EARLY STAGE DECISIONS IN MARINE SYSTEMS DESIGN FOR DEEP-SEA MINING

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SUMMARY

This article studies the prospects for deep-sea mining as a future viable maritime industry, and discuss the commercial, operational, and technical viability of deep-sea mining. By the use of a business development approach originating from the maritime industry, we analyse opportunities for a virtual deep-sea mining project, and identify aspects of stakeholder performance expectations, contextualised by the competitive positioning and identification of related project risks. We discuss strategies and pit-falls when positioning a deep-sea mining venture within the wider mining and metal production value chain, and use a case example in the North Atlantic Ocean to study the prospects for a deep-sea mining operation and subsequent system design implications. Furthermore, we contrast to well-established industries like offshore oil and gas, and traditional land-based mining. The study promotes several critical aspects and problem areas when approaching marine systems design for deep-sea mining.

KEYWORDS

Deep-sea mining; marine systems design; business strategy; value chain; ship design

1. INTRODUCTION

People have known about the abundance of minerals in the deep sea at least since the expeditions of H.M.S. Challenger in the 1870's (Sharma, 2018). The economic potential of deep sea mining was unravelled in the mid sixties and it was predicted that deep sea mining would start in 20 years time from then (Mero, 1965). The feasibility of harvesting abyssal minerals was examined closer in the 1970's and 1980's. Prototype testing was carried out from the late 1970's (Welling, 1981; Deepak *et al.*, 2007), and a number of exploration cruises were funded by countries like the United States, Germany, France, and Soviet Union (Glasby, 2000).

There are mainly two drivers for marine mineral exploitation: Firstly, the potential for profitable mineral exploitation in the future, and secondly the strategic aspiration of nations to secure the supply of metals to support domestic industrial projects (Kowalczyk and Lum, 2017). Particularly critical metals, being essential to economic and national security, have a supply chain vulnerable to disruption and intervention. There has also been an expectancy that minerals would run short in the future which would spike the prices (Martino and Parson, 2012). The deep seabed ores contain, typically, valuable metals such as copper, cobalt, lithium, nickel, and rare earth elements (REE) that are essential components in cell phones, electric cars, wind turbines, etc. (Hein *et al.*, 2013). With its potentially immense resources, the seafloor is of interest both scientifically and due to its potential economic value (Rona, 2003; Sovacool *et al.*, 2020).

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 sellable products. By *marine systems* in this context, we mean the entire ocean infrastructure that will collect, pre-process and ship the minerals to shore, while *systems design* is the architecting and enginering of this infrastructure. Deep-sea mining refers to seabed mining activities that may take place offshore, both in international waters and within exclusive economic zones (EEZs), and at depths that exceed 400 meters. It does not encompass ocean mining in shallow waters, such as the diamond mining operations taking place for example in offshore Namibia or tin mining in UK and Indonesia. As of yet, there are no deep seabed mine in operation. However, countries, such as China, India, France, Korea, Russia, and Germany are positioning themselves by entering into contracts for exploration of minerals in abyssal, international waters. In these areas beyond national jurisdiction, any ocean mining is governed by the International Seabed Authority (ISA), whose function is to organize, regulate, and control seabed mining in international waters (ISA, 2021). Nautilus Minerals is one of the companies that has come closest to commercial operations, in the EEZ of Papua New-Guinea.

Samples from deep sea deposits have been reported to have elevated metal concentrations compared to terrestrial mines. At Nautilus Minerals' most prominent mine

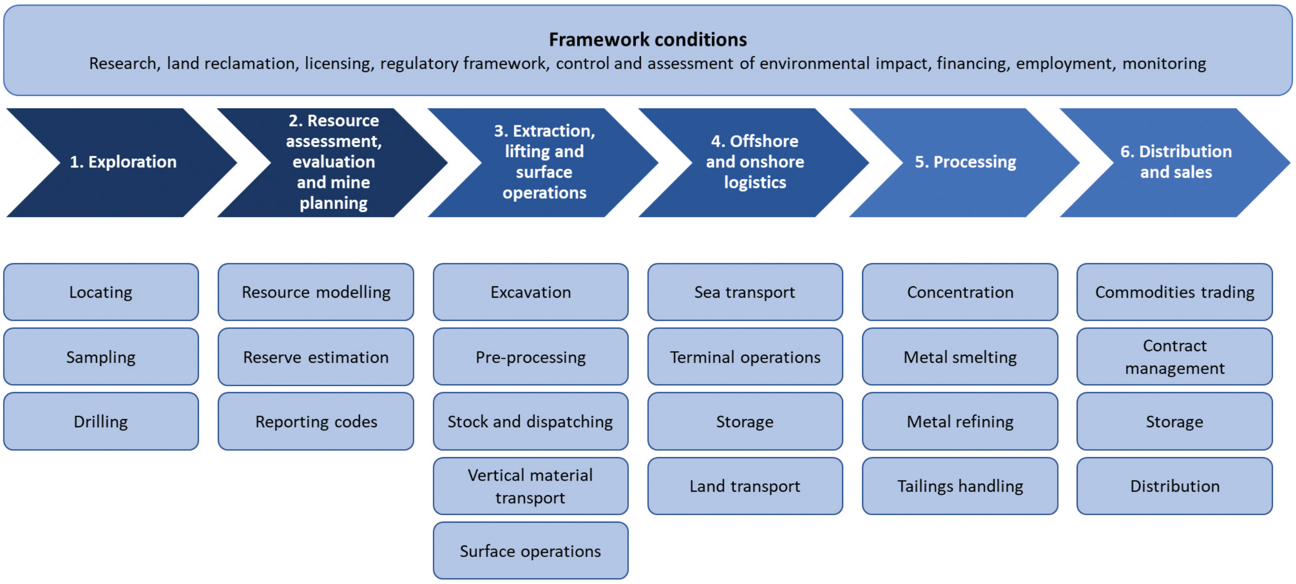

Figure 1. The deep-sea mining value chain. Adapted from ECORYS (2014).

site, Solwara 1, indicated mineral resource estimates for copper ranged from 7.2%-11% (AMC Consultants, 2018). Other exploration cruises by Nautilus Minerals in the Bismarck Sea provided average copper compositions from grab samples up to 11.7% (SRK Consulting, 2010). However, the reported grades from these specific samples might not reflect the average grade of all the underlying mineralization. At the Trans-Atlantic Geotraverse (TAG), samples of drill cores have yielded from 2.7-3.4 wt% copper concentrations (Grant *et al.*, 2018). In comparison, terrestrial copper mines frequently see grades of less than 1% (Juliani and Ellefmo, 2018c).

The question remains whether deep seabed minerals can contribute to the sourcing of a stable metal supply in the future from a commercial perspective. A whole new value chain and regulatory system will need to be developed, with costly and technically complex marine mining systems, for selling an end product into a mature industry dominated by mining companies and metal traders. In this paper, we use a business development approach originating from the management and systems theory applied in the maritime industry. The Accelerated Business Development (ABD) approach involves several stages from business idea to a detailed system specification, for more information, see Brett *et al.* (2006). Here, we enter the first part of the method in order to study the process towards integrated systems design, accounting for business aspects as well as technology and operations, and the important decisions to be made in the corresponding design process.

2. DEEP-SEA MINING

2.1 MINING

The mining process has some distinctive characteristics. First, the specifics of the mine operation is dependent of the resource location, with its political, social, climatic, and environmental context. An orebody could be infeasible to exploit one place while the same orebody at another location could be feasible from a commercial, operational, and technical viewpoint. Second, geological knowledge about an orebody, such as grade, shape, mineral content, and structure, cannot be known to a full extent with a few drill-hole samples. Therefore, taking on such a complex and uncertain project involves a risk due to the sparse information about the resource ahead of production. Third, the resource to be exploited is after all finite and non-renewable, so mobility versus permanency must be carefully handled in the planning of mining activities. The primary asset is consumed and disappear during the course of production, and at some point the mining company must decide on whether to close the mine and continue to a new site. This requires that a new, prosperous site is available for exploitation and that the mining equipment can be de-mobilized and transferred to another geographical location, nearby or further away from the first site.

2.2 THE DEEP-SEA MINING VALUE CHAIN

A high-level land-based and deep-sea mining value chain consist of similar steps (ECORYS, 2014; Abramowski, 2016). The commercial exploitation of mineral deposits in the world's oceans, requires an improved understanding of the mining value chain, see Figure 1. To make decisions regarding processing, distribution and sales activities for a business proposition, it is essential to understand the costs that incur downstream, and how the related activities add value. The framework conditions and consecutive steps of value-creating activities are presented, from exploration to exploitation and further sales. A key difference from land-based mining is that that a considerable part of value chain activities take place in the ocean and on the ocean surface.

The exploration step maps resources, while the resource assessment and evaluation steps will take the mineral deposit from a resource to a reserve. The exploration of mineral resources can be separated into locating, sampling and drilling, corresponding to increasing levels of confidence in the resource. The impact of modifying factors, and the size and grade of the remaining mineral reserve, are found through the resource assessment and evaluation stage. Extraction, lifting and surface operations include all marine operations to be performed by a prospective mining support vessel and the advanced systems that the vessel supports. Offshore and onshore logistics refer to the process of transporting and storing the mined material.

Processing refers to the transformation of the ore into a commoditized metal product, steps adding significant value to the product. After mining an ore, a set of basic processing steps are performed, including comminution, classification and separation that result in an ore concentrate. Finally, metal extraction processes like smelting and refining transform the ore concentrate to a finished product that can be sold in the market place (Wellmer, Dalheimer and Wagner, 2008; Kudelko, 2013). Figure 2 describes the possible value generating activities in the mineral processing phase, using an idealized process for copper as an example.

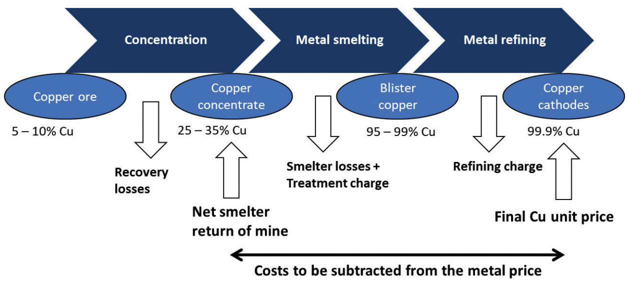

Figure 2. Deriving the net smelter return for a copper mining operation. Adapted from Wellmer *et al.* (2008).

2.3 THE TYPES OF DEEP SEABED MINERAL RESOURCES

Basically, there are three different mineral resource type with great resource potential constituting offshore deep-sea mining: Seafloor massive sulphides (SMS), polymetallic nodules, and ferrometallic crusts.

- **Seafloor massive sulphides (SMS):** Mineral deposits precipitate as hydrothermal fluids at a high temperature come in contact with cool seawater close to the seafloor at hydrothermal vent sites (Hoagland *et al.*, 2010; Boschen *et al.*, 2013). The hydrothermal fluid flow often forms a black smoker through which the fluid flows. Hydrothermal venting systems are found at ocean ridges at depths ranging from 1,000 to 3,000 meters (Rona, 2003; Hoagland *et al.*, 2010; Hannington *et al.*, 2011). Common metals: Copper (Cu), lead (Pb), Zinc (Zn), Nickel (Ni), Au (Gold), Ag (Silver).
- **Polymetallic (manganese) nodules:** Nodules are small rock concretions consisting of layers of iron and manganese hydroxides, found on sediment surfaces in water depths of 3,500-6,500 metres. The regions expected to have greatest abundance of nodules are the abyssal Pacific Ocean and Central Indian Oceans (Rona, 2008; Hein and Koschinsky, 2013; Kuhn *et al.*, 2017; Mizell and Hein, 2018). Common metals: Manganese (Mn), Iron (Fe), Nickel (Ni), Cobalt (Co), Copper (Cu) + trace elements.
- **Ferrometallic (ferromanganese) crust:** Crusts are vast layers accumulated on the hard-rock substrate at 1,000-5,000 meters water depth. The crusts can be found throughout the entire abyssal waters of the earth – including the Pacific, Atlantic, and Indian Oceans (Rona, 2008; Cherkashov, 2017; Halbach, Jahn and Cherkashov, 2017). Common metals: Manganese (Mn), Iron (Fe), Cobalt (Co), Nickel (Ni), Titanium (Ti) + trace elements.

Only SMS will be discussed further in this paper. Seafloor massive sulphides, or hydrothermal vents, were first discovered on the East Pacific Rise in 1979 (Spiess *et al.*, 1980). Since then, many hydrothermal fields have been discovered around the world, such as the Atlantic Ocean and Mid-Atlantic Ridge (Rona, 2003). These formations were anticipated to have high grades of economically attractive metals and exploring these fields occurred from the mid 2000's. Previous research on SMS deposits has focused mostly on the basic geological research relevant in the exploration phase (Pedersen *et al.*, 2010) and on resource assessment (Cherkashov *et al.*, 2010; Juliani and Ellefmo, 2018b, 2018a). When it comes to actually retrieving the minerals, exploitation of sulphides has been attempted by the Canadian industry contractor Nautilus Minerals (SRK Consulting, 2010; AMC Consultants, 2018). Nautilus Minerals attempted for commercial extraction of high metal grade sulphides from the Pacific seabed in territotial waters of Papua New-Guinea (PNG), but the project came to a stop due to financial difficulties. Sulfides have also been sampled in Norway's EEZ by a number of exploration cruises, for instance the MarMine project (Martin Ludvigsen *et al.*, 2016).

2.4 THE NAUTILUS MINERALS CONCEPT

Over the years several attempts for deep-sea mining operations have been suggested and partly tested out in real life situations. Nautilus Minerals' concept proposal included a marine system for excavation at 1,600 meters water – building on technologies from existing offshore oil and gas industries. The marine system consisted of three seafloor production tools (crawlers), 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 were meant to excavate, gather and comminute ore. For further transportation a vertical riser system would carry slurry to the PSV using a large subsea slurry lift pump. Onboard the PSV the slurry would be dewatered, stored, and later transferred to a barge using conveyor belt ship-to-ship transfer. The effluent would then be returned to the water column using the riser. The dewatered ore was to be sent to shore for processing, and further shipped for smelting (Coffey Natural Systems, 2008). See Figure 3 for an overview.

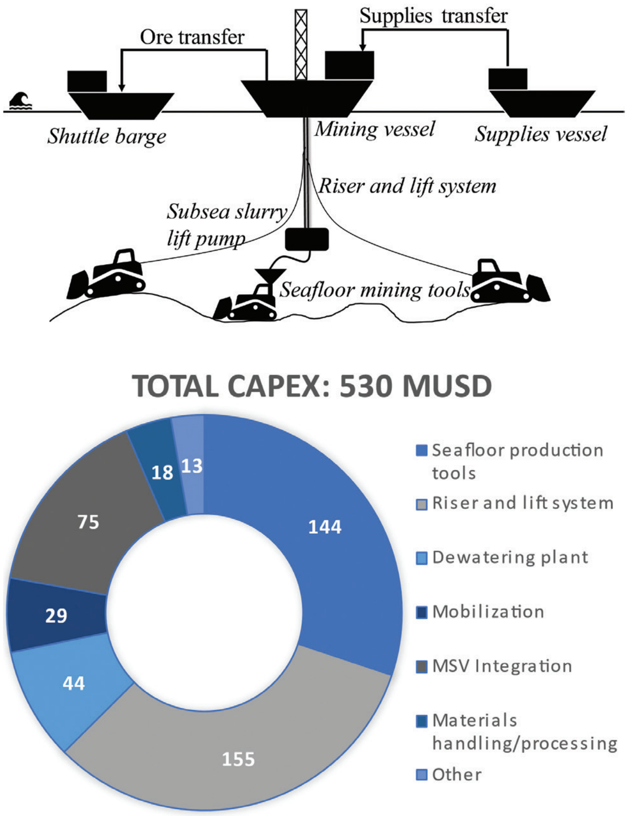

Figure 3. Top: Schematic overview of Nautilus Minerals' intended production system (adapted from *(Solheim et al., 2020)*). Bottom: Contributors to CAPEX for Nautilus Minerals (AMC Consultants, 2018). MUSD=Million US dollars.

The investments in the mining support vessel (MSV) is not included in the cost estimates presented. Ship builders planned to recoup expenditure through vessel charter costs, which were a total of 140,000 USD/day (AMC Consultants, 2018).

2.5 PREVIOUS DESIGN ASSESSMENTS OF SMS MINING OPERATIONS

Economic evaluations of SMS mining operations have mostly assumed that a similar marine system as that planned for the Solwara project can be used. Ellefmo *et al.* (2017) perform a full cycle resource evaluation for mining of SMS deposits on the Arctic Mid-Ocean Ridge in the North Atlantic Ocean. They adapt a methodology used for assessment of technical and economic feasibility of oil and gas projects to the problem of field development for deep-sea mining, and find that commercial viability is highly dependent on the chosen tax regime and discount rates chosen to calculate the net present value. Among three copper price scenarios tested, a field development at Loki's Castle on the Arctic Mid Ocean Ridge becomes profitable at copper prices ranging from $6,100 per tonne, assuming that the project follows the current Norwegian tax regime for the petroleum industry, and that resale of production equipment will be possible. Recently, the copper price surpassed a level of $10,000 a tonne (Mining.com, 2021).

A setup of mining machines similar to that planned for the Solwara prospect was modeled to estimate the economic value of SMS and evaluate the profitability (Lesage, Juliani and Ellefmo, 2018). A key difference is that they assume that the mining system can operate in the North Atlantic Ocean. Revenues and costs associated with mining cubic blocks in an SMS deposit are calculated, yielding a negative net present value for the project. Still, the sensitivity analysis shows that deep-sea mining can become profitable under certain circumstances. Specifically, they find that the project is sensitive to the availability of the mining machines, and the power that is required for cutting rock in the deposit.

Development of technologies for seabed mineral processing of SMS deposits has been an important part of Japan's R&D programs for exploiting hydrothermal fields, and within Japan's EEZ a successful ore lift from 1,600 meters water depth was performed in 2017 (METI and JOGMEC, 2017). Yamazaki *et al.* (2016) discuss current advances by the Japan Oil, Gas, and Metals National Corporation (JOGMEC) to develop systems for mining of SMS deposits. They present an economic evaluation based on a hypothetical case of mining of SMS deposits in the Okinawa Trough in the Pacific Ocean. A key difference from the Solwara project, is that they assume a mining operation that works by use of a seafloor separation process that reduces the total amount of material that is lifted to the surface. They argue that handling the waste from ore processing is a great cost, and they propose seafloor mineral processing to obtain consentrates that can be lifted, consequently minimising the amount of material lifted (Nakajima *et al.*, 2019). China has also conducted research on the extraction of SMS, particularly lab experiments on excavation equipment (Liu *et al.*, 2016).

The conclusion from this review on systems design for deep-sea mining shows that the treatment of design challenges for deep-sea mining so far is limited. There is a need for further research on the connection between business strategies and marine systems design to improve our understanding of the prospects for deep-sea mining.

In this paper, we propose and use an accelerated business development framework using the available information from an example case to improve our understanding of commercial, operational and technical factors.

3. EXAMPLE CASE: TRANS-ATLANTIC GEOTRAVERSE (TAG)

Another area where resouces have been discovered is the Trans-Atlantic Geotraverse (TAG), which is chosen as an example case as it is one of the most studied hydrothermal systems where geological information is available. TAG was discovered in 1985 (Klinkhammer *et al.*, 1986), and the location has been visited by several exploration cruises, for the purpose of additional sampling and resource assessment. The field is situated at water depths between 3,400-3,700 meters on the Arctic Mid-Ocean Ridge system, see Figure 4. This case takes the perspective of a prospective field owner and operator attempting to develop a deep-sea mining operation.

The geology of the TAG hydrothermal field has been studied in the past (Humphris *et al.*, 1995; Grant *et al.*, 2018; Murton *et al.*, 2019; Graber *et al.*, 2020). The height of the mound is about 30 meters, the total water depth is about 3,600 meters. The diameter of the TAG mound is approximately 200 meters, and mineralized material has been confirmed down to about 170 meters below the seafloor. Figure 4 shows the bathymetric expression of the active TAG-mound and the rough 3D geometric model developed, based on (Grant *et al.*, 2018). The mineralized material has been divided into the three zones with respective grade characteristics and estimated tonnages:

- **The stockwork zone:** Low in Cu and Zn. Volume of 1,300,300 m3 gives an approximate tonnage of 4,551,000 t.

And two higher grade zones:

- **The pyrite-silica breccia with a varying amount of anhydrite:** High Cu – up to 7% and low Zn. Volume of 307,570 m3 gives an approximate tonnage of 1,076,000 t.
- **The massive pyrite brecchia and pyrite brecchia:** Low to high Cu and high Zn. Volume of 321,860 m3 gives an approximate tonnage of 1,126,000 t.

The density used in the calculations was found from previous literature review, stating that 3.5 t/m3 is a good intermediate value at TAG (Graber *et al.*, 2020). All-in-all, this gives a total tonnage of approximately 6,753,000 tonnes of mineralization at TAG.

4. METHODOLOGY

The research problem to be explored and discussed in this paper is to *identify and discuss the commercial, operational and technical conditions under which deep-sea mining of seafloor massive sulphide deposits can become a viable maritime industry*. This question is studied through application of the Accelerated Business

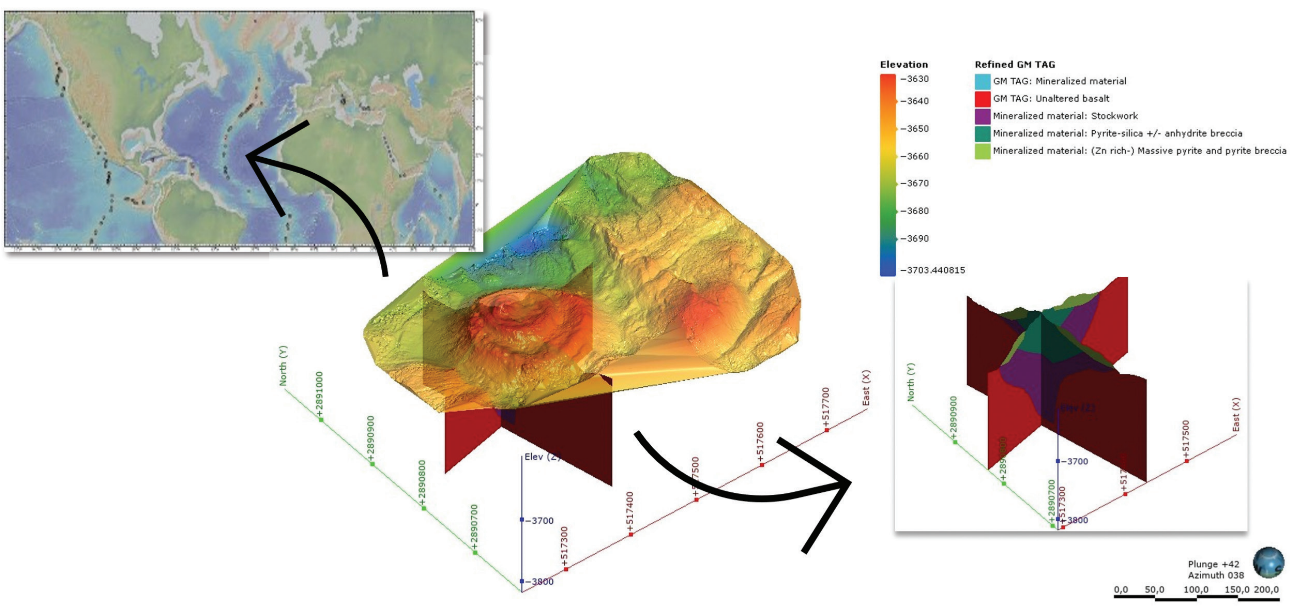

Figure 4. Bathymetric expression of the active TAG mound. Bathymetric data from http://www.geomapapp.org/, *(Reves-Sohn and Humphris, 2004)*, *(Roman and Singh, 2005)*. Accessed 2021-6-4. Left: World map showing the TAG location in the Mid-Ocean Ridge as a red dot. Base map from http://www.geomapapp.org (Ryan *et al.*, 2009). Dots indicating confirmed hydrothermal sites are from the InterRidge Global Database of Active Submarine Hydrothermal Vent Fields, ver 3.4 (Beaulieu & Szafranski, 2020). World Wide Web electronic publication available from http://vents-data.interridge.org Accessed 2021-6-4.

Development (ABD) process, developed and used by the Ulstein Group for maritime business case development and early-stage system designs (Brett *et al.*, 2006). The ABD process is intended for use in a setting in which ship designers and systems engineers consult with miners and ship owners, in order to develop new maritime business concepts, and assess commercial, operational and technical viability. In the current setting, the ABD process was used to guide market analyses and discuss marine systems design implications, conducted through several workshops attended by academics, ship designers, and ship builders, and professionals with network and industrial context experience from deep-sea mining and marine systems design dating back 30 years. The number of participants were five and their affiliations are the Department of Marine Technology, NTNU, Ulstein Shipbuilding, and Ulstein International. The workshop lasted for five days including revisions and documenting, with two days fulltime workshop and three days of 3x1.5 hrs plenary workshop for verification and validation of data and results (Pettersen, 2018).

4.1 MARKET ANALYSIS

The market analysis is subdivided into the following four steps:

Business concept: This step includes i) development of a value proposition, a precise statement about how the project will deliver a value, ii) a specification of system boundaries, which precisely outlines which stakeholders are involved, iii) a motivation for why the project should be done, and iv) how the project will be undertaken.

Performance expectations: This step identifies the performance expectations of all relevant stakeholders. A performance expectation is a reflection of what outcomes a stakeholder wishes to derive from the business concept.

Competitive position: This step analyses the competitive situation of the project, using Porter's five forces and similar techniques. The scope of industrial competition in this case is the mining industry (Porter, 1985). A Likert scale was used during the workshop.

Risk analysis: This step elicits risk factors and assesses the criticality of these, on basis of the proposed business concept and the competitive situation. On basis of the findings of the risk analysis, it may be advisable either to implement mitigating measures, or to terminate the project if some of the risks constitute obvious stoppers.

4.2 MARINE SYSTEMS DESIGN

The central element of the concept development stage is to quickly develop concept solutions that can be expected to perform well, under the conditions derived from the market analysis. By basing the development of concept solutions for the marine system on more extensive knowledge about the market, business concept and stakeholder needs, the design space can more swiftly be reduced, avoiding development of solutions that may seem technically tempting, but that will be unprofitable. In this paper, concept development encompasses the strategic business decisions in the value chain, design implications and operational aspects based on the current knowledge of the TAG mine and the corresponding offshore site.

5. RESULTS

5.1 MARKET ANALYSIS: UNDERSTANDING THE BUSINESS CASE

5.1(a) Business proposition

The motivation for developing a marine system for deep-sea mining operation, is seen from key global trends, including a still increased global population and continued global economic growth, which is expected to fuel the demand for metals. Metals may become in short supply due to their importance in numerous products that are popular amongst the growing middle class, including electronic devices like smart phones and electric cars. Additionally, a motivation is to increase the accessibility of rare earth elements, whose supplies are dominated by a few countries. Hence, the business proposition becomes:

> *To supply the market with metals, both mineral commodities and rare earth elements, to meet future increases in demand competitively and responsibly, by extracting, lifting and processing seafloor massive sulphide deposits.*

Some of the terms selected in this business proposition require further definition. First, by *responsibly*, we mean that the venture will have to achieve this in a *profitable*, *environmentally acceptable* and *safe* manner. Second, by *competitively*, we mean that the venture needs to compete with existing products in the marketplace by either delivering a less expensive product and or contribute to securing supply. Further, the product will have to hold a quality of at least the same level of the land-mined product. *Extracting* refers to the process of excavating minerals. *Lifting* refers to the process of bringing minerals to the surface. *Processing* refers to the range of activities that take place downstream of the marine and mining operation itself. The business concept outlined herein leads to a broad value chain perspective, and should hence be seen as an attempt to outline a case for a hypothetical deep-sea mining consortium.

5.1(b) Performance expectations

Key stakeholder groups in the deep-sea mining value chain includes the deep-sea mining field owner and operator, geology and marine science research, marine equipment suppliers, field developers and contractors, maintenance organization, shipping companies, port authorities, trucking and rail operators, mining companies, metal producers, metal traders, end-users, as well as regulators and the public-at-large. Central stakeholder firms or organizations could come to occupy several roles in the deep-sea mining value chain, as vertical integration is quite common in the mining industry (Kudelko, 2013).

The central decision-making power for the project is held by the field owner who holds the mining concession. The field owner could come to fulfill several other functions in the value chain, including field development and operations, as well as downstream activities, depending on chosen strategy. The roles as field developers and contractors can alternatively be allocated to experienced companies with previous offshore experience. With a new ocean industry, with uncertainty and complexity, we must look for similar operations at sea to learn from, such as the well-established offshore oil and gas industry. Previous work includes the comparison of ultra deep-water drilling and deep-sea mining for mining of manganese nodules in the Pacific Ocean at 4-6,000 meters water depth (Knodt *et al.*, 2016). In Table 1 we compare the offshore oil and gas industry and a future deep-sea mining industry.

Now that key deflection points from existing offshore activities have been outlined, it is reasonable to outline key performance expectations for central stakeholder groups, see Table 2. As this paper has taken the perspective of the field owner, we elaborate more on their performance expectations.

First, the measure of merit proposed to evaluate how well the deep-sea mining project meets the economic expectations of the field owner is the *cash cost of mining* (Wellmer, Dalheimer and Wagner, 2008), which is the unit cost of the mineral product. As seen in Figure 2, this unit cost is derived from the cost of extracting the product (gross value) minus the cost of processing it (net value). The measure allows comparison among completely different means of mining. The equivalent systems measure of merit which is frequently used in the offshore wind energy generation industry is the Levelised Cost of Energy (LCOE) (Kost *et al.*, 2018). Therefore, the economic expectations of the field owner for deep-sea mining can be can be found using the net present value of the cost per tonnes mined and processed, defined by Brett (2019) as the Levelized Cost of Mining (LCOM):

$$LCOM = \frac{\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{X_t}{(1+r)^t}} \left[\frac{USD}{tonne}\right] \quad (1)$$

Here, C_t is the cost of mining in year t, including capital and operational costs. X_t refers to the amount of metal output produced in time unit t, r is the discount rate, and n is the final year in the time horizon. Further, the cost function is defined as:

$$C_t = CAPEX_t + OPEX_t + VOYEX_t \quad (2)$$

Table 1: Qualitative comparison of seafloor massive sulphides and offshore oil and gas.

Offshore oil and gas	**Seafloor massive sulphides**
Longer field lifecycles: In some cases, fields can operate for more than 40 years, as a result of new techniques for increased oil recovery.	*Shorter field lifecycles:* The deposits at Solwara will be depleted in less than a time period of three years. If TAG is produced at the same rate (3,200t/d), it will be depleted in 6-7 years.
Proven technology: The oil and gas industry has accummulated more than 50 years of experience from offshore operations.	*Little proven technology:* Technology is only at trial and testing level, possibly with the exception of the equipment developed as part of Nautilus Minerals' Solwara project. Possibility for some transfer of human capital and technology from oil and gas, including technologies like vessel equipment, control systems and riser technology.
Sizeable supplier industry: Currently high sales volumes, but the impact of market volatility generates interest in new markets.	*Some supplier interest:* Likely small sales volumes due to limited number of marine mining systems being developed.
Safety and environmental risks: Pressurized hydrocarbons implies a risk of blowouts and explosions, as well as oil spills for prolonged periods of time, with severe impact on the marine environment. The awareness of these risks has lead to strict regulation of the industry.	*Environmental risks:* There is no risk of blowouts and oil spills, as there are no hydrocarbons under pressure. Deep-sea mining is connected to other environmental risks, for example due to harmful habitat removal for possibly unique marine fauna intervention.
Resource in fluid phase: For vertical transportation, hydrocarbons flow to the surface through a riser. The reservoir pressure contributes significantly in pushing hydrocarbon products towards the surface.	*Resource in solid phase:* Both excavation and vertical transportation of subsea minerals are challenging. Sufficient downward and grip forces are required to penetrate the rock deep enough to create large fragments. For vertical transportation, it is important to secure a sufficient and stable flow. Significant power supply is provided from topside.

Table 2: Summary of stakeholder performance expectations for a deep-sea mining venture with motivations.

Stakeholder	Expectation	Motivation
Field owner	Cash cost (unit cost)	There can be significant transaction costs associated with changing the supplier of minerals.
	Quality of product	Quality of the product should be equal to quality of a similar land-based product.
	Reliability of delivery	Reliability of delivery needs to be equal to or better than land-based mining. Lightering operations should not limit reliability or availability.
	Mobile marine system – any subsystem must be movable to a new site	Resources will be depleted faster than oil and gas equivalent – companies might be looking at a portfolio of deposits rather than one deposit.
Field contractors, developers and suppliers	Volume of industrial activity	The project must compete against other attractive business opportunities for company resources in the long run. Opportunity costs are high, given the attractiveness of oil and gas activities. Need for continuity in project activities over many years, to build and maintain expertise within the field.
Regulators	Environmentally friendliness	The project needs to be environmentally acceptable from a regulatory perspective. The solution needs to meet both IMO regulations for the marine systems solutions, and comply with flag state and classification rules.
Public-at-large	Environmentally friendliness	The project will need to be environmentally friendly, and be acceptable from a societal perspective.
	Workplaces	The project should increase the number of workplaces.
Customers	*Commodity traders:* Higher volumes of trading	Commodity traders want increased trading volumes.
	Metal producers: Access to ore at a reduced price	Metal producers want access to ore at a lower price and preferably outside the control of unfriendly nations and traders.
	End-users: Access to metal	1) Price: End-users want access to ore at a lower price. 2) Supply security: Companies or nations accept a higher price for securing supply of key metals. Minerals and metals are raw materials into processes in production lines. Securing these input factors might be essential to produce some end-product. The customer receive value in other segments.

Capital expenditure, $CAPEX_t$, are the investment costs, operations expenditure, $OPEX_t$, are the operations and maintenance expenditure. For ocean mining, voyage expenditures, $VOYEX_t$, i.e. fuel and other voyage related expenditures during time t, are included as well.

As the LCOM is the cost per produced unit, it can be directly compared to the market price and a quantitative assessment of the competitiveness would be possible. The field owner and/or end-user might accept a higher price for minerals if used as hedging mechanism for securing supply of minerals or materials that are essential in a company's manufacturing of products.

Second, the quality of the product needs to be of at least as high as a similar product derived from a land-based ore. The quality will be more dependent on the character of the deposit and ore processing methods rather than the choice of the marine system solution.

Third, reliability of delivery of minerals will be important, particularly due to securing the raw materials supply chain. This will be affected by the availability of the marine systems, its capacities and capabilities, which in turn is determined by scheduled and unscheduled downtime. Unscheduled downtime will account for situations where operability limits for the vessel are exceeded, either due to excessive motions for the vertical transport of material to the surface, or due to exceedance of acceptable sea states during loading operations or seabed equipment deployment or recovery. Other sources of unscheduled downtime include a variety of failure modes of the equipment needed for the operations. The downtime will also depend on chosen maintenance policy, including maintenance of mining system and spare parts availability.

5.1(c) Competitive positioning

The analysis of the competitive position accounts for the state of the existing land-based mining industry, the state of technology and regulations, and the uncertainty regarding regulations and the availability of mineral deposits, and aggregate scores are provided in Table 3. To properly distinguish between *competitors* and *new entrants*, we

Table 3: Rank-ordering (most important first, least important last) of the five forces for deep-sea mining. A 9 point Likert scale was used (1-9).

Rank (score)	Competitive force	Definition in this context	Description
1 (8.1)	Substitutes	Products offered by onshore mining	Land-based mining offers the same product already, but with a different cost structure and a large societal and environmental impact. Land-based mining operates with significant economies of scale.
2 (6.6)	Competitors	Field owners/operators in deep-sea mining operations	The number of competitors will likely be small at first due to the novelty of the industry. However, there will be a significant first mover advantage in terms of securing licenses for deposits that have been discovered or securing new exploration licenses.
3 (5.8)	Suppliers	Suppliers to the deep-sea mining operations	Deep-sea mining will likely be a small market for the suppliers, who will typically also supply the offshore oil and gas industry. Supplying this operation will likely rely on development of new technologies.
4 (5.2)	Buyers	Buyers at various stages in the metal value chain	There are many potential buyers of the product in a variety of industries, some of whom may exert control in the market by backward integration. There is little differentiation in terms of the sold product.
5 (2.2)	New entrants	Entities that enter the deep-sea mining market after the first movers	New entrants will likely face uncertainty in the form of market size, regulation, available technology, similar to the current project. New entrants might learn by the first mover's experiences, but there might be a limited number of licenses.

reserve the term *competitor* for entities that enter the market before, or at the same time, as the current unit of analysis. *New entrants* hence refers to entities that are not part of a wave of first movers.

The major competitive threat to the project are the substitutes, represented by land-based mining. To an entity that wishes to enter into deep-sea mining, it will be essential to understand the existing mining industry and the relevant commodities markets. Contrasting to land-based mining reveals two distinct differences: metal grades and overburden. The reported elevated metal concentrations in seabed ores might indicate an important advantage compared to land-based mining where grades can be fairly low. An example is the Aitic mine in Sweden produces 40 million tonnes per year – only 0.3% of this is copper (Karlsson, 2019). Also, they have an additional 40 million tonnes of waste rock which has to be disposed with an incurred disposal cost. Unlike often seen in the mining industry, there is very limited overburden at TAG and the potential ore is available on the seabed surface at the TAG-site. Therefore, there will be no disposal cost related to overburden. However, there will be disposal costs related to waste material handling after processing. The disposal costs will increase if stockwork is to be excavated and processed, due to the lower grades for this part of the mineralization.

5.1(d) Project risks

A summary of project risks for deep-sea mining venture are outlined qualitatively, reflecting the market insights generated as follows:

Excessive costs: Deep-sea mining requires extensive offshore infrastructure, but as no successful deep-sea mining system has been deployed one cannot adequately estimate the cost levels. This can be mitigated by seeking low cost solutions through the choice of proven technologies for vessel subsystems. Cost learning will come into play.

Lack of experience: The first mover will take considerable risks compared to followers who can freeride on available experiences. Ensuring quality of product and reliability of delivery of minerals will require vessel crew with experience within the disciplines of geology, mining and (deep sea) offshore operations. On the subsystem level, there are examples of concept studies and tests of marine equipment (Spagnoli *et al.*, 2016; Yamazaki *et al.*, 2016).

Problems accessing the market: A new entrant to the mining markets may experience problems with respect to accessing the markets, attempting to sell a limited amount of minerals in a market dominated by vertically integrated mining companies and users of minerals. The metal producers and mining industry that control existing market may attempt to prevent marine mining unless they can bargain from seabed mining as well. Mitigation can be achieved establishing partnerships: i) seek the involvement of existing actors in the mining industry as investors, and ii) partner with large actors in the metals supply chains, or iii) partner with buyers in the manufacturing industry.

Lack of availability: The weather in the Atlantic Ocean might reduce the operability of the marine system. The operability limits for both the seafloor mining operation, as well as offloading to transport vessels may be reached commonly. It will be important to decrease time spent on waiting-on-weather and possibly demobilize and decouple system if weather worsens.

Governance: The owner of the resources and the owner of marine infrastructure regulations might have different demands. There will be a difference between being in international waters are controlled by ISA, and national waters controlled by host country. TAG is situated in international waters, and as such the regulatory risks can be mitigated by following and contributing to the development of the regulatory framework through development of environmental impact assessments and contributions to basic research.

Public interest organizations: Environmental organizations may perceive this activity harmful to the environment. Mitigation efforts should therefore focus on reducing the environmental impact of the chosen solution, possibly taking environmental performance indicators into account during the early stages of design.

Uncertainty regarding seabed deposits: The actual size and grade of the *mineable* part of the orebody uncertain before production starts and more information is logged. In addition, there exists uncertainty regarding the metal that can be recovered. Deferring the investment until more geological information is available from exploration activities is a key strategy for mitigation.

Lack of funding: Access to sufficient funding to see the project through to completion is essential to any company. With the uncertainty and risks of a deep-sea mining venture it might be favorable to be a folllower rather than a first mover. This may lead to a wait-and-see position among investors. Degree of asset specificty and ownerships positioning in the marine systems design can be a hedging mechanism.

For a comperehensive overview of the current state of knowledge in potential environmental, legal, economic, and societal implications from deep-sea mining operations as well as a comparison of impacts associated with land-based mining, please see Koschinsky *et al.* (2018).

5.2 MARINE SYSTEMS DESIGN

5.2(a) Strategic business decisions for the value chain

To establish a viable deep-sea mining venture, and to obtain a sufficient understanding of how vertical integration in the value chain can leverage the additional expenses of investing in and operating marine systems for deep-sea mining, there are additional strategic decisions to be made. Whether to include certain downstream activities within the project are strategic decisions that will greatly affect the overall profitability of the deep-sea mining venture (Wellmer, Dalheimer and Wagner, 2008; Abramowski, 2016), and hence provide a threshold for acceptable costs for the marine system solutions:

- **Selling ore to a partner for further processing:** Ore is sold directly, without any value added through processing. This was the chosen solution for the Solwara 1 project, in which Nautilus Minerals had an agreement with Tongling Nonferrous Metals Group, to concentrate the material in a custom-built concentrator at their facilities in the People's Republic of China (AMC Consultants, 2018).
- **Selling ore concentrates to metal producers (for smelting and refining):** Ore concentrate is sold into the existing commodities markets. For copper concentrates, typical grades are 25 – 30 % (Wellmer, Dalheimer and Wagner, 2008). In the Solwara project, there is a trade-off between the concentrate grade for copper and gold, meaning that reducing the concentrate grade for copper may benefit the recovery of gold from the ore (AMC Consultants, 2018).
- **Selling ore after smelting to refineries:** Smelting activities are incorporated in the project, whereas refining is excluded and done by the customer.
- **Selling metal into the commodity markets after refining:** Refining activities are incorporated in the project, meaning that the project at this stage sells metal as a commodity.
- **Selling metal sheets directly to end-users:** In this case, the semi-finished metal products is sold at an agreed price by partnering with a long-term customer, for example in the manufacturing industry (e.g. automotive, aerospace, electronics).

The commodity market option implies a more volatile position, as entering into a longer term contract with a buyer will imply some sharing of price risk. Strategy 4 and 5 differ in the sense that the metal is sold in the commodity markets, or directly to an end-user. The latter option may imply an additional cost associated with distribution to the customer location, which is particularly relevant to the marine system if the transportation is conducted by bulk ships, but the overall system value creation could become significantly higher.

5.2(b) Design implications based on current knowledge about TAG field

More information about the marine system is needed to calculate the LCOM at TAG. However, we can discuss some design implication based on knowledge available about the mine site and offshore site. The TAG deposit with its tonnage of 6.7 million tonnes will be depleted within seven years given a production rate similar to Solwara 1 of 3,200 tonnes/day. The entire area, however, contains an estimated 29 million tonnes of mineralisation. In order to sustain production levels beyond the seven years, the mining system at TAG will have to move to other sites after deposit depletion. Hence, the asset specificity of

Table 4: Environment characteristics influencing the marine systems design requirements.

Environmental factor	Importance	Design implications
Waves	Operability limits based on Hs must be determined for critical marine operations, including deployment and operation of mining machines, operation of the vertical transport system, and offloading operations.	Reduce vessel motions through increased length and beam. Place critical equipment near midship to reduce motions. Dynamic positioning capabilities to reduce probability of loss of position. Consider alternative offloading methods to dry-bulk, such as pumping ore slurry. Possible need for shutdown of operations during winter, i.e. have seasonal production.
Water depth	Water depth affects deployment and recovery time of subsea equipment. TAG is located at 2,000 meter deeper water than Solwara.	Longer weather windows required for deployment of mining machines and equipment. Increasing demand for powering of seafloor production tools and mining machines.
Topography	Difficult to maneuver moving equipment on seabed due to steep and inhospitable environment.	Mining machines on seabed must be designed to cope with uneven topography and cover the mineral-abundant areas on the seafloor.

the marine system should be optimised for a portfolio of deposits and rather than one deposit.

Further, some implications can be made based on the geometry and contents of TAG. The width and length of the TAG field is approximately 200x200 meters. Covering this area with some mining tool will require ability to move or be moved across a distance of at least 200 meters in width and length – including incline and decline capabilities on mounds. The depth of the mineralization ranges from 3,630 meters down to 3,800 meters, giving a maximum seabed excavation depth of 170 meters. The mining tool will either have to vertically dig straight into the ground or cover the area horizontally like an open pit. The former option gives very steep mining process and the company bears the risk of losing the mining tool due to collapsing walls. The latter option would involve less steepness, but because the mining is less focused on the mineral-rich areas, the chances are higher that more waste rock is excavated. The actual contents of the TAG mineralisation is two million tonnes of mineral-rich zones while the rest is a less mineral-rich stockwork zone. After mining the first two million tonnes, the company most likely has to decide on whether to mine this less rich area or move on to other deposits. It will be important to sustain activity levels of infrastructure to avoid expensive idleness when deposits are depleted.

The offshore conditions are also important to assess during the planning stage. Marine operations are affected by the environmental conditions, and during selection of marine systems design for deepwater offshore operations, the significant wave height (Hs) is the dominating parameter (Chen, Cao and Mukerji, 2008). In Table 4, we describe the Hs and other environmental factors, and their implications on design.

It is uncertain whether conveyor belt-based side-by-side offloading to a transportation vessel, that is planned for operations offshore Papua New-Guinea, will be possible to accomplish in the environment faced in the Atlantic Ocean, as operational limits for side-by-side liquid offloading are lower than tandem offloading due to the shorter distance between vessels (Berg and Bakke, 2008). A tandem offloading method, as suggested by Van Nijen, Van Passel, & Squires (2018), will however require dewatering plant on the ore transportation vessel. Stavrou and Ventikos (2014) discuss the risks associated with ship-to-ship transfer, point out that most of the operations investigated have taken place close to shore, and point to accident statistics suggesting that ship-to-ship loading should be prohibited in wave heights exceeding 1.5 meters. In order to illustrate what a weather criterion of Hs=1.5 meters means for the TAG site, we provide probability distributions of the significant wave height from two months during the year 2020, see Figure 5. The operability criterion yields a 81% and 46% probability of exceedence for January and July respectively. During winter season in January, only 19% of the waves are within the criterion, meaning that the chances of obtaining the necessary weather window for this operation is quite low.

6. DISCUSSION

This study has identified several aspects of critical importance when approaching marine systems design for deep-sea mining. We have shown that even though this is an immature industry, insights from existing offshore industries, ship building, and land-based mining can be used to synthesise problem areas for the future deep-sea mining project.

The analysis showed that there is yet information needed about regulations, seabed deposits, and gaining experience with these operations. Moreover, the large upfront capital costs may be a considerable obstacle to ensuring an acceptable LCOM. Overall, measures for mitigating project risks stress the importance of the capability to

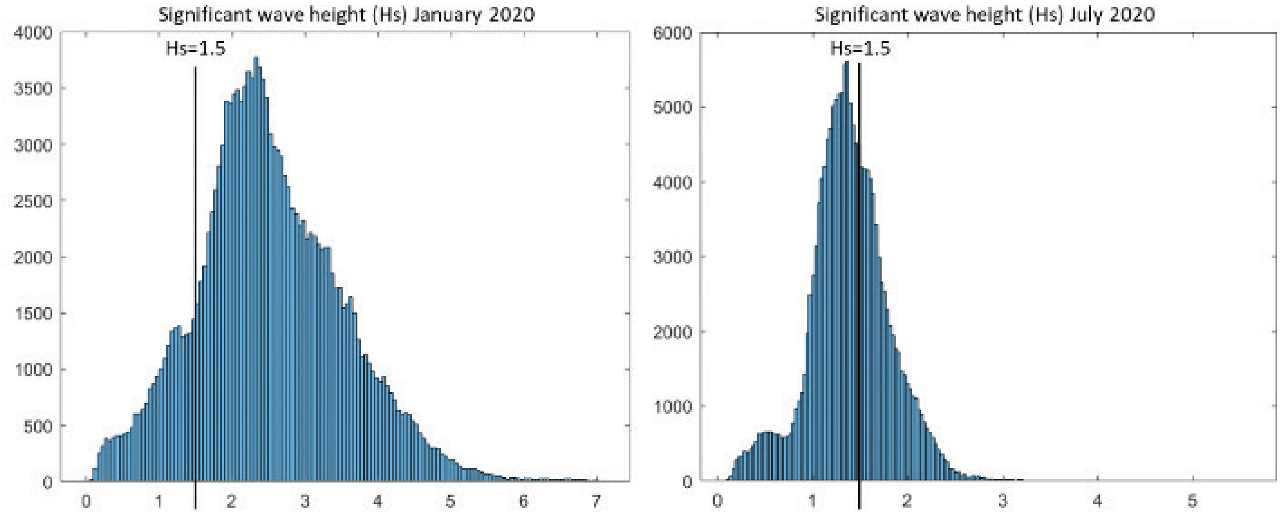

Figure 5. Probability distribution of significant wave height (Hs) for TAG site. Left: January 2020. Right: July 2020. Data from Climate Data Store (Hersbach *et al.*, 2018). Accessed 2021.6.10.

decouple marine assets and seek low cost solutions, and an important strategy might be to aim for proven technologies and equipment which is liquid in secondhand markets.

Design implications from the example case support the findings above. The short life cycle at TAG indicates that the asset specificity of the marine system could be optimised for a portfolio of deposits, requiring a mobile marine system. Also, the environmental characteristics at TAG limits the weather window available for production, particularly during winter seasons. If production cannot proceed due to weather conditions or seasonal production is necessary, it will be important to ensure other revenue-making activities for any idle infrastructure.

In Table 5 we present an overview of the most critical aspects when approaching marine systems design for deep-sea mining. These critical aspects affect LCOM. Demobilization will increase LCOM as production is put on hold and costs related to relocation and mine closure incur. Production continuity may be increased by balancing the capacities of each sub-system and ensuring a seamless integration. Decreasing the time spent on waiting-on-weather depends on the design wave height of vessel and mission equipment, waves at site, the duration of the marine operations, and operational vessels. A closer study of the production of such an operation is still needed to determine in detail the effects of influential factors.

Generally in mining, CAPEX and OPEX are inversely proportional; Increased CAPEX gives a lower OPEX, and a lower CAPEX gives high OPEX. Expensive and more advanced equipment will normally give higher tonnage and lower operating costs, but may vary dependent on e.g. ore geometry, mineral textures, and rock strength variations. OPEX varies with the chosen mining method and applied technology, as well as production tonnage (daily ore tonnage) (Hartman and Mutmansky, 2002, p. 509; Camm and Stebbins, 2020). For different mining methods OPEX may vary from 8 USD/t for the highest production tonnage (45,000 t/d) to 145 USD/t for the lowest (200 t/d) (Camm and

Table 5: Early stage critical aspects when approaching marine systems design for deep-sea mining.

Critical aspect	Description	Key decisions
Mobile marine system	A marine system should have the ability to relocate if deposit is depleted and new prosperous mine sites are found.	Design a marine system for easy demobilization and decoupling Choose assets that are liquid in secondhand markets Optimise asset specificity for a portfolio of deposits rather than a single deposit
Production continuity	Ensuring reliable production and delivery	Reliable equipment and systems Decrease time spent on waiting-on-weather
Processing/vertical integration	Significant value is added to the product during each processing stage	Partnering with onshore processing facilities might be essential to share risk
Alternative use	In some locations, weather may be too harsh to sustain production level during certain parts of the year.	Design system where infrastructure can be used for alternative purposes if deep-sea mining is not possible.

Stebbins, 2020, p. 17). Regarding CAPEX estimates, there may be large variations in land-based mining depending on daily ore production and mine type. A tenfold increase in planned production rate gives an approximate tenfold increase in estimated CAPEX, depending on whether the mine is open pit or underground (Darling and Society for Mining Metallurgy and Exploration, 2011, p. 346). For a deep-sea mine, it is expected that economies of scale must be utilised. A previous study addressing the commercial performance of mining vessel design solutions found that a larger mining vessel gives larger CAPEX, but LCOM may be significantly reduced due to higher production capacities and a vessel with much higher operability. A preliminary estimate showed that LCOM drops significantly from a small vessel to a medium-sized vessel – from 830 USD/t to 250 USD/t, and down to 120 USD/t for a larger vessel. In other words, from the small vessel to large vessel, an 86% drop in LCOM was experienced (Solheim *et al.*, 2022).

Deep-sea mining is an industry that may start in the 2030's. In parallel to this development, the maritime industry is moving towards a reduction in the carbon intensity of ships by various measures related to operational functions, fuel types and machinery configuration. For the ship design, these measures could give an approximate 30-50% increase in CAPEX, and a 3-5x increase in fuel costs compared to conventional solutions, depending on charter arrangements (Ulstein, 2022). Naturally, adopting such measures for a future marine system in deep-sea mining will certainly affect the cost structure. Hybrid configurations with, for instance, onboard batteries might be interesting for handling peaks in power demand. It could also be an option to source power from an external energy producer. Novel and yet unproven approaches to energy-providing infrastructure include floating wind turbines and floating solar structures. There is still uncertainty in required onboard installed power. An estimated range which has been acknowledged by industrial actors with experience from development and testing in this context is 40-50 MW (Solheim *et al.*, 2022), but power use will be highly dependent on chosen vertical lifting system (hydraulic, airlift, or other) and the operation mode. Furthermore, greener fuels are gradually being introduced to the maritime industry, such as ammonia, methanol, and hydrogen. The current challenges of relying on these fuels for a deep-sea mining context are the long distance refuelling requirements, volume of fuel demand, and accessibility; Many of the relevant deep-sea mine sites, including TAG, are located far from mainland and fuel demands are high – higher than what can be supplied by reliable sources on land at an acceptable cost level. A green fuel option which does not need frequent refuelling is nuclear energy. This may be the next generation fuel for deep-sea mining, but currently more research on nuclear energy for marine applications is needed.

7. CONCLUSION

In this paper, we have used a framework for maritime business development to generate insights into the commercial, operational and technical viability of a novel area of offshore operations: deep-sea mining. We used a deep sea mine site from the North Atlantic Ocean as an example case in this study, and presented and discussed important market considerations, strategic decisions in the value chain and design implications based on the current knowledge of the field.

Several important early stage decisions in marine systems design for deep-sea mining are outlined. Designing solutions with these aspects in mind may improve performance and mitigate the risks of entering this industry. The Levelized Cost of Mining (LCOM) was identified as an important benchmark index, and for marine systems design applications it provides an early stage key performance indicator which can be used to make comparisons between concept design solutions. The work has paved the ground for further studies in cost-benefit analyses, conceptual design, and operability analyses for deep-sea mining operations.

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