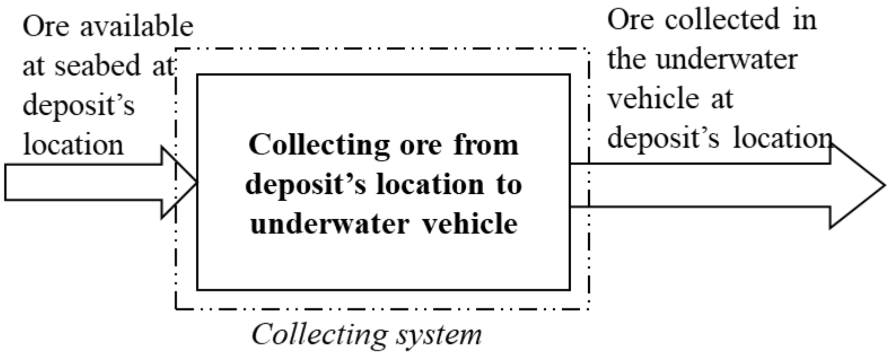


Figure 22: Material flow block diagram for FR1

It was considered to use “underwater system” instead of “underwater vehicle” in order to make the function more general. A system is something inside a defined system boundary, and as such it can be many things. A vehicle gives a bigger indication of the form that the solution would take. It was still decided to choose “vehicle” because of the assumption in this thesis that a vehicle will aid in the transportation. Furthermore, the choice of preposition in the formulation of the function was challenging. Using for instance “into” or “onto” would give an indication on how the ore would be stored. This would give unfavourable indications of the final solution, and the function would thus not be solution-neutral. It was chosen to simply use “to”, which means that there is a transfer *towards* the vehicle without giving any more information that points out a particular solution.

4.2.3. Material flow from deposit’s location to port’s location

The input of the next main function is equal to the output of the previous one, according to the principle of flow conservation. The input thus becomes “ore collected in the underwater vehicle at deposit’s location”. From Figure 18 the output of the second main function is related to the underwater vehicle together with the ore being available at port site. More specifically, the output becomes “ore in underwater vehicle at port’s location”. From both the input and output there is one colloquial term connected to the system and that is the “underwater vehicle”. The difference now is that the ore is at different sites between the input and output. Being at different sites entails that there has been a change in position – a movement. Hence, the second main function (FR2) becomes: “Moving collected ore from deposit’s location to port’s location”. See Figure 23 for a material flow block diagram for FR2.

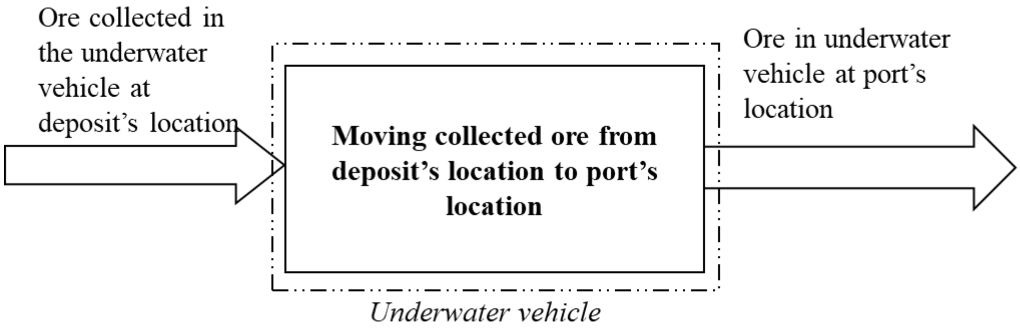


Figure 23: Material flow block diagram for FR2

4.2.4. Material flow from port's location to quayside

From Figure 19 and Figure 20 we see that the ore has moved from port to the quayside. What is different from the other main functions is that we now have two different ways of achieving this: Alternative 1 where collected ore is moved, or unloaded, alone, and alternative 2 where both the underwater vehicle and the collected ore are unloaded from under water. It is important that the main function 3 does not favour or restrict to any of these alternatives, i.e. keeping it form-neutral. The flow conservation principle still counts, and the flow input of main function 3 (FR3) becomes: "Ore in the underwater system at port's location". Further, according to our system boundaries and the findings of the block diagram for the overall function in Figure 21, we can easily find the output of the flow for FR3. Thus, the output of flow for the third main function becomes: "Ore at port's location at quayside". If we look at the action being performed, i.e. "moving", this leads us to FR3: "Moving collected ore from port's location to quayside".

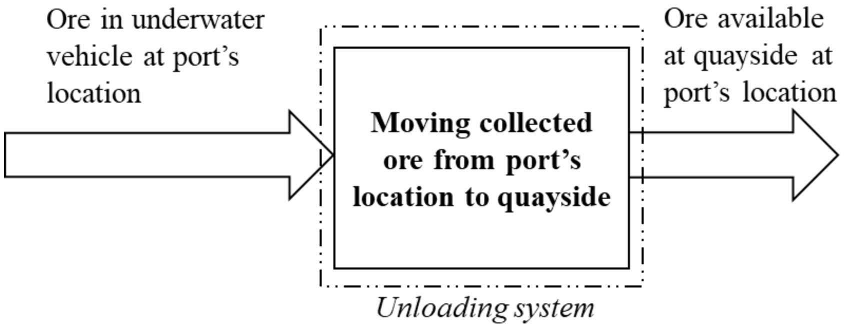


Figure 24: Material flow block diagram for FR3

Figure 24 shows the material flow block diagram for FR3.The system that performs this action is the moving system, or more precisely, the "unloading system".

4.2.5. Final Functional Structure

After reviewing the functional decomposition study, it is seen that there the main functions are: 1) Collecting ore from deposit's location into the underwater vehicle (FR1), 2) Moving collected ore from deposit's location to the port's location (FR2) and 3) Moving collected ore from port's location to quayside (FR3). See Figure 25 for block diagram overview. As explained in Section 3.2 the input of the main function and the first subfunction are identical, and the output of the main function is identical to the output of the last subfunction.

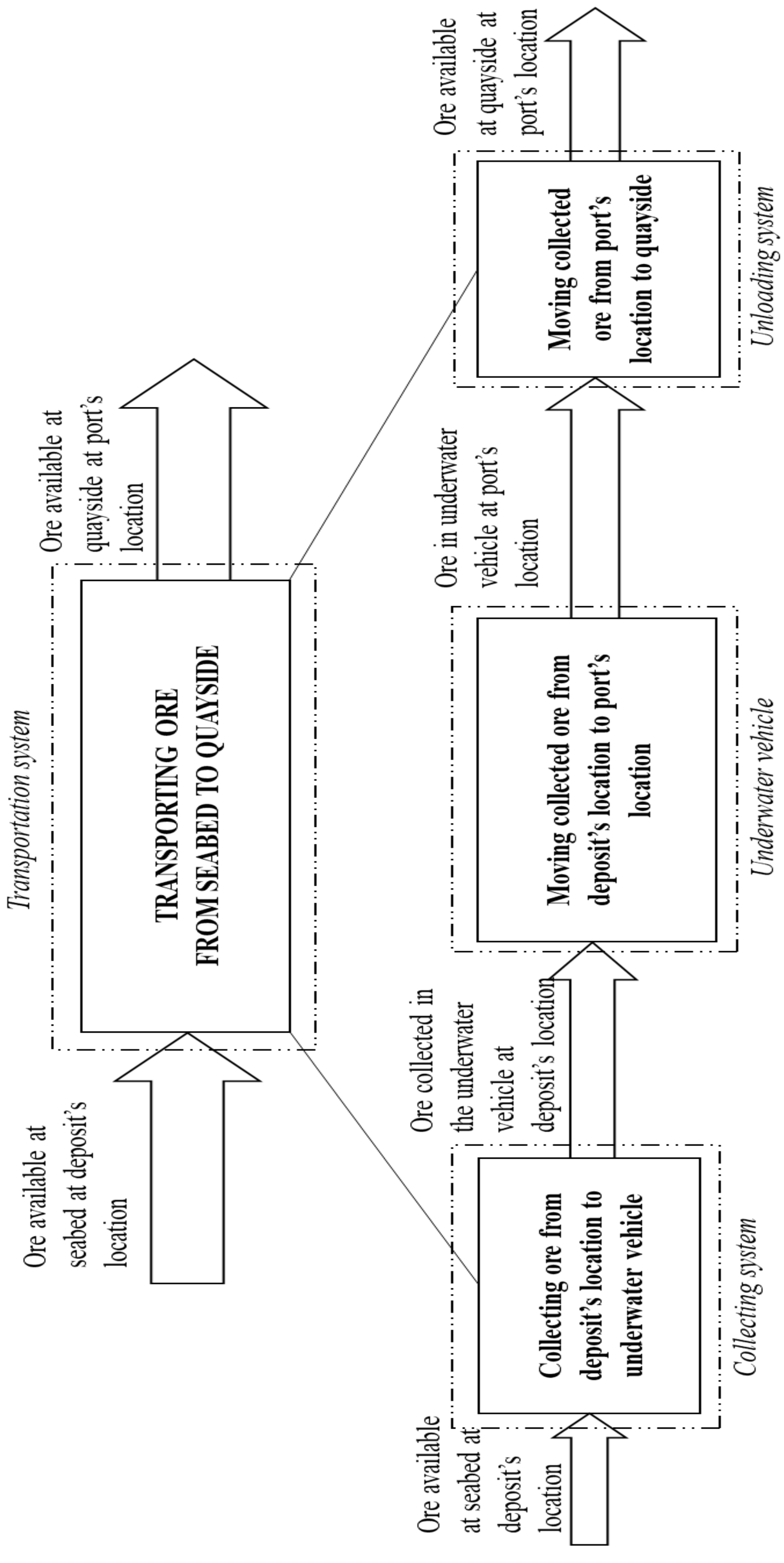


Figure 25: Functional hierarchy for transportation system

The functional hierarchy in Figure 25 consists of two levels. In other words, the main function has been decomposed once. An effort was made in order to identify whether the functional hierarchy as presented here could be decomposed further. According to Section 3.2 there must be a decomposition of functions into subfunctions until one cannot be solution-neutral anymore. Starting with the first main function, a question that arose was whether the material flow could be split into two more processes: gathering and stocking. There were two problems with decomposing to this level. One was that gathering is not in essence that different from collecting. In other words, the 1st level and 2nd level of function structure would have the same function, which is not a decomposition. The other problem was that it is assumed that stocking needs to be a part of the collecting system. This does not have to be the case, since the ore does not necessarily need to be temporarily contained between seabed and underwater vehicle, i.e. this decomposition is not solution-neutral. Moreover, auxiliary functions, such as providing energy and control, were initially considered as part of the functional hierarchy. According to the methodology this is usually not a part of the initial function analysis, and it proved to be too early to state the form of functions that were not a part of the main flow, i.e. more suited for the embodiment design.

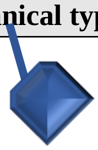
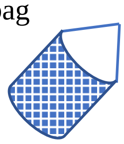
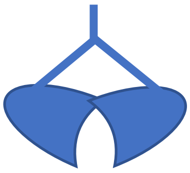
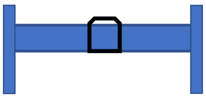
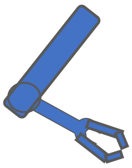
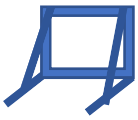
4.3. Searching for working principles associated with functions

4.3.1. FR1: Collecting ore from deposit's location to the underwater vehicle

Upon transportation of the ore it first needs to be assembled in order to be moved by the underwater transportation vehicle. The ore is assumed to be available at the seabed as loose bulk or containerised, see the value chain from Figure 3. Any necessary pre-processing or crushing has already taken place. When the ore is ready for transportation, has been assumed that any extraction and pre-processing required has been finished. The ore may be in bulk form or containerised. If it is containerised, we assume that the container has been filled during or after the excavation process. It is assumed that this is not a task done during the transportation phase, i.e. it will not be a part of the scope of this thesis. In other words, there will be no further actions performed at the underwater vehicle regarding the ore, as we have seen onboard vessels of other concepts in Section 2.2. Such actions include dewatering, processing and tailings handling. The search for working principles has been made in various industries. Most solutions have been found from the dredging industry, but also the offshore industry and cargo handling at port.

Table 1: List of working principles for FR1

WP1	**DESCRIPTION**	**REFERENCE**
Flow type		
Suction dredger 	Bulk ore is drawn using a pipeline with cutter head. This solution requires the suction pump to be in the vehicle. The slurry will need dewatering.	(Georgiopoulou, 2018; Work, 2016)
Submersible slurry pump 	A mix of seawater and gravel is pumped to a desired location. The impeller is mounted directly on the motor, which is encapsulated in a casing. The slurry will need dewatering.	(Bai & Bai, 2010; Lobanoff & Ross, 2013; Mackay, 2004)

Mechanical type		
Shovel 	A shovel scoops bulk ore and disposes it into a desired location.	(Georgiopoulou, 2018)
Mesh bag 	The dredge net is used for scooping and lifting ore. It will need some equipment enabling the movement and lifting. The net is not enclosed, and the ore will be strained.	(Fonteyne, 2001; Georgiopoulou, 2018)
Bucket dredger 	A dredging tool with one or more buckets that collect gravel. There may several buckets are attached to a circulating chain or wheel for continuous collection.	(Randall, 2004)
Clamshell grab 	A clamshell grab is lowered and grabs bulk ore. It needs additional equipment for hoisting.	(Georgiopoulou, 2018; IADC & IAPH, 2010; Randall, 2004)
Spreader 	The spreader connects to a container's four corners and lifts it. A winch, or similar hoisting equipment is needed for retracting the spreader.	(Han, Guo, & Cao, 2011)
Underwater manipulator (gripper) 	The underwater manipulator, or gripper, has a robotic arm which can open and close under water. It can encapsulate an object, such as loose ore, and lift it. They are traditionally designed to operate between 3,000 m and 6,500 m.	(Bemfica, Melchiorri, Moriello, Palli, & Scarcia, 2014; Martin Ludvigsen, Kurt Aasly, Steinar Ellefmo, Ana Hilario, Eva Ramirez-Llodra et al., 2016; Sivčev, Coleman, Omerdić, Dooly, & Toal, 2018)
Container loader 	The container loader is an apparatus which may collect, lift and tilt a container – depending on the design.	(A-ward, 2019)
Towline 	The vehicle attaches to an ore container using a towline.	(Gerwick, 2007, Chapter 6; Hancox, n.d.)

The list presented contains 10 working principles that will be discussed further in the following. The suction dredger, slurry pumping, shovel, mesh bag, bucket dredger and clamshell grab all have in common that they are dredging tools. *Dredging* means underwater repositioning of sediments from the bottom of oceans, rivers, and other aquatic environments. The suction dredger is equipped with a rotary cutter head, for cutting rock and sediments. The dredge is lowered towards the seabed and moved sideways in a sweeping motion before it is sucked into a pipe by a vacuum pump. An in-line booster pump can be used to increase the distance that dredged materials can be pumped (Work, 2016). The submersible slurry pump is utilised for conveying slurry and gravel with solid fragments in aquatic surroundings. The main difference when operating the two pumping systems is that the pump is located in the vehicle for the suction dredger while it is located locally inside the casing for the slurry pump. The shovel is a classic way of moving loose material from one place to another. They often also have excavation capabilities, such as a land-based excavator. It is stated above that they may include a lid to create a box, if necessary. This works by releasing a mechanism when the shovel is filled, which seals the box (Georgiopoulou, 2018). The mesh bag, or trawl net, is based on the same principle as fishing trawlers – pulling a net to capture desired elements inside the water column. For dredging purposes, it is common to drag the net through the upper layer of the seabed to capture loose elements resting on the seabed. Depending on the size of the mesh, smaller elements may be filtered out along with the seawater. The mesh is lowered by a wire, and a heavy anchor chain keeps the net close to the seabed (Georgiopoulou, 2018). The bucket dredger resembles the trawl net in principle, but the captured material more enclosed. The clamshell grab, also called clamshell bucket or grab sampler, is made up of two jaws which capture loose material (Georgiopoulou, 2018). It was considered to merge the clamshell grab and bucket dredger into one joint bucket working principle. However, the uses may be different. For instance, the bucket dredger system may consist of many circulating buckets, as seen in Section 2.2.

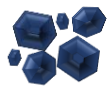
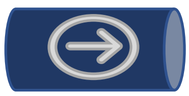
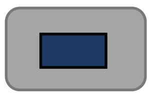
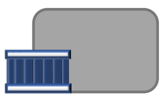
The working principles treated so far are quite common for the dredging industry. The next working principles are collecting tools from other fields. Spreaders are tools that can grab and hold on to a structure, such as a container. It has a locking mechanism which fastens to the four corners of a container. Also, many spreaders can alter its width to fit to the container. The spreader is commonly operated by stacker trucks or cranes in ports (Han et al., 2011). Underwater manipulators are used for different tasks in the subsea industry, like lifting of large heavy objects, carrying of tools for inspection and maintenance and collection of samples. They are constructed to resemble a human arm, and may operate up to 6,500 metres (Sivčev et al., 2018). The container loader is based on the principles of loading and unloading of containers by trucks. The container is either lifted and the contents are empties into the cargo hold or lifted for the vehicle to carry. The towline is the last working principle.

Some collecting solutions were not included in the list. The manipulator and judgement skills of a human diver is incomparable to other systems. However, use of human divers poses a great risk with respect to safety because of the unfavourable environmental conditions. Also, it has not been proved at the high depths that deposits are known to be located (Hawley et al., 1996). Thus, it was chosen to avoid solutions that include human divers. Dredging equipment that require air, a ship, divers, and tide differences are not deemed suitable for our purpose. Examples of such equipment are the air-lift dredger, plough leveller (bar pulled by boat) and scratcher (device with spuds scraping the seafloor as tide changes). Further, a common seafloor collecting equipment is the push corer. The push corer gathers seafloor samples into a small cylinder-shaped retriever using an ROV manipulator, piston corer or similar. An assumption for coring is that the sediments are soft. Also, some corers have depth limitations to shallow waters only (Georgiopoulou, 2018). Push corers and corers of similar nature are therefore not included.

The working principles from Table 1 all have in common that they represent design parameters that fulfil the function of collecting ore. Some working principles, such as the manipulator arm and bucket dredger, are meant for bulk ore. Other are meant for containerised ore, such as the spreader and tow line. Therefore, one distinction that can be made between the working principles is the form of the material to be collected, i.e. bulk (loose) or containerised. It is also seen from the list that the physical principle for collection have been divided into two groups: flow and mechanical. Flow means that the ore travels in a continuous manner, likely in the form of slurry. Mechanical means that the collection method follows the mechanical principle of collecting, and it requires physical contact and application of force to an object. In this case the object is either bulk or container. Furthermore, because of how ore is stored once collected, it will be impacted by the principle of interfacing with transportation system. More specifically, interfacing means whether the ore is contained on the inside or on the outside of the transportation system. This can also be seen from the working principles, where there is a distinction between whether the ore is collected inside or outside the vehicle. It is distinguished between an inside and outside confinement, i.e. cargo hold and contained outside respectively.

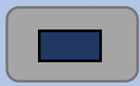
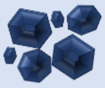
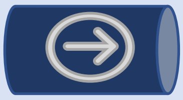
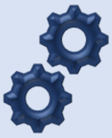
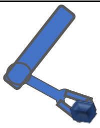
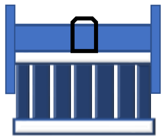
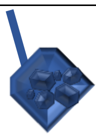
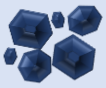
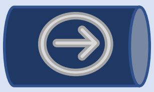
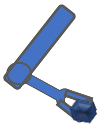
In conclusion, the classifying parameters for FR1 can be divided into three categories: the form of material, the physical principle of which the material is collected and lastly the configuration of the collected ore, see Table 2.

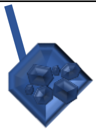
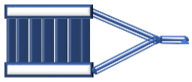
Table 2: Classifying parameters for categorising principles of WP1

Form of material	**Symbol**
Bulk (loose)	
Containerised	
Physical principle	**Symbol**
Mechanical	
Flow	
Ore handling	**Symbol**
Inbuilt cargo hold	
Outside contained	

The ore handling is related to the way the ore and vehicle interact once collected. The first cargo handling method is perhaps the most classic way of transporting cargo in the maritime industry: using a cargo hold. Notice however that we do not constrain the cargo hold to bulk only – the cargo hold can be used for containers too. The outside contained refers to a container being externally attached to the vehicle. This can either happen by the container and vehicle merging into “one transport unit”, or by the container having an outside attachment, such as the tow line. The working principles and classification parameters can be formed into a design catalogue for FR1, see Table 3.

Table 3: Design catalogue for FR1: Ore handling, material form and physical principle

Page 1/2	**Vehicle with inbuilt cargo hold** 	
Material form / **Principle**	**Bulk (loose)** 	**Containerised** 
Flow 		
		
Mechanical 		
		
		
		
Page 2/2	**Vehicle with outside container** 	
Material form / **Principle**	**Bulk (loose)** 	**Containerised** 
Flow 		
		
Mechanical 		

The design catalogue shows the complete set of solutions for FR1. FR1 has three different categories of classifying parameters, and the catalogue is therefore made up of two matrices – or pages. Many of the working principles are repeated, but the practical difference is in the way the ore and vehicle are coupled. For instance, for the manipulator arm, the difference between the two pages are whether the bulk is picked up and placed into the cargo hold or into a container. There are two working principles that do not repeat in the two pages: the towline and the container loader. This is because it is not assumed that the towline will be able to move loose bulk. It may be argued why it is necessary to repeat the solutions – why even have the classification parameter for ore handling at all. After all it may be confusing to have large catalogues. The coupling is important because it conveys how the ore engage with the vehicle – how much space it occupies and how accessible the vehicles hull has to be, which in turn disclose information that is vital during the embodiment phase, such as vehicle internal layout (where cargo, propulsion, energy storage or other possible functions are stored).

4.3.2. FR2: Moving collected ore from deposit's location to port's location

An underwater vehicle will move the collected ore from deposit's location to the port's location. The search for working principles has revolved around known underwater vehicles. There has not been an attempt to search for solutions that have not been proven in the medium in question: salt water. Table 4 presents working principles for moving material under water from the seabed to port. The level of independence, i.e. to what extent they operate on their own without remote input, is also shown.

Table 4: List of working principles for FR2

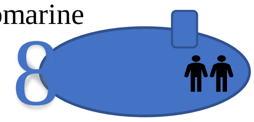
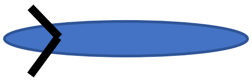
WP2	DESCRIPTION	REFERENCE
Manned		
Submarine 	A submarine is a manned submersible vehicle with ability to stay under water for a long time. It is self-propelled and controlled by crew.	(Allmendinger, 1990; Burcher & Rydill, 1994; Hawley et al., 1996; Jackson, 1992)
Semi-autonomous		
Glider 	An underwater glider is an unmanned underwater vehicle. It can cover long distances with low energy consumption because it is buoyancy-driven. The horizontal transportation has a zigzag pattern.	(Jenkins & D'Spain, 2016; Rossol, Hildebrandt, & Wirtz, 2018)
Fully autonomous		
Autonomous underwater vehicle (AUV) 	An autonomous underwater vehicle is an unmanned submersible vehicle capable of operating without tether from support station. It is self-propelled, and it can guide and navigate on its own.	(Griffiths, 2002; Hawley et al., 1996; V. A. I. Huvenne, McPhail, Wynn, Furlong, & Stevenson, 2009; V. A. Huvenne et al., 2018; Kepler, Pawar, Stilwell, Brizzolara, & Neu, 2018)

Table 4 contains 3 working principles: a submarine, a glider and an autonomous underwater vehicle. The definition of a submarine vehicle varies, but there exist a joint understand in the literature that it is a manned vehicle with the ability to stay submerged in water for a longer period of time, and occasionally resurface (Allmendinger, 1990; Burcher & Rydill, 1994; Hawley et al., 1996). Other underwater vehicles are often referred to as submersibles. The technology advancement has been driven by the military application of submarines. Therefore, many of its features have arisen from warfare use. They are large structures, capable of storing and launching weapons. The maximum depth that the submarine can reach is not possible to find – it is classified information. The most important feature of submarine operation is the propulsion system. It determines the endurance of the vehicle under water (Burcher & Rydill, 1994). A glider uses fins and buoyancy chamber for propulsion, so-called buoyancy-driven. A seawater pump inside the vehicle increases and decreases buoyancy in order to alter the weight. The fins are tilted in order to can move horizontally. Thus, it moves up and down while gliding forward, like a saw-tooth pattern. The glider is autonomous, but it resurfaces from time to time to receive new input about mission – hence semi-autonomous. Unlike the glider, the AUV uses thrusters for propulsion, i.e. it is propeller-driven. They are unmanned and can operate without any physical tether. Their endurance is typically from a few hours to days (Griffiths, 2002; Hawley et al., 1996). The AUVs have high speeds and lower operating costs than manned. The turning radius and manoeuvrability is also a great feature of the AUV (Hawley et al., 1996).

It varies between the vehicles to what extent heavy payload has been a proven technology. Underwater vehicles that were not considered is the remotely operated vehicle (ROV). This receives control and power from a tether, and it is therefore unlikely that it will be able to meet the independence criteria set for the vehicle: to move on its own for longer distances without outside interference. The level of independence could very well be an own classifying criterion. However, there is only one solution for each of the levels of independence, hence we may put the classifying criteria as what they are: underwater vehicles. Further, it was argued in Section 4.3.1 that the ore handling is essential. This continues to be important during underwater movement. There is the cargo hold and outside contained here as well. However, there needs to be a specification on how the movement is done. 'Outside contained' explains only that a container is attached somehow outside of the vehicle, and in order to distinguish between being attached as a part of the vehicle and by towing, the ore handling is divided into three categories: inside cargo hold, container onloading and towing. The categories of classifying parameters for FR2 thus become ore handling and underwater vehicle, found in Table 5.

Table 5: Classifying parameters for categorising principles of WP2

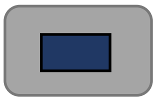
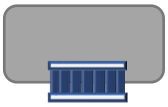
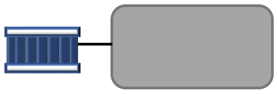
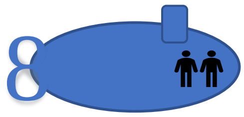
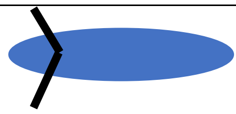
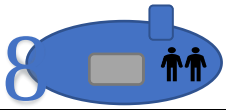
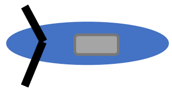
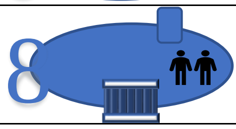
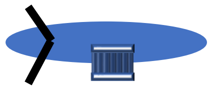
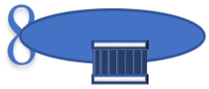
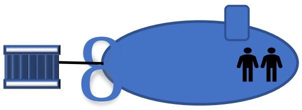
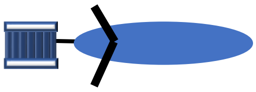
Ore handling	**Symbol**
Inside cargo hold	
Container onloading	
Towing	
Underwater vehicle	**Symbol**
Submarine	
Glider	
AUV	

Table 5 displays how the underwater vehicles can handle cargo. The first two types of coupling resemble how merchant ships transport cargo. Carrying cargo such as ore inside the cargo hold is common for bulk carriers. The characteristic of such vessels is that the cargo is not wrapped or packaged in any way – it is moved loose. This puts some restraints on the way it is unloaded from the vessel in port after the voyage. The container onloading, customary for container ships, is not common for underwater vehicles. The towing solution is established for surface vessels – usually performed by tugs, such as anchor handling tug supply ships (AHTS). Unlike merchant ships which transport cargo, the goal of such ships is normally to change the position of a (large) structure, also known as special operations. Ships, oil rigs and pipelines are examples of structures that may be subject to towing at ocean surface level. Typical characteristics of tugs such as the AHTS are high bollard pull capacity, a winch system capable of pulling hundreds of tonnes and dynamic positioning (DP) system for precise operation (Hancox, n.d.). The final design catalogue for FR2 can be found in Table 6.

Table 6: Design catalogue for FR2: Underwater vehicle and ore handling

UW vehicle / Ore handling	Submarine	Glider	AUV
	Manned	**Semi-autonomous**	**Autonomous**
Inside cargo hold			
Container onloading			
Towed			

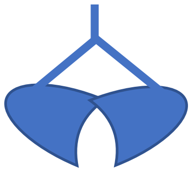
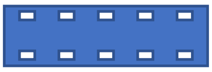
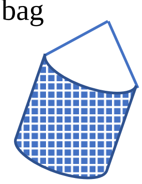
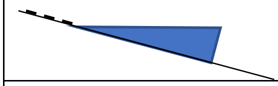
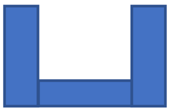
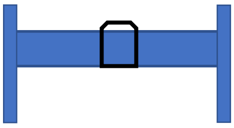
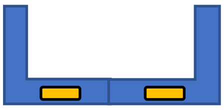
The study of towing from above shows that towing is a demanding operation with respect to machinery system (bollard pull and DP). Also, a sturdy winch is needed. A solution involving opening of the hull for onloading or offloading is demanding because of the compressive forces. However, it is not uncommon for submarines. They require openings for personnel, weapons, spare parts access, etc. (Jackson, 1992). Sudden alteration in weight is not unusual for submarines for instance during weapon discharge.

4.3.3. FR3: Moving collected ore from port's location to quayside

This section will address the technical solutions of moving material from port under water to quayside. The reader may recognise some of the technical solutions from FR1 here. This is because the essence of the function of FR1 and FR3 is similar – movement of cargo. However, FR3 does not require any particular output for the ore transfer. The solutions are found from the dredging industry mainly, but also cargo handling at port. The working principles for FR3 can be found in Table 7.

Table 7: List of technical solutions for FR3

WP3	DESCRIPTION	REFERENCE
Flow		
Suction dredger 	Bulk ore is drawn using a pipeline with cutter head. A pumping system at quayside is needed.	(Georgiopoulou, 2018; Work, 2016)
Pipeline 	Bulk ore is pumped through a pipeline. A pumping system at quayside is needed.	(Fang & Duan, 2014)
Mechanical		

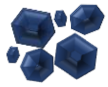
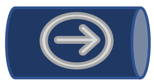
Clamshell grab 	A clamshell grab is lowered and grabs bulk ore. It is connected to a wire and will need hoisting equipment.	(Georgiopoulou, 2018; IADC & IAPH, 2010; Randall, 2004)
Conveyor 	A conveyor (belt) for continuous unloading of bulk ore. Requires direct access to the cargo hold.	(Mubaroq, 2002)
Mesh bag 	The dredge net scoops and lifts ore. It is connected to a wire and will need hoisting equipment. The net is not enclosed, and the ore will be strained.	(Fonteyne, 2001; Georgiopoulou, 2018)
Marine railway 	The marine railway hoists the ore container out of water mechanically along track using cradle and winch.	(Harren, 2013)
Hoister frame 	A structure capable of mechanically hoisting vessel or container out of the water using winches on the sides.	(Harren, 2013)
Graving dock 	A narrow basin where a vessel is floated in, gates of the basin are closed, and water is pumped out. This solution is fixed and requires a pumping system at site.	(Harren, 2013)
Spreader 	Spreaders are tools that can grab and hold on to a structure, such as a container. It has a locking mechanism which fastens to the four corners of a container. This is commonly performed by stacker trucks or cranes in ports.	(Han et al., 2011)
Backhoe dredger 	A backhoe dredger has similarities to a traditional land excavator, but they usually do not provide themselves with propulsion. They can be mounted on ships or pontoons. The backhoe dredger needs an operator.	(IADC & IAPH, 2010)
Buoyancy		
Floating dry dock 	A structure with buoyancy chambers capable of lifting structures. A floating dry dock may also be used for bringing vessels to shore as it is mobile.	(Harren, 2013)

There are 11 working principles for functional requirement number 3 in Table 7. The suction dredger, mesh bag and clamshell grab were explained in Section 4.3.1. The difference between using them at seabed and at quayside is that necessary extra equipment is more accessible. Extra equipment includes a pumping system for the suction dredger and quay cranes for the mesh bag and clamshell grab are. The suction dredger and pipeline are both flow solutions. The difference between them is that the pipeline is a fixed infrastructure while the suction dredger can be moved to the necessary location for dredging, also while it is dredging. With a protected location near shore it is not disturbed by any metocean conditions. Conveyor belts are widely used for transporting bulk materials. It moves different bulk sizes – from dusty fine chemicals to large rocks. They can operate continuously with limited maintenance and interference. In addition, they are quite inexpensive when considering the amount of bulk that can be moved over long distances (Mubaroq, 2002). There are three types of docks among the working principles: the graving dock, the hoister frame and the floating dry dock. They have in common that they are immersed into the water. Next, the vehicle (usually a ship or submarine) enters the dock. The floor is then raised in order to make the vessel available for maintenance or other operations. For the graving dock the floor is below the adjacent water, and the water is pumped out when needed. It also has a gate for closing the basin. The floating dry dock uses buoyancy to lift and it is also mobile so that it can be moved. For this reason, it may retrieve ships and other structures from the water to the port's location (Harren, 2013). The backhoe dredger resembles the land excavator, but it is mounted on a barge or pontoon for dredging of marine sediments. The bucket-like collecting device may dredge far into the water collecting bulk of various grain size (IADC & IAPH, 2010). The marine railway can lift large structures along an inclined track, or cradle, which extends into the water. It uses a winch with hauling chain to pull the construction. Some maintenance on the moving parts is required (Harren, 2013).

Many of the solutions are quite commonly in use today, such as the spreader and conveyor belt. One solution here that is 'missing' from the list is the port crane. A crane is a hoisting equipment located at the quayside, used for loading and unloading operations (Meisel, 2009, p. 11). The reason that it is not included in the list of working principles is that the crane works in *enabling* the moving of cargo, and it can be seen from the list that many working principles, such as the clamshell grab, are dependent on hoisting equipment. The winch is also an example of such movement supporting equipment. What we are interested in is connection device between the payload and the crane – the physical contact between payload and attaching device. If this is the case, can we not say the same about the backhoe dredger and clamshell grab – that they are more or less just a bucket, only enabled by either a crane or excavator? The fundamental difference here however is that the backhoe dredger is more mobile in the sense that it can be physically moved almost anywhere – it is not fixed to one port. Also, the backhoe itself can move more freely in many degrees of freedom and excavate during collection.

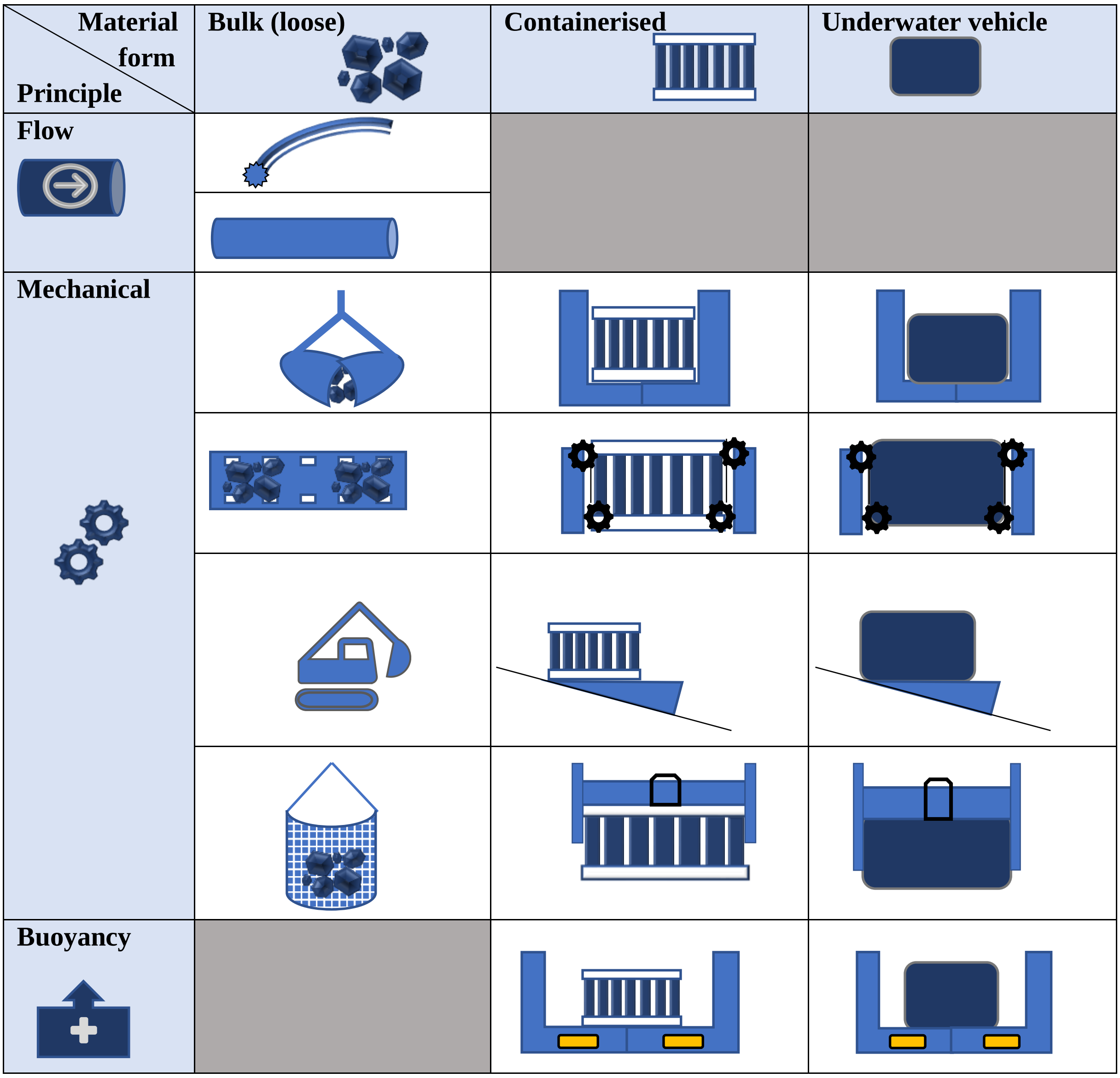
The classification parameters are based on form that is being collected, as we have seen before. However, this time the vehicle is included as possible to move to the quayside as well. In addition, we have the physical principles for moving as before, but including buoyancy this time as well. Thus, the solutions can be categorised into two classifying parameters: the form of material (bulk, container and underwater vehicle) and the physical principle answering to the function (mechanical, flow and buoyancy), see Table 8.

Table 8: Classifying parameters for categorising principles of WP3

Form of material	**Symbol**
Bulk (loose)	
Containerised	
Underwater vehicle	
Physical principle	**Symbol**
Mechanical	
Flow	
Buoyancy	

The form of the material decides in what form the payload is moved. Either the ore can be moved as bulk, or it can be moved while being inside a container, or the entire vehicle can be moved with bulk inside it in a cargo hold directly or in a container. The latter solution – moving the entire vehicle to the quayside – might seem like too much effort, but it should not be left out yet. The reason is that it is not desired to leave out this classification parameter yet – particularly when it is known that many of the working principles that have been identified are usually used for big structures like ships.

Table 9: Design catalogue for FR3: Material form and physical principle



It is seen that moving from port's location to quayside may take many forms based on the physical principle and material. The choice of physical principle has great influence on the amount of solutions available. For flow and buoyancy principles there are only four designs in total compared to mechanical with 12. The form of the material particularly influences the type of effort related to the cargo handling. For instance, both the clamshell grab and spreader will need hoisting equipment, but the lift is likely to be heavier with container than bulk. For the vehicle it depends on the size. Many of the combinations in the matrix are familiar from before, such as the docks carrying vehicles, which is common at shipyards for both surface vessels and submarines. Also, the container and spreader is a known combination. The vehicle and spreader combination not a part of the literature found, but it emerged in the catalogue. It may be questioned to what extent the ore is available if it is moved as a vehicle by for instance the hoister frame. The ore is still inside the vehicle and not directly available for processing or shipment. There is need for access to the ore inside the vehicle. However, it must be remembered that the functional requirement is merely to move the ore from port's location to quayside, i.e. providing the material flow – the transfer – between these two locations. As long as this is fulfilled, it is an appropriate working principle, and the ore is considered 'available'. Yet, there are some working principles that work better together in achieving the overall goal than others. The next section will investigate compatibility between solutions.

4.4. Combining working principles into working structures

The three design catalogues can now be combined into a final design catalogue, the morphological matrix from Section 3.4. This gives us an overview of all the main functions that fulfil the overall solution and their respective working principles. The morphological matrix can be found in Appendix A. By combining the functions, classifying parameters and solutions into catalogue, it does not just provide a practical overview – also there are principles that are similar or adjacent. An example is the bulk and container form, which is a classifying parameter for both FR1 and FR3. Therefore, if we choose a container solution in FR1, it is seen which container solutions that fit with this choice in FR3. Also, there are the two classifying parameters of containing on the outside for FR1 and FR2 – these may very well be a compatible match. The morphological matrix may also aid in finding an overall solution if parts of the solution is known. In the following, an example using the matrix is presented. If some chosen port is equipped with a graving dock, the matrix can give which classification parameters that this working principle is based on by following row B and C to the left. The container and vehicle form are identified as classification parameters – meaning that the ore can be moved from port's location to quayside containerised or inside the vehicle.

There is a vast number of combinations that can be made using the morphological matrix. The question of which ones to combine is challenging. Therefore, a more systematic and careful selection must be made in order to distinguish between promising and non-promising combinations. As stated in Section 3.4, the compatibility between the functions and classification parameters are studied. The idea is that the overall solution does not only have to contain solutions that are individually sound – they must be effective together as well. The way the payload is collected and moved inside and between the functions needs to be addressed because this is connected to the main flow. Also, it is the main flow that directly connects the functions. Therefore, the material flow classification parameters 'material form' and 'ore handling' are pursued in the compatibility matrices.

4.4.1. FR1 and FR2 compatibility

After viewing the classification parameters and design catalogues, we see that the way that the payload and vehicle are coupled is a classifying parameter in both FR1 and FR2. For FR1 we have vehicle with inbuilt cargo hold and vehicle with outside-built container, while for FR2 we have ore handling through inside cargo hold, container onloading and towing. The compatibility matrix is found in Table 10.

Table 10: FR1 and FR2 compatibility matrix with material flow classification parameters

FR1 / FR2	**Collected into cargo hold**		**Collected on the outside**	
	Bulk	**Containerised**	**Bulk**	**Containerised**
Moved underwater inside cargo hold	*Bulk is collected into cargo hold and moved inside cargo hold*	*Container is collected into assigned cargo hold*	*Collecting ore into container and collecting container into cargo hold*	*Ore is collected into container and further into assigned cargo hold*
Moved underwater as outside container	*Bulk is collected into cargo hold while also onloading a container*	*Containerised ore is collected into cargo hold while also onloading a container*	*Bulk is collected into container, and container is moved outside. Have assumed not to fill container*	*Containerised ore is collected and moved on the outside*
Moved underwater by towing	*Moving ore into cargo hold and towing a container*	*Containerised ore is collected into cargo hold, and containerised ore is moved by towing*	*Bulk is being collected into container, and container is moved by towing*	*Containerised ore is being towed*

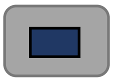
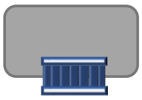
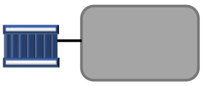
	Incompatible		Less compatible		Compatible

In Table 10 there is a variety of incompatible, less compatible and compatible solutions. The solutions with classification parameters ‘bulk’ and ‘moved by towing and outside’ are overrepresented as incompatible and less compatible solutions. The incompatible squares all have in common that they increase the complexity of the solution to an extent that is deemed unnecessary or unfavourable. These solutions have *two* types of ore handling that do not combine well. The reason for this is that FR1 will be fulfilled in two procedures, which will lead to two forms performing the same function. The way this is seen is that there are no working principles that are *similar* for the container and bulk classification criteria. For instance, at deposit’s site it is not possible to collect both bulk and container using a mesh bag. One could perhaps argue that a (big) shovel could collect a container – however, this is likely to require unnecessary effort as the shovel would have to scoop the container before collecting. The less compatible cells are also possible solutions, and do not contain the same level of complexity as the incompatible cells. However, they make the collecting process difficult by introducing more stages to the collection process. For instance, collecting or into a container and further move the container into assigned cargo hold inside vehicle might be more effort than just collecting bulk directly into the cargo hold, or just attaching the container on the outside. The compatible cells represent the solutions that are most promising. The number of stages when performing the function is smaller: The three compatible container solutions does not include the filling of the container before moving, and the bulk is collected into cargo hold directly. These cells may therefore entail less effort and time spent because the number of actions to be performed is lowered.

4.4.2. FR2 and FR3 compatibility

In order to achieve an overall solution that is fulfilling, the compatibility between FR2 and FR3 also needs to be studied. A compatibility matrix for FR2 and FR3 is found in Table 11. The table shows the compatibility between how payload is moved for FR2 and FR3. For FR2 there is the same classification parameters as before, and for FR3 there is the form of the material: bulk, container, and underwater vehicle.

Table 11: FR2 and FR3 compatibility matrix with material flow classification parameters

FR2 / FR3	**Moved inside cargo hold** 	**Moving outside container** 	**Moved by towing** 
Moved to quayside as bulk 	*Bulk is moved from cargo hold to quayside. Access must be provided to cargo hold inside underwater vehicle*	*Bulk is moved from outside container to quayside. Container can be detached from underwater vehicle. Access must be provided to contents in container*	*Bulk is moved from container to quayside. Container can be detached from underwater vehicle. Access must be provided to contents in container*
Moved to quayside as container 	*Container is moved from cargo hold to quayside. Access must be provided to cargo hold inside underwater vehicle*	*Container is detached from underwater vehicle and moved to quayside*	*Container is detached from rope connection and moved to quayside.*
Moved to quayside as underwater vehicle 	*Underwater vehicle is moved from port to quayside with payload inside cargo hold*	*Underwater vehicle is moved from port to quayside with outside container attached. May be unnecessary effort to move both when container can be detached*	*Underwater vehicle moved when no payload attached has no purpose*

	Incompatible		Less compatible		Compatible

The number of compatible solutions in the compatibility matrix is quite high. The underwater vehicle solution performs poorly in the matrix by representing less compatible and incompatible combinations. It may already be seen that this classification parameter will not be preferential further. Solutions for moving as bulk or containerised ore to quayside are all found compatible. For some of the solutions there is an extra requirement of providing access to ore contents or disposing of the container. They have still been deemed compatible and Table 11 displays more compatible cells than

Table 10. One may wonder why this is since some of the cells involve more than one processes, just like in some of the less compatible or incompatible cells of Table 10. For instance, the 'moving on the outside' alternatives involve first releasing the container from the vehicle and further bringing the container to the quayside. According to principle of flow conversion, this is a two-step process: first releasing the ore at the port's location and second bringing it to quayside. One may even wonder whether this means that FR3 should be divided into two separate subfunctions: one for abandoning at port's location and one for moving from port's location to quayside. However, there are several reasons why this was not pursued. First, the higher level function cannot have the same action as the lower level functions, i.e. 'moving' in order to 'move' is not of any use because it does not provide any more insight into what action is taking place. Second, the decomposition assumes that the unloading has to happen in two steps, which does not need to be the case. In the upper left cell, for instance, the bulk can be collected directly from the cargo hold of the vehicle. And lastly, the compatibility matrix presented does not exclude the option to separate into two steps. The bulk from the previous example may be dropped onto the seabed if the vehicle is built with such capabilities. To have more compatible solutions gives an indication of which function is more difficult to fulfil because the combination options are more limited. I.e. FR1 and FR2 might be more challenging to fulfil in a satisfactory manner when starting the selection process.

4.5. Selecting working structures

The compatibility between functions based on material flow classification parameters have now been found. The most important findings were that any containers ought to already have been filled before being collected, and that the underwater vehicle movement performed poorly. There is multiple possible overall solutions, and focus is now on the promising combinations. The biggest leap in the design process is made: eliminating the solutions in the compatibility matrices that are deemed incompatible or less compatible. As discussed in Section 4.5, these combinations are either unreasonable to pursue or involve unnecessary effort. In other words, only compatible combinations are pursued. In the following, we combine the classifying parameters that are compatible from Table 10 and Table 11. The combinations are found in Appendix B Table 10 contains the cells 'bulk collected into cargo hold' and 'moved under water inside cargo hold'. When studying Table 11 it is seen that 'moved under water inside cargo hold' is compatible with 'moving bulk to quayside'. By having a look in the morphological matrix in Appendix A, the compatible solutions can be found in row A except columns 3 and 4 (outside movement), and column 5. This constitutes the first working structure set. The next compatible cell is 'container collected into cargo hold and moved inside cargo hold'. When looking at FR3 principles, the principle from FR2 matches the same cell as above: 'moving bulk from cargo hold to quayside'. The working principles compatible in the morphological matrix are row B, row A column 8-9 and column 5. This becomes the second set of working structure. The next cell in Table 10 is 'containerized ore being collected and moved on the outside of the vehicle'. The FR2 principle matches two different cells in Table 11, and there will be several options. For FR3 bulk can be moved from container to quayside, or container can be moved in its entirety to the quayside. The first will involve access being provided to the cargo hold. Also, the vehicle may detach the container with both solutions. The relevant working principles of the morphological matrix are found in row B, column 6 and column 8-10 apart from row C. This becomes working structure set 3. The last compatible cell is 'collect on outside and move by towing'. Towing gives us two different options if we look at FR2 and FR3 when arriving at port. Either the bulk is removed directly from the container, or the container moves in its entirety to the quayside. In both cases the container can or must detach from the vehicle. In the morphological matrix this is found to be limited to the cell containing the rope solution, the towing solutions in column 7 and columns 8-10 apart from C. This constitutes the fourth working structure set. The compatibility study leads to sets of working structures containing working principles, summarized in Table 12.

Table 12: The set of working structures and relevant classification parameters after compatibility check

Set of WS	CP for collecting ore from deposit	CP for moving from deposit to port	CP for moving from port to quayside	Designation in MM
1	Collect bulk	Move inside cargo hold	Move as bulk	
2	Collect containerised ore	Move inside cargo hold	Move as bulk or container	
3	Collect containerised ore	Move as outside container	Move as bulk or container	
4	Collect containerised ore	Move by towing	Move as bulk or container	

An emphasis is made on using charts, such as the compatibility matrix, in order to do a rapid selection of working structures (Pahl et al., 2007, p. 186). Such a selection was tried using mathematical methods, but it was deemed too abrupt, meaning that the solution space was cut too quickly. Thus, sets of working structures, instead of just working structures, were made to be able to systematically address the classification principles, and their strengths and weaknesses. The compatibility study that was done has eliminated some solutions in the morphological matrix in Appendix B. First and foremost, we may notice that row C – the row containing the solutions for moving the entire vehicle to the quayside – is not at all a part of the sets found. Thus, this has been eliminated through compatibility study. Other parts of the morphological matrix that have been eliminated are column 3 and 4 in row A. This gave a constraint that a container should already be filled before transportation. The solution space has been gradually narrowed into sets of working structures which will now assessed further. Emphasis is made on the compatibility between working principles with respect to the overall task, type of environment and of course the features of the working principle.

4.5.1. WS set 1: Bulk moved inside cargo hold of underwater vehicle

The first working structure set is the only one of the four with bulk as material form as classifying parameter for WP1. Here, both flow solutions and mechanical solutions are included. The flow working principles are the suction dredger and submersible slurry pump, while the mechanical working principles are the manipulator arm, the mesh net, the bucket dredger and the shovel. The suction dredger and subsea submersible pump will both need pumping systems. The bulk is collected by one of these working principles into the cargo hold of either a submarine, an AUV or a glider, as seen in Appendix B. The bulk is then moved inside the vehicle with the collection device being either on the outside or brought inside the vehicle, depending on which is chosen. The choice of vehicle may be important to WP1. If the vehicle is manned, i.e. the submarine, it is the crew may aid in control and any steering of the WP from inside the vehicle. If the vehicle is a glider, the collection must be done by the vehicle without human interference during the operation. When arriving in port, the modified morphological matrix shows that the choices of WP3 is based on bulk principle as well. The vehicle may now either drop the bulk in port, for instance by opening a hatch in the keel, or give access to the cargo hold so that the ore can be moved out. The choices for flow solution are the suction dredger and pipeline, while for the mechanical principle there is the clamshell grab, conveyor belt, backhoe dredger and mesh net. By now, the bulk is inside the cargo hold of the vehicle, either in slurry form or as loose rocks or chunks. The material form largely determines which working principle is chosen in port. For instance, if the suction dredger is chosen as WP1, the mesh net might be an unfortunate solution as WP3– depending on the grain size. The flow solutions, the suction dredger and pipeline, are good options when dealing with slurry. However, the backhoe dredger may also be used since it may handle different grain size, as seen in Section 4.3.3.

4.5.2. WS set 2: Container moved inside cargo hold of underwater vehicle

In the next working structure set in Appendix B the collection working principle is container-based. Only mechanical principle is available for WP1: the container spreader and the container loader. The container is onloaded directly into the cargo hold of the vehicle. This means that the vehicle has an open hull at the point of onloading. The spreader must be lowered down from the vehicle using a winch or similar, and further it must grab on to the corners of the container and attach to it. After that the container can be collected. The container loader depends somewhat on the configuration of the loader, but essentially it grabs on to the vehicle, either under, on the sides or both, and collects it pulling or lifting. As for set 1, the crew of a submarine may aid in control and steering of the WP. When the container has been onloaded, the WP1 should be contained near or inside the vehicle so that it minimises appendage and possibly form resistance in water when moving. Since the glider and AUV are without human remote control when collecting the container, the precision and manoeuvrability when collecting is crucial – especially for the loader solution. When arriving in port, there are many WP3 to choose from. The ore is container-based and moving it to quayside as a container too is an option. In that case the container must be released by opening the hull of the vehicle. If a mechanical bulk solution is chosen, the ore may be moved directly from the container inside the vehicle, or simply from the container itself. The flow bulk solutions presuppose a slurry inside the containers.

4.5.3. WS set 3: Container attached to underwater vehicle

This set contains the container collection working principles, the container is carried externally, and all WP3 may be chosen. The towline WP1 will give the same solution as the fourth working structure set, so it will not be studied here. The spreader and loader are familiar from working structure set 2, however this time they are not required to move the container into the hull itself. The WP3 depends on whether ore is moved directly from the container or whether it is brought ashore. As opposed to the previous sets, disposing of the container may be easier since it is carried externally by the vehicle. There is no need for opening hulls. Therefore, the container may be disposed of somewhere close to the quayside. Where this will be depends on the port conditions and WP3 chosen. There are several methods for bringing the ore to the quayside, as seen from WP3. It might come directly from the container using bulk solutions or the container may be moved in its entirety.

4.5.4. WS set 4: Container towed by underwater vehicle

The fourth set is based on a towing solution. The towline is the only working principle for fulfilling FR1 in this set. The vehicle and the towline connect to the container by some type of hook-up mechanism. It is important that the towline is of sufficient strength, and that it does not interfere with thrusters if the AUV is chosen as vehicle. When the underwater vehicle starts to move, the container is accelerated. In order to avoid friction of movement along the seabed, there should be a vertical or diagonal movement at the beginning. If the container is moved by a glider, it will experience the zigzag motion pattern. If it is moved by an AUV it may have a more straight-forward path. When arriving in port, there are both container-based and bulk-based solutions for moving from port’s location to quayside. The vehicle may release the container and go on to the next mission.

4.6. Firming up solution variants using AMOR location

It is now time to firm up promising solution variants from the sets found by using the example case presented in Section 2.1.3. Information applied concerns the features of seafloor massive sulphides, the Atlantic Mid-Ocean Ridge and the port at Svalbard to obtain knowledge about which solutions are favourable here. The criteria from Section 3.6 and information from Section 4.5 are used when firming up solution variants:

A. Being compatible with the overall task and one another
B. Incorporate safety measures
C. Being attainable with respect to performance, layout, and costs

Criterion A has been important since the compatibility matrices in Section 4.4. However, now it will be important to see how this compatibility is influenced by the choice of location. This is because the practicality of classification criteria may change with the constraints that the location puts on the solution space. For instance, the deposit's location and SMS will have a great influence on whether bulk or container is favourable. Moreover, some solutions in port may be difficult because of potential ice formation at Svalbard. Criterion B and criterion C are highly influenced by the location because the convenience of the working sets depends on the operation. These two criteria will need more data material in order to make estimates, and therefore discussions will be provided with the information that has been obtained this far.

Before the sets are studied and evaluated, there is one solution that already becomes challenging. The site is at a couple of thousand meter depth. When it comes to the choice of vehicle, it may be asked whether we want to bring humans – a submarine – down to this depth, knowing that we are far from shore, supplies and aid. As seen in Section 4.3.2 it is not known that submarines have travelled to this depth before. No doubt it is an interesting solution because of the operability, payload-carrying capabilities and energy, but for safety reasons the submarine will be eliminated from consideration from this point onwards. Inability of meeting criterion B is a reason alone for eliminating the solution. It can also be mentioned that the costs of a submarine are very dependent on the size and (number of) operational requirements. Compared to a surface vessel, the submarine is a vehicle with special features that drive up the costs. Strict regulations regarding safety set constraints on materials. Also, some equipment, like weapons and sensors, is special order equipment with few manufacturers. Moreover, keeping crew inside a metal cavity in the water column leads to necessity of extra safety measures and duplicate systems – which are not only expensive to buy, but also require maintenance and quality assurance testing (Burcher & Rydill, 1994, pp. 232–240). Thus, the submarine is removed from consideration.

4.6.1. Selecting from WS set 1

The requirement of a pumping system for the slurry pumping and subsea submersible pump make these solutions less compatible at the site. The bucket dredger and shovel solution will require either pulling or a movement during collection. For collecting of SMS chunks the bucket dredger could be too impractical because it might be difficult to get a proper hold of the chunks on seabed. One might need a manipulator arm or other type of equipment with steering to put the ore into the basket. The manipulator arm has limited collecting capacity. The manipulator and subsea basket were used in collection of samples during the MarMine cruise at site. However, an ROV was used during this exploration which suggests that continuous surveillance and interference by humans was possible during the collection. By looking at the potential costs versus payload transported the manipulator arm does not seem like a favourable solution. Also, an attachment to the vehicle will give an extra drag due to appendage, as seen in Section 2.4. The drag will be mostly apparent during transportation, due to the friction between hull and water. Thus, it should be avoided if possible. This ultimately leaves out the WP1 available in the set, and it is not possible to obtain an overall solution.

Also, it can be mentioned that when the underwater vehicle arrives at port it must be contained somehow to allow the offloading of bulk ore. Either the vehicle must be docked, or it must maintain neutral buoyancy in water to allow access to the cargo hold. A third alternative could be that the vehicle simply opens a hatch at the keel and drops the ore without spending too much time in port. However, this alternative seems somewhat disorganised – particularly because of the plumes and sediments that will appear. It might be considered as an exception for emergency reasons instead. The bulk flow solutions require a pumping system onboard the vehicle. Moreover, we see that since the cargo hold must be available when offloading, the time spent in port may be longer that if we simply disposed of a container.

4.6.2. Selecting from WS set 2

From working set 2 and onwards the solutions assume that containers can be filled and placed on the seabed, awaiting transportation. The spreader is an interesting WP1 due to the range between vehicle and seabed. The glider is a buoyancy-driven underwater vehicle, but the precision when positioning for onloading is limited due to the saw-tooth pattern horizontal propulsion. Furthermore, the release of container in port needs a closer review. If the bulk is collected from the container after the container resides on the seabed, the container will have to be opened beforehand. Perhaps this must be done manually or there is some automatic solution available. Either way it is assumed further that this is a relatively uncomplicated task that there will be some solution to should we choose it. If the container is dropped in proximity to the quayside it will reside under water and be ready for offloading of ore. The vehicle may continue its voyage, if needed. If the container is not dropped in the proximity of the quayside, this puts special requirements to WP3. The working principle must 1) be able to offload at a distance from port, and 2) cope with a shock load from the impact of the container. The solutions that are feasible in this respect are the floating dock, marine railway, and backhoe dredger placed on a barge or pontoon. The remaining bulk solutions may also be used, depending on the equipment available. If a crane on a barge is available, the clamshell grab and dredge net may be used too, and the container may be just dropped on the seabed. Due to the possibility of ice cover at Svalbard, the marine railway is favoured. Thus, we have a solution from WS set 2, see Figure 26.

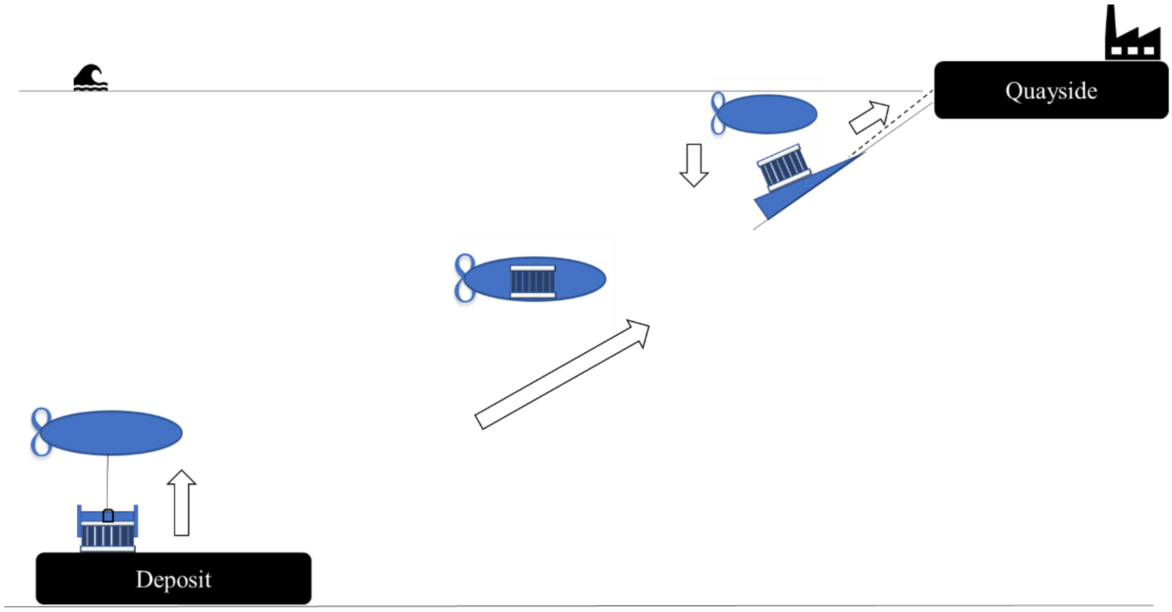


Figure 26: Solution variant 1: AUV with spreader for collection and a marine railway in port

4.6.3. Selecting from WS set 3

This WS set is based on carrying a container outside. This may have some disadvantages related to movement in water. The ellipsoid shape of the underwater vehicles minimises the drag resistance in water, and it is fair to say that any abruption in this shape due to a container with sharp edges will increase this resistance. In other words, this working structure highly depends on where the container is placed. If it is under the vehicle, it will be very bad for the overall shape and flow around the structures. It might be that containing it in the aft is better for the flow. However, this excludes the spreader solution from consideration since it is based on lifting. The container loader might be used as WP1 in this case. Yet, the loader requires a shorter distance between vehicle and container because of the moment that develops during the collection and depending on the site this might be questionable.

It was found that this solution is demanding during transportation because of the drag effects due to appendage, and the container loader was favoured as WP1 over the spreader due to the opportunity to store the container in the aft. The applicability of the loader was however dependent on the site. At the Mohn's Ridge, the topography might be uneven, and it is likely to be unsuited for close contact between seabed and vehicle. The safety of the vehicle cannot be properly ensured with respect to interference. The loader is therefore not a suitable alternative. This means that for the most critical function there are no fitting solutions left. Therefore, it is determined that there are no solutions from working structure set 3 that are suitable at the Mohn's Ridge and Loki's Castle.

4.6.4. Selecting from WS set 4

The towline is the only available WP1 of this set. The type of propulsion system will be important to the choice of vehicle. This has to do with both the capacity to pull the container and the wake from any thrusters. Based on the required towing capacity which is likely to be high, it is suggested that an AUV performs the task of moving from seabed to port's location. There should however be a study of where to optimally place the thrusters. Also, the optimal length of the towline should be carefully studied. The attachment itself to the container is a subject for discussion. The vehicle must first locate the container and then attach to it using the towline. The attachment equipment is a subject for embodiment design, but it may be considered to use some sort of hooks, magnets, etc. Moreover, the unloading in port was deemed a challenge due to the container inertia which makes it harder to control the drift of the container. It was found that a solution where the container can be released at a good distance from port was inevitable. The ice cover in Svalbard excludes any solutions that operate at surface level. Thus, the remaining WP3 is the marine railway. A simple sketch can be found in Figure 27.

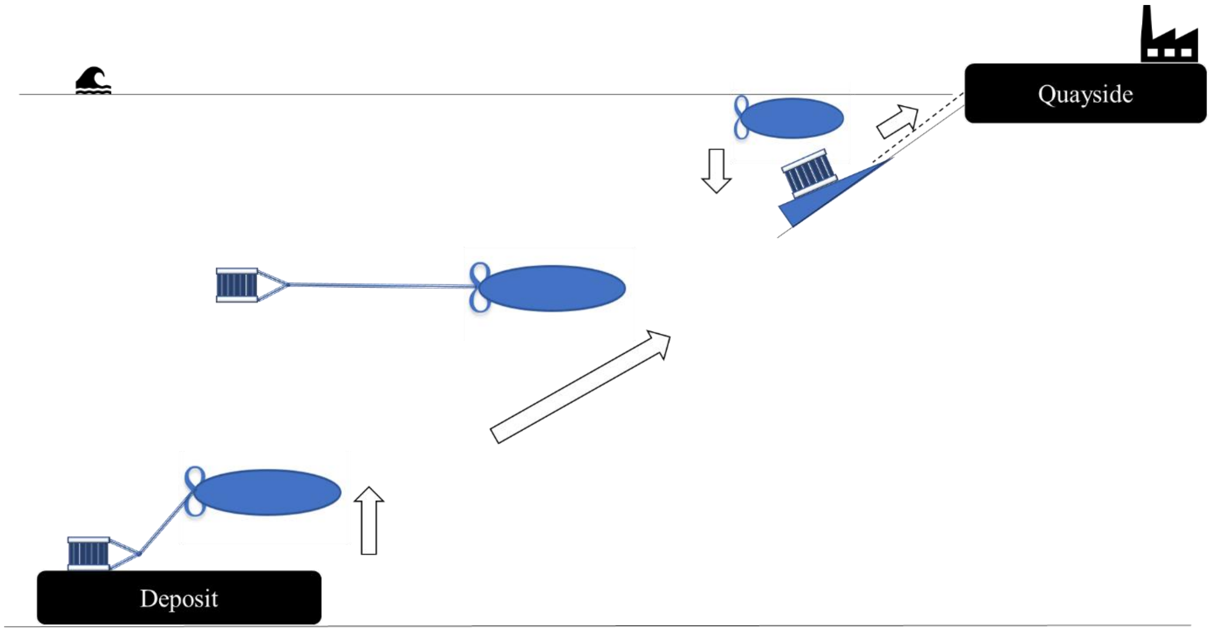


Figure 27: Solution variant 2: AUV towing a container and a marine railway in port

However, when the vehicle arrives in port, the towing solution might give some challenges. The inertia of the container in water makes it drift even after the vehicle has stopped moving. In worst case, it might hit the vehicle. This hazardous situation might be avoided by having very slow speed when approaching the harbour. However, it is not expected that the vehicle will be able to aid in a seamless docking of the container because of the towline. A solution could be that the vehicle simply releases the container, as we have seen before.

Either way it is important to have in mind that any use of a vehicle with propellers, such as the submarine and AUV, will create a wake which pushes the container backwards if the towline is too short. This creates more resistance which increases the required towing force. Depending on the size of the container, an idea could be to place the thrusters somewhere on the vehicle where the wake does not push the container. This would be a job for the embodiment design. If the vehicle is a glider, the wake problem vanishes, but it is uncertain whether towing is suitable for gliders that are dependent on a smooth movement in a saw-tooth pattern. Also, towing requires a high capacity in pulling, which is quite unlikely that the glider can do.

The design process is now finalised with two different solution variants: 1) with container spreader and marine railway, and 2) AUV towing container and marine railway in port. In Chapter 5, discussion, the results are evaluated.

5. DISCUSSION

The discussion aims to reflect on and evaluate the findings in this thesis. It begins with a discussion of the usefulness of the step-wise findings from the results section. Further, the final results are discussed, including limitations and uncertainties. A focus will be on how well the solutions found fulfil the functions identified. As this is an early stage design, there are several directions that future research may take. Promising paths for further work will be presented at the end.

Results

This thesis presented several findings throughout the results section. In Section 4.4 a morphological matrix was created with all working principles and classification parameters for achieving the functions of ore transportation from seabed to shore. The matrix is found in Appendix A, and it can be used to create a number of solutions other than the ones presented here. In Section 4.5 working structure sets based on compatibility check between functions and chosen classification parameters were found. The sets represent the working principles that are deemed most promising for combination into an overall solution. These sets are not location-specific, unlike in Section 4.6, where AMOR with its SMS deposits was used as an example location for firming up solution variants. In other words, if a solution were to be found for another location and/or resource, the final results might have been different. Depth, resource features and distance to shore are some consideration that might have given other solution variants.

The AUV with spreader concept largely depends on the technological development of AUVs. Also, the collecting process is sensitive. When onloading a container the vehicle is likely to experience an abrupt change in weight. This is something that must be accounted for by the vehicle in order to avoid a hazardous situation such as hitting the seabed. Regarding the vehicle, there will be a container input at the seabed, and a container output at port. An interesting question is whether we want to bring a container back – to utilise the cargo space when returning to the site. Reasons for this could be if we need supply of containers on the seabed. We could also ask whether we want to bring something back. The literature review showed that sediment residue is an unfavourable biproduct from.

The most unexpected result is the second option – towing container using AUV with towline. This was a solution inspired from surface movement of large structures where this is a common procedure. However, there has also been prototype testing of AUV steering plane dynamics for towing a large payload (Kepler et al., 2018). It was seen that the resistance due to drag and wake of thrusters was of concern. The thrusters of the AUV push the water backwards in order to move forward through the water, and this increases the speed of the water that meets the container. For the container, this means that the water that it meets has a speed working in the opposite direction of the travel direction. This increases the speed that the container must have through the water. From the resistance equations in Section 2.4 speed is found as a significant contribution to the total resistance. To compensate for this, the AUV must use more energy to pull the container through the water. This is an unfortunate consequence, and more research on how to minimise this resistance should be done. When looking at the terms of the total resistance, it is seen that the form resistance is important. Sharp edges contribute to increased drag and oscillating flows in the wake, see for instance Davis, Moore, & Purtell (1984) for study of flow around a rectangular cylinder. The edges of the container are likely to interrupt the flowlines of the water. The incoming water flow is not uniform due the flow irregularity caused by the thrusters of the AUV. Turbulent flow is a phenomenon which gradually vanishes as the water comes to rest. This suggests that there should be a study of the optimal distance between container and AUV, in other words a study of the optimal towline length. It could also be beneficial to find alternative shapes of the container to allow smoother flow around the structure. A container with round edges or even an ellipsoid-like container could be interesting to explore. Moreover, research into the optimal placement of thrusters on the AUV could also aid in minimising resistance. Some AUVs have a thruster in the aft, while others have two thrusters on the sides of the vehicle.

Although this solution comes with uncertainties as discussed above, it also has some advantages. Unlike the glider, the tow AUV does not need any additional space for buoyancy tanks. Moreover, the towline itself is unlikely to need any significant extra functionality during the operation. It was discussed that the coupling procedure between container and towline when collecting might be challenging, but an investigation into different hook-up options is not expected to be technologically advanced. It should however be emphasised the importance of keeping a good distance to the seabed for safety reasons. Also, the necessary elasticity and yield strength of the towline should be studied to avoid snapping of towline due to heavy loads. The method allowed for a systematic expansion of the solution field, and the AUV tower solution might not have been found without the abstraction of classification parameters, and the subsequent tabularisation into design catalogues.

The glider was a very hopeful solution for a long time due to features such as range and energy efficiency. As seen in the introduction, the glider has been identified as having great potential for underwater transportation (Jenkins & D'Spain, 2016). However, research has focused mostly on increasing energy efficiency, for instance by harvesting energy from sun, waves, and the decent in water (Javaid, Ovinis, Nagarajan, & Hashim, 2014). Limited cargo space inside suggests that this concept is more promising for research purposes than full-scale production for the time being. Also, the lack of precision and manoeuvring is problematic. However, the buoyancy feature of the glider is interesting. The collecting of a container requires a force by the vehicle pulling the container upwards. By Newton's third law there will be an opposite force originating from the vehicle pulling it downwards. Since the buoyancy force represent an upwards force originating from the vehicle, this might indicate that a gradual collecting force will give the vehicle a chance to adjust buoyancy gradually as well. Or even more unsophisticated: the vehicle may use the buoyancy force alone as lifting force if the spreader is chosen as WP1.

The two solutions presuppose that a container can be placed and filled in advance of transportation. It is not known to what extent the topography at site is convenient for this. Locating the container is also an auxiliary function which may be demanding. If the AUV gets off course, it might not be able to reach the container after all. A way to aid in this is to place beacons along the route which communicate with the AUV. When the AUV arrives within some radius of the beacon, it measures the distance between beacon and AUV, and uses this to steer the vehicle in the right direction. Upon arrival to the deposit's site, the specific location of the container may be found if it is equipped with subsea sensors. Another option could be to use several vehicles, for instance AUVs as transportation vehicles and gliders as auxiliary vehicles for control.

Further work

The next stage of the design process as seen in Figure 2 is embodiment design, and as such a suggestion of further work is to take one or both of the concepts proposed into the embodiment design phase. This is where layout is designed. Here, auxiliary functions can be addressed, such as navigation and energy supply, and arrangement can be found, such as were to place the thrusters on the AUV.

This could also be a good way to use the strength of the method to test the results of this thesis – to go into embodiment phase and iterate back again.

Another possible road for further work which may take the work in a new direction, is to pick a concept from the morphological matrix found in this thesis. We may think of this matrix as a grocery store: it contains many items that may be put into several dishes of your own choice. An idea could be to change the location or resource type and see which promising solutions that arise from the different constraints and product type here. After that make a selection from morphological matrix. Suggestions on other locations are the CCZ in the Pacific – the deposit, depth and weather conditions are quite different than the North-Atlantic, and this is likely to influence the favourable design to some extent.

Towing of a container under water was an unexpected solution from the design process. This is a procedure which is familiar at surface, but not under water. As seen, there are many issues related to the total resistance in water, and a study into this, either by hydrodynamic experiments or use of software, would be interesting for different incoming water speeds. Another experimental approach would be to test the performance and energy use of the collection solutions, as these were identified as critical regarding compatibility. A towline hook-up or spreader prototype under water could be tested. Depending on the depth, the true water pressure may be difficult to resemble, unless having a pressure tank, but the effects of added mass when collecting may be uncovered.

Before these solutions are tried for deep sea mining, research on the collection and transportation with the vehicles should be performed. Both collection and movement under water with payload are novel procedures still. This knowledge would be useful to research and industry communities, and for different applications. Also, the interaction between vehicle and collection is critical because of precision and safety.

6. CONCLUSION

This research aimed to systematically find design concepts for transportation of ore from seabed to quayside. The hypothesis of the thesis:

Underwater transportation can be an alternative transportation solution for deep sea mining.

Final solution variants were obtained by narrowing to an example location. The resulting solution variants for operation at Atlantic Mid-Ocean Ridge were:

1. An AUV with a spreader for collecting a container. A marine railway is used for unloading of containers
2. An AUV for towing of a container using a rope. A marine railway is used for unloading of containers

The concepts contain design parameters that fulfil the functions needed for obtaining the goal in the hypothesis. Thus, the hypothesis cannot be rejected, but it cannot be confirmed either. This is because further research is needed in order to determine the layout and detail design. During the next design stage – embodiment design – there should be a particular focus on auxiliary functions, such as energy supply and control. These functions are essential, but also challenging. Moreover, in order to validate the solutions, they should be tested by experiments, preferably in similar environments before potentially progressing to full-scale operation.

Other important contributions include:

- A systems design and marine technology principles implementation to a recognised conceptual engineering design approach
- A matrix containing design parameters that can be utilised by anyone wanting to design an (underwater) transportation system for deep sea mining, but also other transportation of similar character
- An adapted method for using working structure sets for combability check and selection of large solution field
- An update of the value chain with respect to the decoupling of excavation and transportation

7. REFERENCES

A-ward. (2019). 20/40ft Tilting Container Loaders. Retrieved December 11, 2019, from https://a-ward.com/equipment-and-solutions/container-loaders/

Abramowski, T. (2016). *Value chain of deep seabed mining*. Szczecin, Poland.

Abramowski, T., & Stoyanova, V. (2012). Deep-sea polymetallic nodules: Renewed interest as resources for environmentally sustainable development. *12th International Multidisciplinary Scientific GeoConference SGEM 2012*, *1*, 515–521.

Ali, S. H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., … Yakovleva, N. (2017). Mineral supply for sustainable development requires resource governance. *Nature*, *543*, 367–372. https://doi.org/10.1038/nature21359

Allmendinger, E. E. (Ed.). (1990). *Submersible Vehicle Systems Design*. New Jersey: The Society of Naval Architects and Marine Engineers.

Amann, H. (1982). Technological Trends in Ocean Mining. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*. https://doi.org/10.1098/rsta.1982.0118

Amdahl, J., Berge, S., Dukan, F., Endal, A., Hals, J., Holm, H., … Æsøy, V. (2014). *Havromsteknologi* (L. Lundby, Ed.). Retrieved from http://www.marin.ntnu.no/havromsteknologi/Bok/Bok.pdf

Bai, Y., & Bai, Q. (2010). *Subsea Engineering Handbook*. Oxford: Elsevier.

Bemfica, J. R., Melchiorri, C., Moriello, L., Palli, G., & Scarcia, U. (2014). A three-fingered cable-driven gripper for underwater applications. *Proceedings - IEEE International Conference on Robotics and Automation*, 2469–2474. https://doi.org/10.1109/ICRA.2014.6907203

Blanchard, B. S., & Fabrycky, W. J. (1998). *Systems Engineering and Analysis* (3rd ed.). New Jersey: Prentice Hall.

Bloodworth, A., & Gunn, G. (2012). The Future of the Global Minerals and Metals Sector: Issues and Challenges out to 2050. *Geosciences*, (15), 90–97.

Blue Mining. (2018). Retrieved from http://www.bluemining.eu/download/project_results/public_reports/Blue-mining-Public-Report-2018.pdf

Brown, C., & Clark, R. P. (2010). Using a Novel Vehicle Conceptual Design Utility to Evaluate a Long-Range , Large Payload UUV. *OCEANS 2010 MTS/IEEE SEATTLE*, 1–10. https://doi.org/10.1109/OCEANS.2010.5664540

Burcher, R., & Rydill, L. (1994). *Concepts in Submarine Design* (I. Dyer, R. E. Taylor, J. N. Newman, & W. G. Price, Eds.). New York: Cambridge University Press.

Carlton, J. (2007). Ship resistance and propulsion. In *Marine Propellers and Propulsion*.

https://doi.org/10.1016/b978-075068150-6/50014-0

Chakravartty, A. (2001). The semantic or model-theoretic view of theories and scientific realism. *Synthese*. https://doi.org/10.1023/A:1010359521312

Cho, S. gil, Park, S., Oh, J., Min, C., Kim, H., Hong, S., … Lee, T. H. (2019). Design optimization of deep-seabed pilot miner system with coupled relations between constraints. *Journal of Terramechanics*, *83*, 25–34. https://doi.org/10.1016/j.jterra.2019.01.003

Coffey Natural Systems. (2008). Environmental Impact Statement: Nautilus Minerals Niugini Limited, Solwara 1 Project Volume A - Main Report. In *Nautilius Minerals Niugini*.

Connelly, D. P., Copley, J. T., Murton, B. J., Stansfield, K., Tyler, P. A., German, C. R., … Wilcox, S. (2012). Hydrothermal vent fields and chemosynthetic biota on the world's deepest seafloor spreading centre. *Nature Communications*. https://doi.org/10.1038/ncomms1636

Coyne, R., Rosenman, M., Radford, A., Balachandran, M., & Gero, J. (1990). *Knowledge-Based Design Systems*. Reading, MA: Addison Wesley.

Crawley, E., Cameron, B., & Selva, D. (2016). *System Architecture: Strategy and Product Development for Complex Systems*. Hoboken, NJ: Pearson Higher Education.

Cross, N. (2000). *Engineering Design Methods: Strategies for Product Design* (3rd ed.). Chichester: John Wiley & Sons.

Davis, R. W., Moore, E. F., & Purtell, L. P. (1984). A numerical-experimental study of confined flow around rectangular cylinders. *Physics of Fluids*. https://doi.org/10.1063/1.864486

De Beers. (2019). Marine. Retrieved November 27, 2019, from https://www.debeersgroup.com/the-group/about-debeers-group/mines/namibia/offshore

Deepak, C. R., Ramji, S., Ramesh, N. R., Babu, S. M., Abraham, R., Shajahan, M. A., & Atmanand, M. A. (2007). Development and testing of underwater mining systems for long term operations using flexible riser concept. *Proceedings of the ISOPE Ocean Mining Symposium*.

Earney, F. (1990). *Marine Mineral Resources*. New York: Routledge.

ECORYS. (2014). *Study to investigate the state of knowledge of Deep Sea Mining*. Rotterdam/Brussels.

Edmonds, H. N., Michael, P. J., Baker, E. T., Connelly, D. P., Snow, J. E., Langmuir, C. H., … Graham, D. W. (2003). Discovery of abundant hydrothermal venting on the ultraslow-spreading Gakkel ridge in the Arctic Ocean. *Nature*. https://doi.org/10.1038/nature01351

Ellefmo, S. L., Ludvigsen, M., & Frimanslund, E. K. T. (2017). Full Cycle Resource Evaluation of SMS Deposits Along the Arctic Mid Ocean Ridge. *ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering. Volume 6: Ocean Space Utilization*. https://doi.org/10.1115/OMAE2017-62525

Fang, H., & Duan, M. (2014). Submarine Pipelines and Pipeline Cable Engineering. In H. Fang & M. Duan (Eds.), *Offshore Operation Facilities: Equipment and Procedures*. https://doi.org/10.1016/b978-0-12-396977-4.00006-8

Fonteyne, R. (2001). Fishing Methods and Fishing Fleets. In *Encyclopedia of Ocean Sciences* (2nd ed.). https://doi.org/10.1016/B978-012374473-9.00446-X

Georgiopoulou, A. (2018). Seafloor Sediment and Rock Sampling. In A. Micallef, S. Krastel, & A. Savini (Eds.), *Submarine Geomorphology* (pp. 75–92). https://doi.org/10.1007/978-3-319-57852-1_6

Gerwick, B. (2007). *Construction of Marine and Offshore Structures* (3rd ed.; M. D. Morris, Ed.). https://doi.org/10.1201/9781420004571

Griffiths, G. (2002). Technology and Applications of Autonomous Underwater Vehicles. In G. Griffiths (Ed.), *Technology and Applications of Autonomous Underwater Vehicles*. https://doi.org/10.1201/9780203522301

Halbach, P. E., Jahn, A., & Cherkashov, G. (2017). Marine co-rich ferromanganese crust deposits: Description and formation, occurrences and distribution, estimated world-wide resources. In *Deep-Sea Mining: Resource Potential, Technical and Environmental Considerations*. https://doi.org/10.1007/978-3-319-52557-0_3

Han, H., Guo, X., & Cao, X. (2011). Design and analysis for hydraulic travel system of container stacker. *Advanced Materials Research*. https://doi.org/10.4028/www.scientific.net/AMR.168-170.230

Hancox, M. (n.d.). *Towing, Positioning & Hook-up for Offshore Production: The Towmasters' Handbook*. Ledbury, England: Oilfield Publications.

Hannington, M., Jamieson, J., Monecke, T., Petersen, S., & Beaulieu, S. (2011). The abundance of seafloor massive sulfide deposits. *Geology*, *39*(12), 1155–1158. https://doi.org/10.1130/G32468.1

Harren, P. A. (2013). *Safe Operation and Maintenance of Dry Dock Facilities*. https://doi.org/10.1061/9780784410875

Hawley, J. G., Nuckols, M. L., Reader, G. T., & Potter, I. J. (1996). *Design Aspects of Underwater Intervention Systems*. Dubuque, Iowa: Kendall/Hunt Publishing Company.

Hein, J. R., & Koschinsky, A. (2013). Deep-Ocean Ferromanganese Crusts and Nodules. In *Treatise on Geochemistry: Second Edition*. https://doi.org/10.1016/B978-0-08-095975-7.01111-6

Hein, James R., Conrad, T. A., & Staudigel, H. (2010). Seamount Mineral Deposits: A Source of Rare Metals for High-Technology Industries. *Oceanography*, *23*(1), 184–189. https://doi.org/10.5670/oceanog.2010.70

Hein, James R., Mizell, K., Koschinsky, A., & Conrad, T. A. (2013). Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources. *Ore Geology Reviews*. https://doi.org/10.1016/j.oregeorev.2012.12.001

Hoagland, P., Beaulieu, S., Tivey, M. A., Eggert, R. G., German, C., Glowka, L., & Lin, J. (2010). Deep-sea mining of seafloor massive sulfides. *Marine Policy*. https://doi.org/10.1016/j.marpol.2009.12.001

Hubka, V., & Eder, W. E. (2002). Theory of technical systems and engineering design synthesis. In A. Chakrabarti (Ed.), *Engineering Design Synthesis : Understanding, Approaches and Tools*. https://doi.org/10.1007/978-1-4471-3717-7

Huvenne, V. A. I., McPhail, S. D., Wynn, R. B., Furlong, M., & Stevenson, P. (2009). Mapping Giant Scours in the Deep Ocean. *Eos, Transactions American Geophysical Union*. https://doi.org/10.1029/2009eo320002

Huvenne, V. A., Robert, K., Marsh, L., Iacono, C. Lo, Bas, T. Le, & Wynn, R. B. (2018). ROVs and AUVs. In A. Micallef, S. Krastel, & A. Savini (Eds.), *Submarine Geomorphology*. https://doi.org/10.1007/978-3-319-57852-1_7

IADC, & IAPH. (2010). *Dredging for development* (N. Bray & M. Cohen, Eds.). Netherlands: International Association of Dredging Companies (IADC).

IEA. (2019). *Global EV Outlook 2019*. Retrieved from https://www.iea.org/publications/reports/globalevoutlook2019/

ISA. (2019a). Deep seabed minerals contractors. Retrieved December 5, 2019, from https://www.isa.org.jm/deep-seabed-minerals-contractors

ISA. (2019b). Exploration Areas. Retrieved November 4, 2019, from https://www.isa.org.jm/contractors/exploration-areas

Jackson, H. . (1992). Fundamentals of Submarine Concept Design. *SNAME Transactions*, *100*, 419–448.

Javaid, M. Y., Ovinis, M., Nagarajan, T., & Hashim, F. B. M. (2014). Underwater gliders: A review. *MATEC Web of Conferences*. https://doi.org/10.1051/matecconf/20141302020

Jenkins, S. A., & D'Spain, G. (2016). Autonomous underwater gliders. In *Springer Handbook of Ocean Engineering*. https://doi.org/10.1007/978-3-319-16649-0_12

Jones, J. C. (1992). *Design Methods* (2nd ed.). London: John Wiley & Sons.

Juliani, C., & Ellefmo, S. L. (2018). Probabilistic estimates of permissive areas for undiscovered seafloor massive sulfide deposits on an Arctic Mid-Ocean Ridge. *Ore Geology Reviews*. https://doi.org/10.1016/j.oregeorev.2018.04.003

Kepler, M. E., Pawar, S., Stilwell, D. J., Brizzolara, S., & Neu, W. L. (2018). Steering Plane Dynamics of a Small Autonomous Underwater Vehicle that Tows a Large Payload. *2018 IEEE/OES Autonomous Underwater Vehicle Workshop (AUV)*. https://doi.org/10.1109/auv.2018.8729715

Krypton Ocean. (2019a). Krypton AUV 1. Retrieved November 6, 2019, from http://www.kryptonocean.com/krypton-auv-1.html

Krypton Ocean. (2019b). Krypton MUV 1. Retrieved November 6, 2019, from http://www.kryptonocean.com/krypton-muv-1.html

Krypton Ocean. (2019c). RCUMA. Retrieved November 6, 2019, from http://www.kryptonocean.com/rcuma.html

Kuhn, T., Wegorzewski, A. V., Rühlemann, C., & Vink, A. (2017). Composition, formation, and occurrence of polymetallic nodules. In *Deep-Sea Mining: Resource Potential, Technical and Environmental Considerations*. https://doi.org/10.1007/978-3-319-52557-0_2

Lesage, M. (2019). *Morphological Matrices*. Trondheim.

Lesage, M., Juliani, C., & Ellefmo, S. (2018). Economic Block Model Development for Mining Seafloor Massive Sulfides. *Minerals*, *8*(10), 468. https://doi.org/10.3390/min8100468

Levander, K. (2012). *System Based Ship Design*.

Lobanoff, V. S., & Ross, R. R. (2013). *Centrifugal Pumps: Design and Application* (2nd ed.). https://doi.org/10.1016/C2009-0-26797-3

Mackay, R. (2004). *The Practical Pumping Handbook*. https://doi.org/10.1016/B978-1-85617-410-7.X5000-0

Malinetsky, G. G., & Smolin, V. S. (2019). Robotic solutions for Arctic transit corridor cargo autonomous undersea vehicles. *Procedia Computer Science*, *150*, 702–708. https://doi.org/10.1016/j.procs.2019.02.021

Martin Ludvigsen, Kurt Aasly, Steinar Ellefmo, Ana Hilario, Eva Ramirez-Llodra, F., Søreide, Ismael Falcon- Suarez, Cyril Juliani, Amanda Kieswetter, Anna Lim, C., & Malmquist, Stein M. Nornes, Emil Paulsen, Hauke Reimers, Ø. S. (2016). *MarMine Cruise Report: Arctic Mid-Ocean Ridge (AMOR)*. Retrieved from https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2427715/NTNU-MARMINE-041%2BMarMine%2BCruise%2BReport%2B2016.pdf?sequence=3&isAllowed=y

Meisel, F. (2009). *Seaside Operations Planning in Container Terminals*. https://doi.org/10.1007/978-3-7908-2191-8

METI, & JOGMEC. (2017). World's First Success in Continuous Ore Lifting test for Seafloor Polymetallic Sulphides. Retrieved July 30, 2019, from https://www.meti.go.jp/english/press/2017/0926_004.html

Mizell, K., & Hein, J. R. (2018). Ferromanganese crusts and nodules: Rocks that grow. In *Encyclopedia of Earth Sciences Series*. https://doi.org/10.1007/978-3-319-39312-4_101

Mubaroq, A. (2002). *Belt Conveyors for Bulk Materials* (5th ed.). US: Conveyor Equipment Manufacturers Association.

NASA. (2007). *Systems Engineering Handbook*. https://doi.org/10.1016/0016-0032(66)90450-9

Nautilus Minerals. (2019a). PNG. Retrieved October 27, 2019, from http://www.nautilusminerals.com/irm/content/png.aspx?RID=258

Nautilus Minerals. (2019b). Technology Overview. Retrieved July 30, 2019, from http://www.nautilusminerals.com/irm/content/technology-overview.aspx?RID=329

OECD. (2015). *Material Resources, Productivity and the Environment*. https://doi.org/10.1787/9789264190504-en

OECD. (2019). *Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences*. https://doi.org/10.1787/9789264307452-en

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. H. (2007). Engineering design: A systematic approach. In K. Wallace & L. Blessing (Eds.), *Engineering Design: A Systematic Approach* (3rd ed.). https://doi.org/10.1007/978-1-84628-319-2

Pedersen, R. B., Rapp, H. T., Thorseth, I. H., Lilley, M. D., Barriga, F. J. A. S., Baumberger, T., … Jorgensen, S. L. (2010). Discovery of a black smoker vent field and vent fauna at the Arctic Mid-Ocean Ridge. *Nature Communications*. https://doi.org/10.1038/ncomms1124

Pedersen, R. B., Thorseth, I. H., Nygård, T. E., Lilley, M. D., & Kelley, D. S. (2013). Hydrothermal Activity at the Arctic Mid-Ocean Ridges. In *Diversity of Hydrothermal Systems on Slow Spreading Ocean Ridges*. https://doi.org/10.1029/2008GM000783

Pettersen, B. (2004). *Kompendium TMR4247 Hydrodynamikk*. Trondheim. Department of Marine technology: Akademika forlag.

Porter, M. E. (1985). Technology and Competitive Advantage. *Journal of Business Strategy*, *5*(3), 60. https://doi.org/10.1108/eb039075

Prior, T., Giurco, D., Mudd, G., Mason, L., & Behrisch, J. (2012). Resource depletion, peak minerals and the implications for sustainable resource management. *Global Environmental Change*, *22*(3), 577–587. https://doi.org/10.1016/j.gloenvcha.2011.08.009

Randall, R. E. (2004). Dredging. In G. P. Tsinker (Ed.), *Port Engineering - Planning, Construction, Maintenance, and Security*. John Wiley & Sons.

Rawson, K. J., & Tupper, E. C. (2001). *Basic Ship Theory* (5th ed.). https://doi.org//10.1016/B978-0-7506-5398-5.X5000-6

Regjeringen.no. (2019). *Blå muligheter: Regjeringens oppdaterte havstrategi*. Retrieved from https://www.regjeringen.no/globalassets/departementene/nfd/dokumenter/strategier/nfd_havstrategi_2019_norsk_uu.pdf

Renilson, M. (2015). Hydrostatics and control. In *Submarine Hydrodynamics: SpringerBriefs in Applied Sciences and Technology* (Vol. 169, pp. 5–17). https://doi.org/10.1007/978-3-319-16184-6_2

Rona, P. A., Klinkhammer, G., Nelsen, T. A., Trefry, J. H., & Elderfield, H. (1986). Black smokers, massive sulphides and vent biota at the Mid-Atlantic ridge. *Nature*. https://doi.org/10.1038/321033a0

Rona, Peter A. (2003). Resources of the Sea Floor. *Science*, *299*(5607), 673–674. https://doi.org/10.1126/science.1080679

Rona, Peter A. (2008). The changing vision of marine minerals. *Ore Geology Reviews*. https://doi.org/10.1016/j.oregeorev.2007.03.006

Roonwal, G. S. (2018). *Mineral Exploration: Practical Application*. https://doi.org/10.1007/978-981-10-5604-8

Rossol, T., Hildebrandt, M., & Wirtz, M. (2018). Miniaturized Underwater Gliders as Payload Transfer Units. *2018 IEEE/OES Autonomous Underwater Vehicle Workshop (AUV)*. https://doi.org/10.1109/auv.2018.8729763

Schander, C., Rapp, H. T., Kongsrud, J. A., Bakken, T., Berge, J., Cochrane, S., … Pedersen, R. B. (2010). The fauna of hydrothermal vents on the Mohn Ridge (North Atlantic). *Marine Biology Research*. https://doi.org/10.1080/17451000903147450

Sharma, R. (2011). Deep-sea mining: Economic, technical, technological, and environmental considerations for sustainable development. *Marine Technology Society Journal*. https://doi.org/10.4031/MTSJ.45.5.2

Sharma, R. (2017). *Deep-Sea Mining: Resource Potential, Technical and Environmental Considerations*. Cham, Switzerland: Springer International Publishing.

Sivčev, S., Coleman, J., Omerdić, E., Dooly, G., & Toal, D. (2018). Underwater manipulators: A review. *Ocean Engineering*, *163*(June 2017), 431–450. https://doi.org/10.1016/j.oceaneng.2018.06.018

SRK Consulting. (2010). Offshore Production System Definition and Cost Study. Retrieved July 12, 2019, from http://actnowpng.org/sites/default/files/Solwara 1 Production System Definition and Cost Study 2010.pdf

Stopford, M. (2009). *Maritime Economics* (3rd ed.). London; New York: Routledge.

Suh, N. (2001). *Axiomatic Design: Advances and Applications*. https://doi.org/10.1016/j.clineuro.2008.04.006

Ulrich, K. T., & Eppinger, S. D. (2012). Product Design and Development. In *The McGraw-Hill Companies* (5th ed., Vol. 5th). https://doi.org/10.1016/B978-0-7506-8985-4.00002-4

UNOET. (1987). *Delineation of mine-sites and potential in different sea areas*. London.

Welling, C. G. (1981). An advanced design deep sea mining system. *Proceedings of the Annual Offshore Technology Conference*. https://doi.org/10.4043/4094-ms

Woods, J., & Rosales, A. (2010). Virtuous Distortion: Abstraction and idealization in model-based science. In L. Magnani, W. Carnielli, & C. Pizzi (Eds.), *Model-Based Reasoning in Science and Technology: Abduction, Logic, and Computational Discovery*. https://doi.org/10.1007/978-3-642-15223-8

Work, P. A. (2016). Dredging. In *Encyclopedia of Earth Sciences Series*. https://doi.org/10.1007/978-94-017-8801-4_250

Yamazaki, T. (2017). Fundamental geotechnical considerations for design of deep-sea mining systems. In *Deep-Sea Mining: Resource Potential, Technical and Environmental Considerations*. https://doi.org/10.1007/978-3-319-52557-0_9

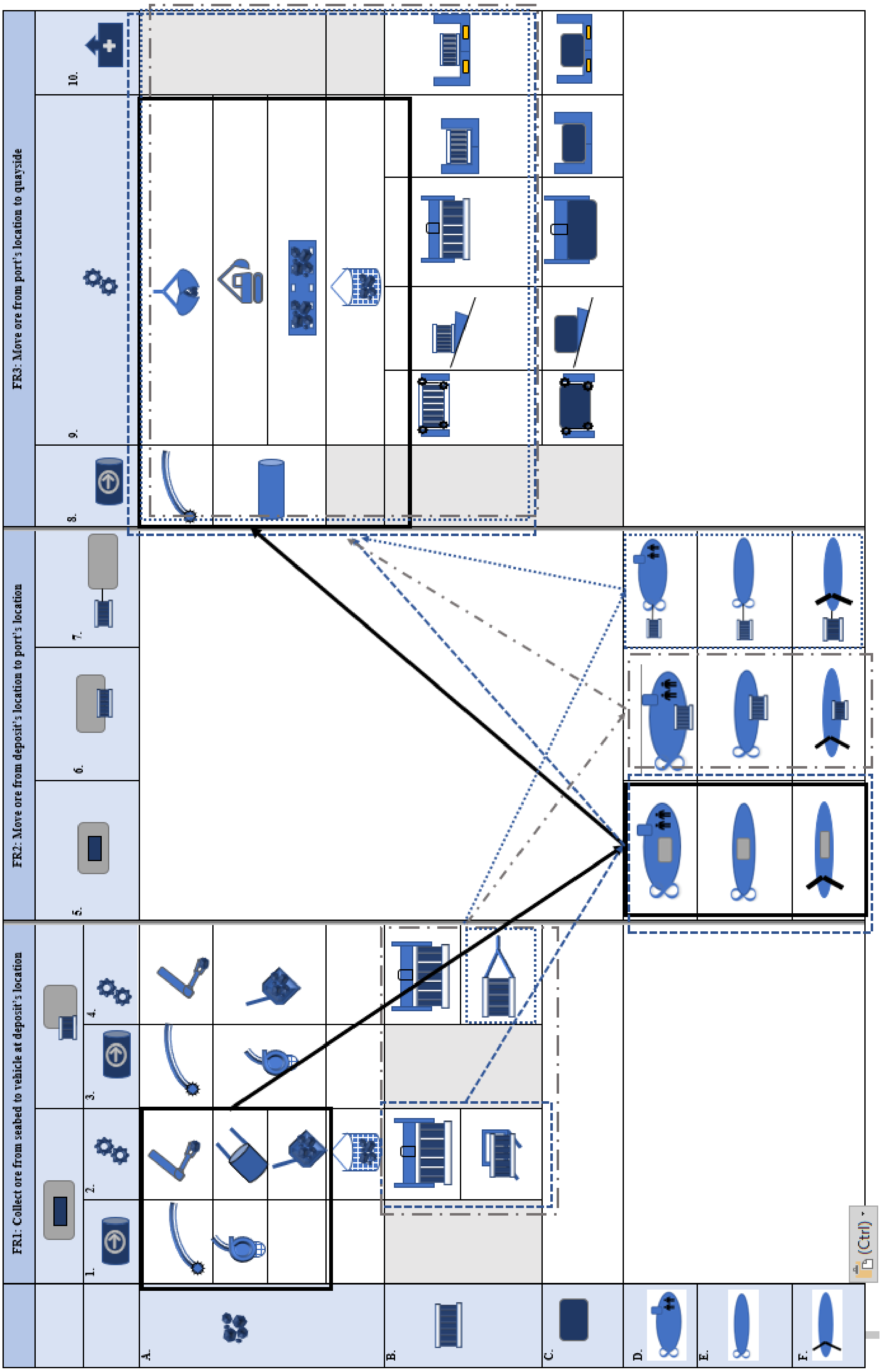
Zhang, S., Ding, Y., Liu, B., & Chang, C. chi. (2017). Supply and demand of some critical metals and present status of their recycling in WEEE. *Waste Management*, *65*, 113–127. https://doi.org/10.1016/j.wasman.2017.04.003

Zwicky, F. (1967). The Morphological Approach to Discovery, Invention, Research and Construction. In *New Methods of Thought and Procedure*. https://doi.org/10.1007/978-3-642-87617-2_14

APPENDIX

A. MORPHOLOGICAL MATRIX

B. MORPHOLOGICAL MATRIX WITH WS



NTNU

Kunnskap for en bedre verden