**Proceedings of ASME 2020 39th International Conference on Ocean, Offshore & Arctic Engineering
OMAE2020
June 28-July 3, Fort Lauderdale, FL, USA**

OMAE2020-18655

DEEP SEA MINING: TOWARDS CONCEPTUAL DESIGN FOR UNDERWATER TRANSPORTATION

Astrid Vamråk Solheim[1a], Maxime Lesage[2], Bjørn Egil Asbjørnslett[1], Stein Ove Erikstad[1]

[1]Department of Marine Technology, NTNU[b], Trondheim, Norway
[2]Department of Geoscience and Petroleum, NTNU, Trondheim, Norway

ABSTRACT
This paper presents the first steps towards conceptual design for the underwater transportation of minerals from seabed to shore for deep sea mining (DSM). The methodology is based on conceptual design using a systematic approach. Abstraction was used to identify the fundamental entities of the problem, and a function structure containing the overall function and subfunctions was established based on the abstraction. Further, an extensive search for working principles (WP) was conducted in order to find forms associated with the functions. This was done by exploration of solutions within different industries such as the oil and gas industry, subsea industry and dredging industry. The discovered working principles were then listed and categorized based on their physical principles, i.e. classifying criteria. For each function, the working principles were combined into design catalogues with classifying criteria in the rows and columns. Further, compatibility between principles was reviewed. This led to the selection of four working structure sets: one based on ore moved as bulk, and three based on ore moved inside a container. The container-based solutions are different in how the container is moved: inside the cargo hold, carried outside, or towed by underwater vehicle. A completion of the last steps of the conceptual design process is needed to obtain a principle solution.

Keywords – Deep sea mining, conceptual design, marine system design, marine technology, underwater transportation.

1. INTRODUCTION
Metals such as copper, lithium, cobalt, nickel and rare earth elements are essential components in cell phones, electric cars, wind turbines, and more [1]. Demand for these metals is expected to increase in the future due to population growth, growing economies and a growing renewables industry [2], [3]. With its immense resources, the seafloor is of interest both scientifically and due to its potential economic value [4], [5]. 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 meters water depth. Prototype testing of deep sea mining systems has been carried out since the 1970's, see for instance [6], [7]. Moreover, various deep sea mining concepts have been proposed for decades [8]. Despite the continuous investigation of deep sea mining, full-scale production has not happened yet. The current proposed concepts have in common the use of a supporting vessel as a mother station at the ocean surface, see for instance [10], [11]. These concepts involve the extraction with costly, advanced equipment submerged on the deep seabed – followed by an extensive ore lift of several kilometers towards the ocean surface.

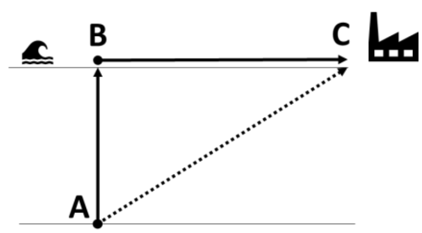


FIGURE 1: Traditional upstream transportation (solid line): Vertical transportation from A to B, and further shipping from B to C. The paper explores the opportunity to ship between A and C under water (dotted line).

The transportation during a deep sea mining operation has been identified as challenging regarding the efficiency [8], [9]. The term *transportation* is here defined as *changing position of payload*, with position being any point in space and payload being a given cargo. Further, *deep sea mining support vessel* (DSMSV) is used for production vessels for deep sea mining in order to differentiate from the established acronym platform supply vessel (PSV) in the maritime industry.

[a] Correspondance: astrid.v.solheim@ntnu.no
[b] The Norwegian University of Science and Technology (www.ntnu.edu)

When reaching the ocean surface, one may meet some of the harshest and most technically complex ocean environments, with waves, wind, ice and darkness. For deep sea mining, the conventional solution transports ore vertically from the seabed (A), to a standby mother station (B), and further transports horizontally to port (C), see Figure 1. This paper will investigate whether transportation can happen directly from A to C without going through B. An assumption is that the underwater transportation is assisted by a vehicle. This leaves out other transportation solutions such as pipeline infrastructure, tracks, hyperloops, etc.

2. LITERATURE REVIEW

2.1. Deep sea marine mineral resources

Polymetallic (manganese) nodules are independent dark-colored, potato-shaped rocks found at 3,500-6,500 meters 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 [12]–[15]. An area of high concentration and commercial interest is the Clarion-Clipperton Zone (CCZ) in the North-East 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, such as China, Germany, and Korea [16].

Ferromanganese (Fe-Mn) crusts are large dark layers covering the hard-rock substrate on the seabed at 1,000-5,000 meters water depth. The formation contains mostly manganese and iron, but also cobalt, nickel, titanium, copper, and rare earth elements – in addition to trace elements. The crusts can be found throughout the entire abyssal waters of the earth – including the Pacific, Atlantic, and Indian Oceans [15], [17].

Seafloor massive sulfides (SMS), or hydrothermal sulfides, are chimney-like formations found at 1,200-3,500 meters [18]. They consist of mostly iron, copper, zinc and lead, and some deposits exhibit gold and silver as well. SMS are found at the Mid-Ocean Ridge, but also in back-arc basins in the West Pacific [4], [19].

2.2. State-of-the-art in deep sea mining and underwater cargo transportation

The company that has been closest to a commercial realization of a full-scale deep sea mining operation is Nautilus Minerals. Nautilus Minerals intended to commence production of SMS in Papua New-Guinea at 1,600 meters water depth. Nautilus Minerals' deep sea mining system proposal includes technologies within dredging, oil and gas and offshore mining for mining minerals at high depths [20]. Their proposed solution consists of three seafloor production tools, a riser and lifting system (RALS), a deep sea mining support vessel, and ore transportation using shuttle barges in addition to onshore processing activities [10], see Figure 2. The crawlers on the seafloor are used to excavate, gather and comminute ore. After extraction, the minerals are transported as a slurry through the RALS to the DSMSV using a large subsea slurry lift pump (SSLP). Onboard the DSMSV the slurry is dewatered, stored, and later unloaded to a transportation barge using a conveyor belt – i.e. ship-to-ship transfer. The effluent is returned to the seabed using the riser's auxiliary pipes. The dewatered ore is transported to the shore by the shuttle barge for processing, and further shipped for smelting [10].

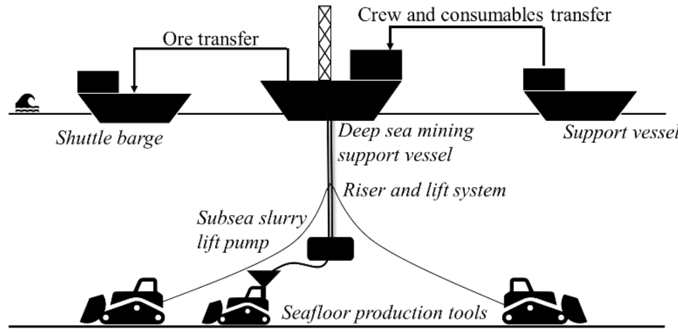


FIGURE 2: Schematic view of Nautilus Minerals' intended production.

Krypton Ocean 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 to be mined is polymetallic nodules. However, they also explore other mineral resources. Krypton Ocean has developed three different types of concepts: 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. 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. The collector is designed for transporting up to 1 ton of minerals, and it has a 110 kW power unit powered by hydrogen fuel cells with reserves for up to 8 hours operation. The Krypton MUV 1 is an autonomous/manned underwater vehicle for exploration and underwater operations. The vehicle resembles the AUV in its characteristics. The manned version has room for 3 crew members, and it can supply oxygen for 1 hour. Considering the oxygen supply and the immersion rate, it is reasonable to believe that the manned version is designed for operations at shallower water depths, although this is not specified [11]. 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 3. 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 a ballast tank system, immersing its deck area. This feature supports the loading operations of the tugs and AUVs. The tugs are used for driving the AUVs onto the submerged deck.

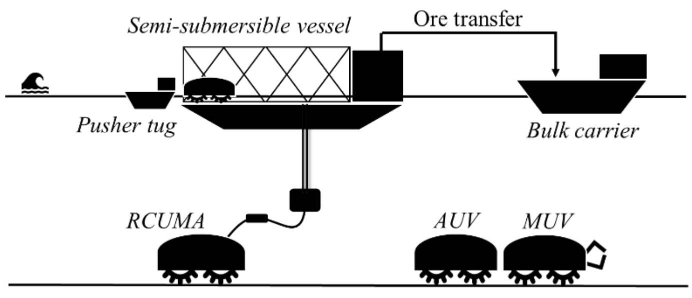


FIGURE 3: Schematic view of Krypton Ocean vehicles and mining system.

A large, long-range unmanned underwater vehicle (UUV) with payload-carrying capabilities has been presented earlier [21]. The UUV is designed to pick up, carry, and drop off a large weight payload. The vehicle is designed to carry up to 4.5 tons at a water depth of maximum 450 meters, and the transit range is between 20 and 300 nm (~40 to 550 km). They present three different concepts: 1) Internal Payload Vehicle, 2) Expandable Internal Payload Vehicle, and 3) External Payload Vehicle as shown in Figure 4. The first and second concepts have payload inside the vehicle while the third concept has 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".

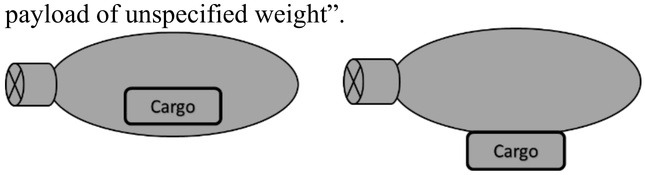


FIGURE 4: Large, long-range UUV with internal and external payload integration.

Others have investigated the use of Cargo Autonomous Underwater Vehicles for the underwater transportation of cargo under the ice-covered Arctic Ocean [22]. The potential ice cover in this area may pose limitations to the use of surface vessels due to the necessity of navigating through thick ice. The need for specialized underwater vessels was demonstrated after military submarines experiments revealed that although this kind of operation is possible, there were several economic challenges, such as the low payload-carrying capabilities of the submarines, the complexity of load/unload-operation, and the inability to enter shallow ports. The transportation system consists of lighters (i.e. barges) carrying 1,000-2,000 20 ft containers, AUVs, and a seafloor train system. Lighters are used for parts of the route that are without ice formation. When the lighter reaches the ice border, the AUV deploys robotic devices with hatches weighing more than 10,000 tons that clasp the lighter. The hatches and the AUV are connected by hawsers, and the lighter is lowered into the water by AUV winding the hawsers. The lighter and AUV then travel underwater as one unit using the seafloor train system. When approaching the area where the ice formation ends, the lighter is detached by releasing the hatches, and it floats up for further surface shipping. A summary of the AUV's mode of operation is presented in Figure 5.

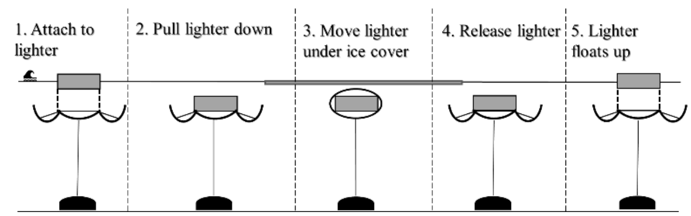


FIGURE 5: Cargo autonomous underwater vehicle's mode of operation.

2.3. Design for the marine environment

Any structure or vehicle designed for the marine environment must account for the challenging surroundings, such as total darkness, hydrostatic pressure, drag resistance due to seawater's viscosity, and the possible irregular topography [23]. This section will investigate the forces relevant for designing an underwater system. The basic requirements of a vehicle's operation in the marine environment are flotation and stability. The weight of the liquid displaced is the volume of the solid body times the density, i.e. buoyancy [24]. Both an immersed vehicle and a surface vehicle will experience hydrostatic forces from the water onto the wet surface. A submerged vessel will experience pressure, p, increasing with depth according to the following formula

$$p = \mathrm{p}_0 + \rho g h \quad (1)$$

where p_0 is the atmospheric pressure, ρ is the seawater density, g is the gravitational acceleration and h is the immersion depth [25]. The deeper a vehicle 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 altered by the ballast systems [26]. Ballast systems are used by underwater vehicles as well in order to adjust the trim [27]. Trim represents the attitude of the vehicle either pitching or rolling. 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 may be desirable in order to support the navigation. E.g. gliders' movement in a so-called "saw-tooth pattern" is provided by combining an adjustable trim and the buoyancy of the vehicle. This motion philosophy is desirable for this type of vehicles in order to save energy [28]. When at surface, marine vehicles are subjected to waves, currents and winds. Waves and currents excitations are found throughout the whole water column and surface level. The forces resulting from these phenomena 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 [24]. A vessel or structure will gain a response from the excitation and added mass depending on factors like size, mass, and shape. 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 [29]. A vehicle moving in water will also experience drag, or water resistance, see [26] for an overview of hydrodynamic estimates. The magnitude of the total drag resistance is relevant to the design because it determines the required amount of force – and subsequently power – for achieving movement. The total resistance is made up of the bare hull resistance, R_{BH}, and the appendage resistance, R_{APP}:

$$R_T = R_{BH} + R_{APP} \quad (2)$$

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

$$R_{BH} = \frac{1}{2}\rho A V^2 C_t \quad (3)$$

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

$$C_t = C_f + \Delta C_f + C_r + C_w \quad (4)$$

where C_f denotes the resistance due to friction between water and hull, ΔC_f represents the surface roughness resistance 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, or form, of the vehicle. The physics behind relates to where separation of flow occurs, and 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. Summarized, 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:

$$R_{APP} = \frac{1}{2}\rho A V^2 C_{t-app} \quad (5)$$

Examples of such deviations are submarine sail and manipulator arms. The appendage coefficient, C_{t-app} is estimated empirically [26]. The required (effective) power for vessel propulsion is found by the same means for both surface vessels and submerged vessels. It can be defined as the product of the total resistance and vessel speed [30]:

$$P_E = R_T \cdot V \quad (6)$$

The power required for the underwater transportation as well as the duration of the operation affects the energy storage capacity required for the operation and it can also be a measure of the vessel's efficiency. For underwater vessels, the efficiency represents the endurance of the system. For surface vessels, the energy is stored as diesel or liquified natural gas, while for underwater vessels the energy systems are based on either nuclear or secondary battery systems, where the former is used merely by military submarines. The difference in endurance between the two energy supply systems is several orders of magnitude – the nuclear is almost unlimited in energy supply while batteries are limited to hours and days [26].

3. METHODOLOGY

The paper's methodology is based on conceptual design using a systematic approach as described in [31], and the steps represented in Figure 6.

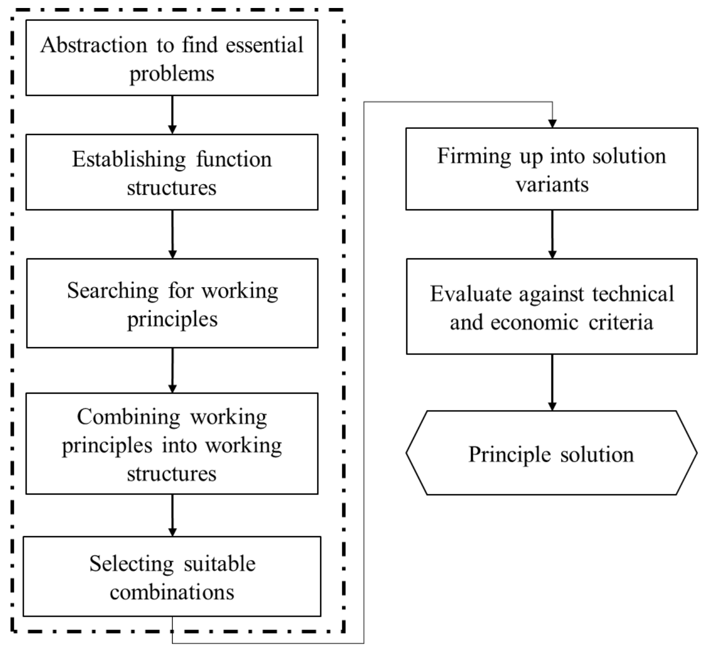


FIGURE 6: Methodology overview with the scope of the paper in dash-dotted line.

Abstraction is a way of extracting the general and abstract information and ignoring the incidental information [31, p. 161]. It requires the designer's ability to unlock the mind from thinking in objects and visual images. The physical process of the transportation activity is coherently studied to establish what state the material is in, and how it converts from one state to another. Functions are actions that are undertaken in order to achieve a goal. 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. In this paper, block diagrams are used, as shown in Figure 7. A rough function structure is created based on the steps identified during abstraction. The work starts from the system boundary and inwards, determining the inputs and outputs of functions. The output of one function, will be the input of the following function, thus keeping the consistency of flows. The relationship between functions must be logical, but also related to the physical process as identified through abstraction [31, p. 179]. To exemplify, think of the difference between "lifting" and "moving" something. Which is the most general? The first function indicates that something changes position vertically, while the last function indicates that something simply changes position. After finding the stages of flow conversion, the subfunctions can be obtained by studying flow inputs and outputs. Together, the overall function and subfunctions make the function structure.

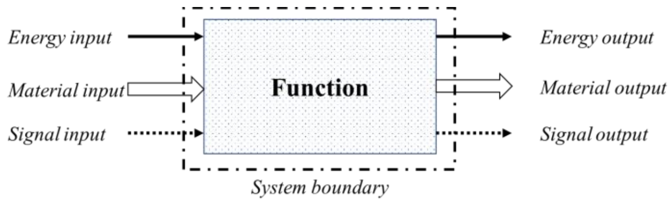


FIGURE 7: Block diagram of energy, material, and signal flow input and output. Adapted from [31, p. 30].

A working principle represents the physical solution (i.e. form) selected for realizing a function. When searching for working principles several methods may be used, such as literature searches and intuition-based methods. For this paper, the literature search will be oriented towards technical solutions found in the subsea and offshore industry, the mining industry and the dredging industry. For classification purpose, the list of working principles is analyzed for information related to their characteristics and physical principles. These principles are called *classifying criteria*. The classifying criteria are derived through discursive methods, which do not exclude intuition. The overall solutions are made from combining one working principle from each subfunction, known as a *working structure*. Further, the solution space is carefully confined by studying compatibility between classifying criteria. The scope of this paper is limited to selecting working structure sets based on compatibility.

4. RESULTS

The goal for the system to be designed has been defined as “To transport ore from the deposit at seabed to the quayside”. The entities that the task consist of are the ore, the seabed deposit, the underwater vehicle and the quayside. The main flow is of type “material” and represents the different states of the ore during the operation. It is assumed that, as a starting point, the ore is available to the underwater vehicle at the seabed in some form – either loose or contained – and that the ore will be available at quayside once the mission is finished, as an end point. The underwater vehicle has positioned itself in proximity of the ore to be collected. The ore must now be connected to the vehicle by some form of physical attachment, i.e. the first material flow concerns the collection of ore from seabed towards the underwater vehicle at the deposit’s location. Next, a vertical and horizontal movement under water is needed during the transfer. This becomes the second material flow conversion. 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 quayside (above surface). This can happen in two different ways: 1) the collected ore is transferred to the quayside alone, or 2) the underwater vehicle and collected ore are transferred to the quayside together as one unit. 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 containerized the separation between vehicle and container may look more straight forward. The second alternative involves bringing the ore and vehicle together as one unit to the quayside. This initially seems like too much effort. It may be questioned why one 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. It is here argued that it is brought further into consideration because there may be

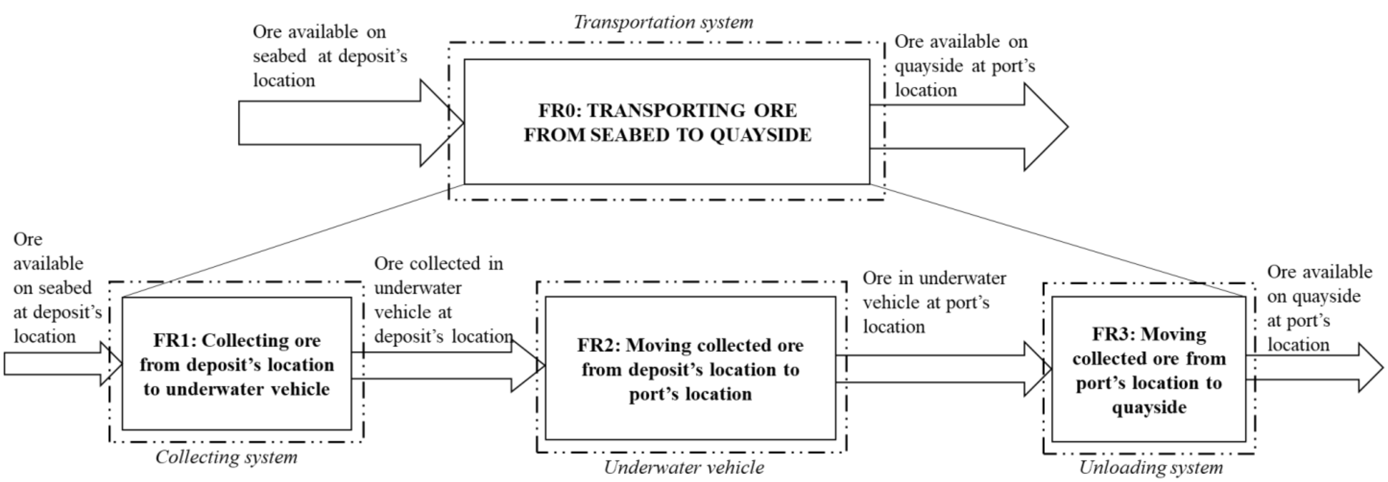


FIGURE 8: Block diagram of material input and output for the overall function.

needs that are unknown today that may lead to the consideration of this option after all. Such needs may for instance be related to operation, and inspection, maintenance and repair.

The material flow abstraction exercise shows 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. The function structure is further established, and an overview of the resulting structure is found in Figure 8. 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 overall function FR0 becomes "transporting ore from seabed to quayside", made possible by a transportation system. The overall function is further decomposed into subfunctions. FR1 starts with flow input being the available ore at seabed. From the abstraction it was seen that the ore was attached to the underwater vehicle. I.e. FR1 becomes 'collecting ore from deposit's location to underwater vehicle', where 'collecting' refers to the movement and/or storage of ore to the vehicle. It is not given that movement *and* storage is needed to attach the ore in proximity of the vehicle, and thus this subfunction is not decomposed further. After FR1 has taken place, the ore is stationed in the underwater vehicle at the deposit's location. The input to the next subfunction is the collected ore in the underwater vehicle at deposit's location. The desired ore flow output is the vehicle with the collected ore being available at port's location. The abstraction showed that an underwater movement was necessary to obtain this. Therefore, FR2 becomes 'moving collected ore from deposit's location to port's location'. The ore is however not yet available at quayside, and another function is needed to achieve this. FR3 therefore becomes 'moving collected ore from port's location to quayside'. The system for obtaining this is an unloading system.

TABLE 1: List of working principles for the three functions with classification criteria and appurtenant reference.

Working principles for FR1 (WP1)	Reference(s)
Flow	
Suction dredger	[32], [33]
Submersible slurry pump	[34], [35]
Mechanical	
Shovel	[32]
Mesh bag	[32], [36]
Bucket dredger	[37]
Clamshell grab	[32], [37], [38]
Container spreader	[39]
Underwater manipulator	[40]
Container loader	[41]
Towline	[42], [43]
Working principles for FR2 (WP2)	**Reference(s)**
Manned	
Submarine	[26], [44], [45]
Unmanned	
Glider	[28], [46]
AUV	[26], [47]–[49]
Working principles for FR3 (WP3)	**Reference(s)**
Flow	
Suction dredger	[32], [33]
Pipeline	[50]
Mechanical	
Clamshell grab	[32], [37], [38]
Conveyor belt	[51]
Mesh bag	[32], [36]
Marine railway	[52]
Hoister frame	[52]
Graving dock	[52]
Container spreader	[39]
Backhoe dredger	[38]
Buoyancy	
Floating dry dock	[52]

After the function structure has been established, the next step in the design process is to determine which working principles can be selected for realizing each subfunction of the function structure. The working principles for fulfilling the subfunctions above are found, see Table 1. For the WP1 list, the suction dredger, slurry pumping, shovel, mesh bag, bucket dredger and clamshell grab are all dredging tools. Dredging is defined as 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. The submersible slurry pump is utilized 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 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. 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. The mesh is lowered by a wire, and a heavy anchor chain keeps the net close to the seabed. The bucket dredger resembles the trawl net in principle, but the captured material more enclosed, and several buckets may be used simultaneously, known as a bucket chain dredger. Moreover, the clamshell grab, also called clamshell bucket or grab sampler, is made up of two jaws which capture loose material.

In the list of WP2, the submarine, glider and autonomous underwater vehicle are the identified working principles for moving the ore under water. The definition of a submarine vehicle varies, but there exists 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. Other underwater vehicles are often referred to as submersibles [26], [44], [45]. The technology advancement has been driven by the military application of submarines. Therefore, many of its features have arisen from warfare use, such as capability of storing and launching weapons [45]. The glider uses fins and

buoyancy chamber for propulsion, it is so-called buoyancy-driven. A seawater pump inside the vehicle increases and decreases buoyancy, and the fins are tilted in order to 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 and perhaps recharge using solar panels – thus 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 around a few hours to days. The AUVs have higher speeds, and lower operating costs than manned vehicles. The turning radius and maneuverability is also a great feature of the AUV [26].
For the WP3 list, the suction dredger, mesh bag and clamshell grab were explained. The difference between using the suction dredger, mesh bag and clamshell grab for seabed versus at quayside is that necessary extra equipment is more accessible. Such equipment includes a pumping system for the suction dredger and quay cranes for the mesh bag and clamshell grab. 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 relocated, also while dredging. 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. 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, and the vehicle (usually a ship or submarine) may enter the dock. Further, the floor of the dock is 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. The floating dry dock uses buoyancy for lifting and it may also be relocated. For this reason, it may retrieve ships and other structures from the water to the port's location. The backhoe dredger resembles the land excavator, but it is mounted on a barge or pontoon for dredging of marine sediments. The collecting device is a bucket which may dredge far into the water collecting bulk of various grain size. 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. By studying all working principles and the principle differences between them, the classifying criteria are found, see Table 2.

TABLE 2: Categorization of working principles of the three functions.

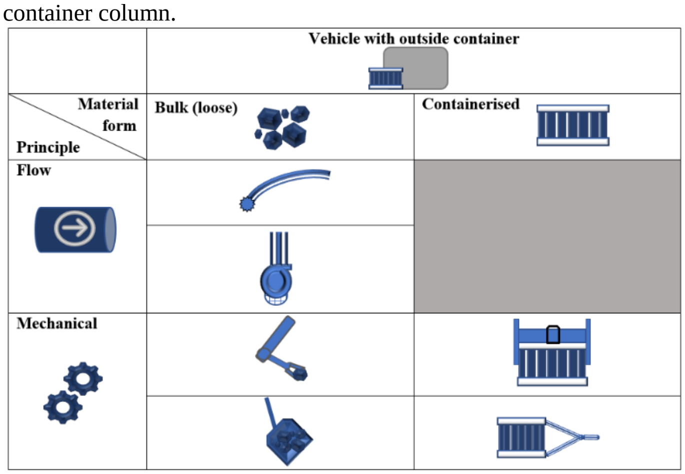
Classifying criteria of WP1 list	
Form of material	Bulk (loose)
	Containerized
Physical principle	Flow
	Mechanical
Ore handling	Inbuilt cargo hold
	Outside contained

Classifying criteria of WP2 list	
Ore handling	Inside cargo hold
	Container onloading
	Towing
Underwater vehicle	Submarine
	Glider
	AUV

Classifying criteria of WP3 list	
Form of material	Bulk (loose)
	Containerized
	Underwater vehicle
Physical principle	Mechanical
	Flow
	Buoyancy

Having the working principles and classifying criteria, the design catalogue can be made. An excerpt from one of the catalogues is found in Table 3.

TABLE 3: Excerpt from FR1 design catalogue on WP1 for cargo contained outside. The catalogue shows the suction dredger, submersible slurry pump, manipulator arm, and shovel respectively in the bulk column, and container spreader and towline respectively in the container column.



From Table 1 and design catalogues such as exemplified in Table 3, it is seen that there are classifying criteria that are similar between functions. This includes material form and ore handling, and they are particularly interesting because they provide the opportunity to utilize compatibility in working principles between functions, which may result in a higher quality overall solution. Only compatible solutions are pursued further in this design process, and they can be divided into working structure sets:

1. Collect bulk ore + move inside cargo hold + move as bulk to quayside
2. Collect containerized ore + move inside cargo hold + move as bulk/container to quayside
3. Collect containerized ore + move as outside container + move as bulk/container to quayside
4. Collect containerized ore + move by towing + move as bulk/container to quayside

The first working structure set is the only one of the four with bulk as material form as classifying criteria 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 submersible slurry 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. The bulk is then moved inside the vehicle with the collection device being either on the outside or brought inside the vehicle. The choice of vehicle may be important to WP1. If the vehicle is manned, as in the case of a submarine, the crew may aid in control and any steering of the WP1 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 choices of WP3 are 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 unloaded. 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. 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.

In the second working structure set the collection working principle is container-based. Only mechanical principle is available for WP1: the container spreader and the container loader. The container is loaded directly into the cargo hold of the vehicle. This means that the vehicle has an open hull at the point of loading. 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 by lifting. As for set 1, the crew of a submarine may aid in control and steering of the working principle. When the container has been loaded, the WP1 should be contained near or inside the vehicle so that it minimizes 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 maneuverability 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 is an option as well. 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.

This set contains the container collection working principles, the container is carried externally, and any WP3 may be chosen. 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. 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.

The fourth set is based on a towing solution. The towline is the only working principle which fulfils 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 has 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.

5. DISCUSSION

An unexpected solution that emerged was transportation by towing. This solution was not identified during the first assessment of solutions and came as a result of a systematic search. The next stages of the design process can be seen in Figure 6. Firming up into solution variants is performed by elimination and preference of working structure sets.

Elimination is where the theoretically possible, but practically infeasible working principles are removed. Preference is given to working structures based on criteria such as compatibility with task, safety, performance, layout, and costs. Examples of problematic working principles may be the submarine, which is not known to have travelled to the depths where the deep sea mineral resources are known to be found. Moreover, the glider may be unfavourable because it has a saw-tooth movement pattern which may give rise to difficulties in precision and manoeuvrability. This is critical during collection because of the proximity to the seabed, i.e. the safety of the vehicle may be challenged.

When the conceptual design phase has provided a principle solution, the next step is embodiment design. Here, the classifying criteria may be more detailed, for instance by classifying mechanical into electrical, hydraulic and pneumatic. Moreover, this is where layout is designed, e.g. tanks and placement of thrusters. Auxiliary functions are also addressed, such as control and energy supply. This procedure could also be beneficial for using the strength of design methods to test the results by going into embodiment phase and iterate back again to conceptual design.

6. CONCLUSION

This paper aimed to handle the first steps of systematic conceptual design for the underwater transportation of ore from seabed to quayside. Four working structure sets were obtained. A completion of the conceptual design process will lead to a principle solution after which embodiment design can be pursued.

NOMENCLATURE

AUV	Autonomous underwater vehicle
DSM	Deep sea mining
DSMSV	Deep sea mining support vessel
FR	Functional requirement
SMS	Seafloor massive sulfides
UUV	Unmanned underwater vehicle
WP	Working principle
WS	Working structure

REFERENCES

[1] J. R. Hein, K. Mizell, A. Koschinsky, and T. A. Conrad, "Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources," *Ore Geology Reviews*. 2013.

[2] OECD, *Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences*. Paris: OECD Publishing, 2019.

[3] A. Bloodworth and G. Gunn, "The Future of the Global Minerals and Metals Sector: Issues and Challenges out to 2050," *Geosciences*, no. 15, pp. 90–97, 2012.

[4] P. A. Rona, "Resources of the Sea Floor," *Science (80-.).*, vol. 299, no. 5607, pp. 673–674, 2003.

[5] B. K. Sovacool *et al.*, "Sustainable minerals and metals for a low-carbon future," *Science (80-.).*, vol. 367, no. 6473, pp. 30–33, 2020.

[6] C. R. Deepak *et al.*, "Development and testing of underwater mining systems for long term operations using flexible riser concept," in *Proceedings of the ISOPE Ocean Mining Symposium*, 2007.

[7] C. G. Welling, "An advanced design deep sea mining system," in *Proceedings of the Annual Offshore Technology Conference*, 1981.

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

[9] H. Amann, "Technological Trends in Ocean Mining," *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, 1982.

[10] SRK Consulting, "Offshore Production System Definition and Cost Study," 2010. [Online]. Available: http://actnowpng.org/sites/default/files/Solwara 1 Production System Definition and Cost Study 2010.pdf. [Accessed: 12-Jul-2019].

[11] Krypton Ocean, "Description and Main Characteristics of the Mining Fleet," 2019. [Online]. Available: https://info.kryptonocean.com/en/. [Accessed: 12-Jul-2019].

[12] K. Mizell and J. R. Hein, "Ferromanganese crusts and nodules: Rocks that grow," in *Encyclopedia of Earth Sciences Series*, 2018.

[13] T. Kuhn, A. V. Wegorzewski, C. Rühlemann, and A. Vink, "Composition, formation, and occurrence of polymetallic nodules," in *Deep-Sea Mining: Resource Potential, Technical and Environmental Considerations*, 2017.

[14] J. R. Hein and A. Koschinsky, "Deep-Ocean Ferromanganese Crusts and Nodules," in *Treatise on Geochemistry: Second Edition*, 2013.

[15] P. A. Rona, "The changing vision of marine minerals," *Ore Geol. Rev.*, 2008.

[16] ISA, "Exploration Areas," 2019. [Online]. Available: https://www.isa.org.jm/contractors/exploration-areas. [Accessed: 04-Nov-2019].

[17] P. E. Halbach, A. Jahn, and G. Cherkashov, "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*, 2017.

[18] M. Hannington, J. Jamieson, T. Monecke, S. Petersen, and S. Beaulieu, "The abundance of seafloor massive sulfide deposits," *Geology*, vol. 39, no. 12, pp. 1155–1158, 2011.

[19] P. Hoagland *et al.*, "Deep-sea mining of seafloor massive sulfides," *Mar. Policy*, 2010.

[20] Nautilus Minerals, "Technology Overview," 2019. [Online]. Available: http://www.nautilusminerals.com/irm/content/technology-overview.aspx?RID=329. [Accessed: 30-Jul-2019].

[21] C. Brown and R. P. Clark, "Using a Novel Vehicle Conceptual Design Utility to Evaluate a Long-Range , Large Payload UUV," *Ocean. 2010 MTS/IEEE SEATTLE*, pp. 1–10, 2010.

[22] G. G. Malinetsky and V. S. Smolin, "Robotic solutions for Arctic transit corridor cargo autonomous undersea vehicles," *Procedia Comput. Sci.*, vol. 150, pp. 702–708, 2019.

[23] F. Earney, *Marine Mineral Resources*. New York: Routledge, 1990.

[24] K. J. Rawson and E. C. Tupper, *Basic Ship Theory*, 5th ed. Elsevier, 2001.

[25] J. Amdahl *et al.*, *Havromsteknologi*. Trondheim: NTNU Institutt for Marin teknikk & Fagbokforlaget, 2014.

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

[27] M. Renilson, "Hydrostatics and control," in *Submarine*

Hydrodynamics: SpringerBriefs in Applied Sciences and Technology, vol. 169, Cham: Springer, 2015, pp. 5–17.
[28] S. A. Jenkins and G. D'Spain, "Autonomous underwater gliders," in *Springer Handbook of Ocean Engineering*, 2016.
[29] B. Pettersen, *Kompendium TMR4247 Hydrodynamikk*. Trondheim. Department of Marine technology: Akademika forlag, 2004.
[30] J. Carlton, "Ship resistance and propulsion," in *Marine Propellers and Propulsion*, 2007.
[31] G. Pahl, W. Beitz, J. Feldhusen, and K. H. Grote, *Engineering design: A systematic approach*, 3rd ed. London: Springer, 2007.
[32] A. Georgiopoulou, "Seafloor Sediment and Rock Sampling," in *Submarine Geomorphology*, A. Micallef, S. Krastel, and A. Savini, Eds. Cham: Springer, 2018, pp. 75–92.
[33] P. A. Work, "Dredging," in *Encyclopedia of Earth Sciences Series*, 2016.
[34] V. S. Lobanoff and R. R. Ross, *Centrifugal Pumps: Design and Application*, 2nd ed. Gulf Professional Publishing, 2013.
[35] R. Mackay, *The Practical Pumping Handbook*. 2004.
[36] R. Fonteyne, "Fishing Methods and Fishing Fleets," in *Encyclopedia of Ocean Sciences*, 2nd ed., Elsevier Ltd, 2001.
[37] R. E. Randall, "Dredging," in *Port Engineering - Planning, Construction, Maintenance, and Security*, G. P. Tsinker, Ed. John Wiley & Sons, 2004.
[38] IADC and IAPH, *Dredging for development*. Netherlands: International Association of Dredging Companies (IADC), 2010.
[39] H. Han, X. Guo, and X. Cao, "Design and analysis for hydraulic travel system of container stacker," in *Advanced Materials Research*, 2011.
[40] S. Sivčev, J. Coleman, E. Omerdić, G. Dooly, and D. Toal, "Underwater manipulators: A review," *Ocean Eng.*, vol. 163, no. June 2017, pp. 431–450, 2018.
[41] A-ward, "20/40ft Tilting Container Loaders," 2019. [Online]. Available: https://a-ward.com/equipment-and-solutions/container-loaders/. [Accessed: 11-Dec-2019].
[42] B. Gerwick, *Construction of Marine and Offshore Structures*, 3rd ed. Boca Raton, FL: CRC Press, 2007.
[43] M. Hancox, *Towing, Positioning & Hook-up for Offshore Production: The Towmasters' Handbook*. Ledbury, England: Oilfield Publications.
[44] E. E. Allmendinger, Ed., *Submersible Vehicle Systems Design*. New Jersey: The Society of Naval Architects and Marine Engineers, 1990.
[45] R. Burcher and L. Rydill, *Concepts in Submarine Design*. New York: Cambridge University Press, 1994.
[46] T. Rossol, M. Hildebrandt, and M. Wirtz, "Miniaturized Underwater Gliders as Payload Transfer Units," in *2018 IEEE/OES Autonomous Underwater Vehicle Workshop (AUV)*, 2018.
[47] G. Griffiths, *Technology and Applications of Autonomous Underwater Vehicles*. London; New York: Taylor & Francis, 2002.
[48] V. A. Huvenne, K. Robert, L. Marsh, C. Lo Iacono, T. Le Bas, and R. B. Wynn, "ROVs and AUVs," in *Submarine Geomorphology*, A. Micallef, S. Krastel, and A. Savini, Eds. Cham: Springer, 2018.
[49] M. E. Kepler, S. Pawar, D. J. Stilwell, S. Brizzolara, and W. L. Neu, "Steering Plane Dynamics of a Small Autonomous Underwater Vehicle that Tows a Large Payload," in *2018 IEEE/OES Autonomous Underwater Vehicle Workshop (AUV)*, 2018.
[50] H. Fang and M. Duan, "Submarine Pipelines and Pipeline Cable Engineering," in *Offshore Operation Facilities: Equipment and Procedures*, H. Fang and M. Duan, Eds. Elsevier, 2014.
[51] A. Mubaroq, *Belt Conveyors for Bulk Materials*, 5th ed. US: Conveyor Equipment Manufacturers Association, 2002.
[52] P. A. Harren, *Safe Operation and Maintenance of Dry Dock Facilities*. American Society of Civil Engineers, 2013.