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TECHNOLOGY TRANSFER IN NOVEL SHIP DESIGN: A DEEP SEABED MINING STUDY

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ABSTRACT

Designing new ships for new purposes, in this case deep seabed mining, without using proper selected reference vessels, if available, is challenging. In this paper, we show that the vessel features of a future deep seabed mining vessel have many similarities to offshore vessels in the deep-sea offshore oil and gas industry and can be used as such. We evaluate and discuss the technical, operational, and commercial performance of three possible vessel design solutions developed based on such a case ship.

KEY WORDS

Ship design, technology transfer, business development, concept design, deep seabed mining

INTRODUCTION

The discrepancy between the future availability of critical minerals and the world demand is an increasing global concern (IEA 2021). Minerals harvested from a deep seabed mining operations contain valuable metals such as copper, lithium, nickel, and rare earth elements (REE) that are essential components in cell phones, electric cars, wind turbines, and more (Hein et al. 2013). Mineral-rich ores are found at water depths ranging from 400 meters to 6,500 meters. The essence of deep seabed 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 (Solheim et al. 2022). Deep seabed mining is now regarded as one of the emerging ocean industries (European Union 2021).

At the same time, there are many offshore vessels that are searching for other missions in today’s market. The maritime industry has gone from being centred around the offshore oil and gas industry to becoming more diversified. Ship designers and ship owners have shifted their product portfolio to meet other maritime industries, and offshore vessels are repurposed to meet needs in other contexts, such as aquaculture, offshore wind, and other ocean industries. An example is Platform Supply Vessels, which are being converted to serve as Service Operation Vessels for the offshore wind industry – a cheaper alternative to a newbuilt vessel.

Extensive offshore infrastructure will be needed to support the extraction and shipment of the deep sea minerals. The marine system that will produce these minerals is not yet given as there is currently no known active deep seabed mining operation. An option may be reusing offshore support vessels, which has two advantages: one is that obsolete technology, meaning the work platform, is being reused in the spirit of circular economy, and two is that technology from offshore drilling is put to new uses in offshore mining. In this paper, we show that the vessel features of a future deep seabed mining vessel have many similarities to offshore vessels in the deep-sea offshore oil and gas industry, and experience and expertise from designing such vessels can easily be transferred to the emerging ocean industry of deep seabed mining.

The rest of the paper is organised as follows: Section 2 gives a literature review of the history of ship design and operation for deep seabed mining. Section 3 describes the methodology used in the paper. Section 4 provides the

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mission description, while section 5 portrays the business case and section 6 the conceptual design phase. The following sections 7, 8, and 9 are results, discussion, and conclusion respectively.

TECHNOLOGY TRANSFER FROM OFFSHORE OIL AND GAS DEVELOPMENTS TO DEEP SEABED MINING

Technology transfer between the offshore oil and gas industry and offshore mining has been addressed to some extent previously (Williams, Mcbride, and Kinnaman 1977; Knodt et al. 2016; Sarangdhar 2018). Once the economic potential of minerals had been pointed out in 1965 (Mero 1965), a series of initiatives such as exploration cruises and pilot tests commenced from the late 1970's onwards. Pilot tests were conducted with SEDCO 445, the world's first dynamically positioned drillship. The mission was to collect 5,000 short tons of manganese nodules at a water depth of 5,300 meters (Williams, Mcbride, and Kinnaman 1977). The experiences from these trials were documented to emphasise the need of technology transfer between the offshore drilling industry and the offshore mining industry, even at that time. An overview of the important milestones in deep seabed mining and need of technology transfer is outlined in (Knodt et al. 2016). A more recent example is the former ultra-deepwater drill ship MV Vittoria 1000, now known as MV Hidden Gem, which has been undergoing conversion. A special nodule collection system is being developed and the existing capabilities of being a drillship allows a deployment of a 4,500-meter-long collector riser. The vessel is 228 m long, 42 m wide, and can accommodate 200 persons on board (POB).

Most retrofit projects deal with low-quantity mining, related to mineral exploration or pilot tests only. For a commercial mining vessel, larger scale will be needed. The only known successful industrial production of seabed ore is taking place outside Namibia, where diamond ores are mined at water depths of roughly 150 meters. Here, they use both retrofits and purpose-built vessels. The MV SS Nujoma and MV Benguela Gem are mining vessels built in 2016 and 2021 respectively. The Norway-built MV SS Nujoma is essentially an offshore oil and gas related Construction Support Vessel (CSV) with special outfitting for an ore processing facility on deck and subsea mounting equipment.

The most well-known purpose-built deep seabed mining vessel is MV Nautilus New Era. In the Nautilus Minerals concept, a set of three mining machines perform the excavation functions. Vertical transportation was to be accomplished by pumping ore as a slurry, mixed with salt water, through a riser system. The only ore processing done onboard the mining support vessel was dewatering of the slurry mix. Next, the ore was to be stored, awaiting offloading by a conveyor belt system to a bulk carrier (AMC Consultants 2018). Designers of this ship has referred to this vessel type as "a strange mix of an Offshore Support/Construction/SPS vessel with accommodation for nearly 200 persons, a Bulk Carrier, a Tanker, a Drill Ship, a FPSO for ore – all in one ship" (Sarangdhar 2018). Another proposal for a mining ship design presented a discussion on the technical aspects of a mining vessel as well as a general ship layout (Abramowski and Cepowski 2013).

The small number of purpose-built deep seabed mining vessels means that there are not enough samples to make parametric analyses as a basis for new vessel designs (Sarangdhar 2018; Abramowski and Cepowski 2013). However, there still might be significant learning potential from a few mature designs and mature technology when establishing vessels for new industries. As seen in this section, the mission equipment of drill ships meant for pilot testing mission in deep sea mining operations has been highly useful previously. The remainder of this paper documents the design process of a deep seabed mining vessel based on three production scenarios.

METHODOLOGY

The Accelerated Business Development (ABD) process is developed and used by the Ulstein Group for maritime business case development and early-stage system design. ABD originated from the EU-funded LOGBASED-project (Brett et al. 2006), which sought to develop a logistics-based ship design method. The ABD process is hence part of the growing literature recommending a closer methodical connection between business strategy and naval architecture in the maritime industry based on a systemic approach and systems theory (see also (Hagen and Grimstad 2010) or (Ulstein and Brett 2015)). The process emphasizes the need for mapping out the real-world problem situation, to reveal the complexities that may arise during project decision-making (Checkland 1981). Research on complex systems development projects state that the major sources of project failure are of a social, rather than a technical, character (Bar-Yam 2003). Especially when little previous experience exists, it may be unclear whether stakeholders agree on what a given system design project is to achieve. The ABD process is intended for use in a setting in which ship designers consult with ship owners and other stakeholders, in order to develop new maritime business concepts, and assess commercial, operational and technical viability. The process should hence facilitate elicitation and negotiation of requirements and identify solutions for further development.

The paper starts by describing the mission and location where the fleet will operate. Furthermore, we elaborate on the business case, which involves several steps. The first is sketching the system and defining system boundaries. The second step is the performance expectations, where we will list important factors that affect the success of the vessel. Further, we map revenue and cost drivers, before arriving at vessel objectives – strategies and the engineering tactics manifested in the strategies.

Next comes the marine systems design. There are various ship design methods known and available which can be applied in the conceptual design phase. Here, we will use the Fast-Track Concept Design Analysis (FTCDA) – a part of the ABD approach. This is a method for configuring and investigating trade-offs during the concept ship design phase, developed by Ulstein International (Ebrahimi, Brett, and Garcia 2018). It is a holistic tool combining technical, operational, and commercial factors of conceptual ship design. The objective of FTCDA is to reduce time spent on the vessel concept design phase. The tool did not previously have a mining vessel interface, and we therefore start out by presenting the mended and upgraded version. Thus, we present the mining vessel features: ship systems and mission systems, before presenting three mining vessel designs.

After arriving at design solutions, it is time to measure the performance of the vessels. This process can be examined from different perspectives (Ulstein and Brett 2015). Perspective A concerns efficiency of the vessel by dealing with the technical, operational, and commercial performance. The technical aspects say whether a vessel has the abilities to perform a certain task. The operational aspect is related to the performance of different assignments, while the commercial aspects is about making the vessel an attractive investment during its lifetime. Perspective B deals with a smarter, safer, and greener vessel. A smarter vessel means a vessel that achieves more with less – creating a clever and elegant ship. Safer aspects mean that the vessel is designed to reduce risk of undesirable or dangerous events. The greener aspects concern the vessel's environmental footprint and a meticulous utilisation of resources and energy. Perspective C is about the effectiveness of the vessel – its, flexibility, agility, and robustness. A flexible ship can be modified to meet new conditions and accomplish different operations. Agility concerns the time aspect of the vessel's performance – its ability to act quickly to new operations, but also its ability to decrease time spent on lengthy tasks. Robustness concerns the vessel's ability to meet changes in context without having to change its configuration. At the end of this paper, we discuss the vessel design solutions from this set of perspectives.

MISSION DESCRIPTION

This section describes the perceived and anticipated location of mining and other mission-related information. The production takes place at the Mohn's Ridge site, north on the Mid-Atlantic Ridge. The deposit sits between the island of Svalbard and the island of Jan Mayen – just between the Barents Sea, Greenland Sea, and the Norwegian Sea. The distance to shore is 360 nm, and the water depth at this site is 2,600 meters. The production is dependent on a bulk vessel that arrives to collect the ore that has accumulated in the mining vessel. Bulk vessels will shuttle transport ore to a base on the coast of Norway on a regular basis, as part of the total mining system operation, see Figure 1.

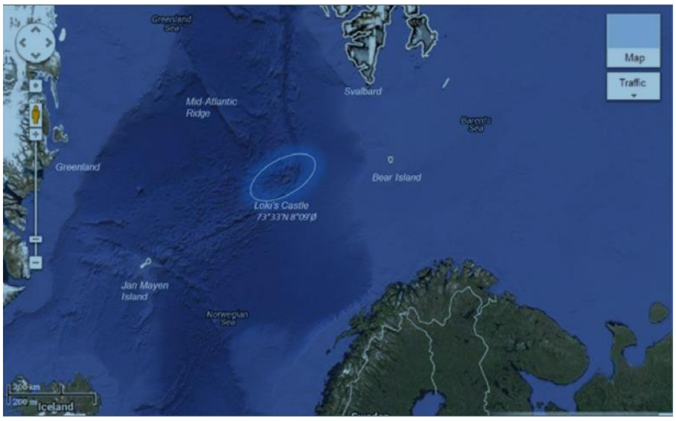


Figure 1: Map showing Mohnsryggen, from GoogleMaps.

The ship's capacity must ensure an economical mining system viability and a sustainable operation. The production rate is an important starting point in design considerations. The paper studies three cases of expected target production of ore per day, shown in Table 1.

Table 1: Production and logistics key figures for each case.

	Case 1	Case 2	Case 3
Daily production	1,000 t/d	3,500 t/d	7,000 t/d

The shuttle transport vessel logistics cycle consists of transit to the mine site, loading ore from the mining vessel by ship-to-ship transfer, the return transit with ore, and offloading ore in port. A margin is added to the total estimated days of the bulk shuttling vessel cycle to account for events such as waiting-on-weather (WoW), please see Table 2.

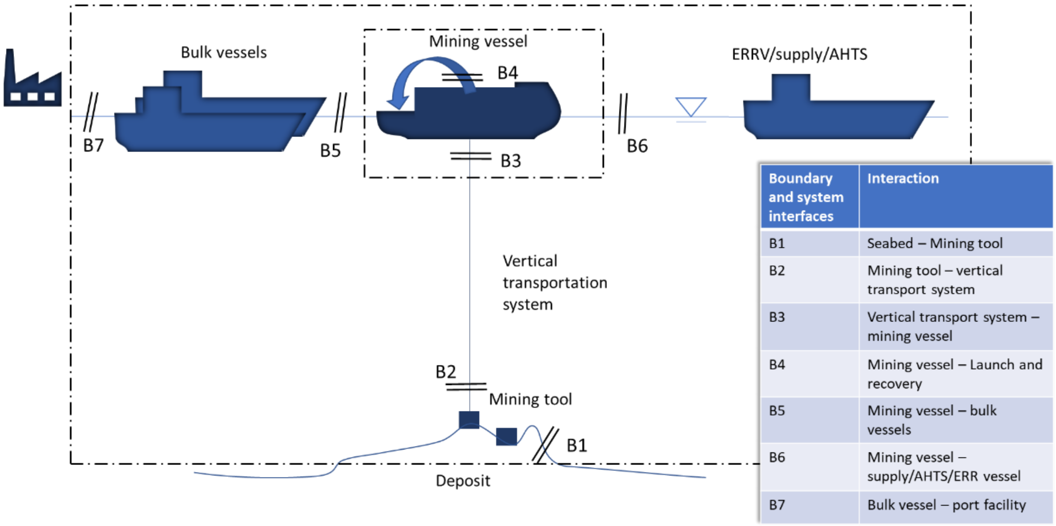
Table 2: A bulk vessel logistics cycle and estimated duration of each phase.

Transit	Loading	Return transit	Offloading	Margin (WoW)	Total
3 days	3 days	3 days	2 days	3 days	14 days

BUSINESS CASE

System Definition and Boundaries

The main purpose of this new vessel is to support the seabed mining operation taking place in deep waters on a DP-based position and holding technology solution. An overview of the marine system and its boundaries is shown in Figure 2.



Boundary and system interfaces	Interaction
B1	Seabed – Mining tool
B2	Mining tool – vertical transport system
B3	Vertical transport system – mining vessel
B4	Mining vessel – Launch and recovery
B5	Mining vessel – bulk vessels
B6	Mining vessel – supply/AHTS/ERR vessel
B7	Bulk vessel – port facility

Figure 2: Mining system overview with boundaries and system interfaces.

The outer system is comprised of three vessel types: one mining vessel whose main task is to facilitate the mining operation, bulk shuttling vessels that facilitate the ore shipment from site to port, and a mining system supply, rescue and replenishment vessel which ships replenishment, fuel, and crew. The outer system also has mining tools and a vertical transport system to enable the excavation and lifting of ore from the seabed deposit. Once the ore is on board a bulk shuttling vessel, it will be shipped to a land-based plant for further processing.

The inner system is the mining vessel, which constitutes the unit of analysis in this paper. The mining vessel will act as an offshore work platform – supporting the mining operation as well as launch and recovery of subsea systems. It will also enable the crushing and dewatering of ore onboard and the transfer of ore to the bulk vessel which takes place offshore.

The mining vessel must have the necessary capabilities and capacities to support excavation of the seabed, vertical transportation of ore, as well as treatment onboard. There will also need to be necessary facilities to support the handling of equipment on board, and more general support functions such as machinery and hotel spaces. Further, the vessel must be able to transfer the ore to a receiving vessel. The shipping functions can be resolved through a contract of affreightment with a ship owner, a common arrangement for transportation of bulk cargoes (Stopford 2009). This allows the shipowner a large degree of flexibility in terms of what ship to use for the operation, and to optimize the use of their fleet. Ore transportation and replenishment of supplies to the mining support vessel can most likely be carried out by existing vessels. To allow for emergency preparedness and possibly towing assistance, an Emergency Response and Rescue Vessel (ERRV) is chosen for supply functions.

Performance Expectations

Performance expectations for a deep seabed mining vessel owner is outlined in Table 3. The list of performance expectations was obtained after a series of organized workshops attended by academics, miners, and marine systems designers, and an overview of this process and results can be found in (Solheim et al. 2022).

Table 3: Some important performance expectations, from (Solheim et al. 2022).

Category	Performance expectation	Description
Politics	Security	Secure mineral supply
Market	Market availability	Availability of bulk vessels affects price negotiation and OPEX
Sustainability	Environment	Impact from mining activity on seabed
Economic	LCOM	Minimising the levelized cost of mining
Strategic	Exit/escape possibilities	Deposits might be depleted, or weather might require seasonal prod. → ensuring missions for the vessel
Operational	Productivity	Ensuring efficient material flow
	Station-keeping	Important due to sensitive riser operation
	Reliability	Reliable system important for production continuity

In the following, the performance expectations are elaborated further.

The levelized cost of mining (LCOM) will be used in this paper to compare the vessel designs. LCOM is found in Equation 1 as (Solheim et al. 2022):

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

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 number of time periods. Capital expenditure, $CAPEX_t$, are the investment costs, operations expenditure, $OPEX_t$, are the operations and maintenance expenditure. Voyage expenditures, $VOYEX_t$, i.e., are fuel and other voyage-related expenditures during time t.

Operational factors, like station-keeping, and reliability, were found to be important. The mining vessel is connected to a riser, which based on the experience from offshore oil and gas, is sensitive to high motions. In the North Atlantic Ocean, the weather can be quite unfriendly. See Figure 3 for a histogram showing significant wave height (Hs), from (Solheim 2018).

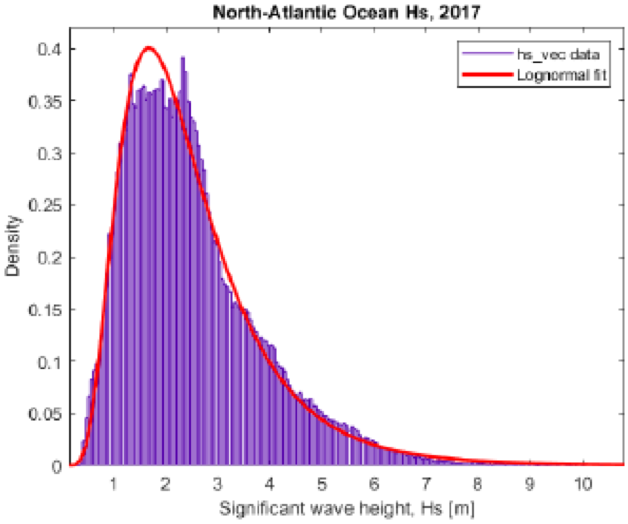


Figure 3: Histogram showing significant wave height (Hs) for the production site in the North Atlantic Ocean. Data from (ECMWF 2018).

As seen in the figure, extreme wave heights can be as high as 7 to 9 meter Hs, which means they can be as high as 9 to 10 meters in real life, if not higher. The wave heights are subject to seasonal variations. To illustrate these variations, Hs time series from 2017 are shown in Figure 4.

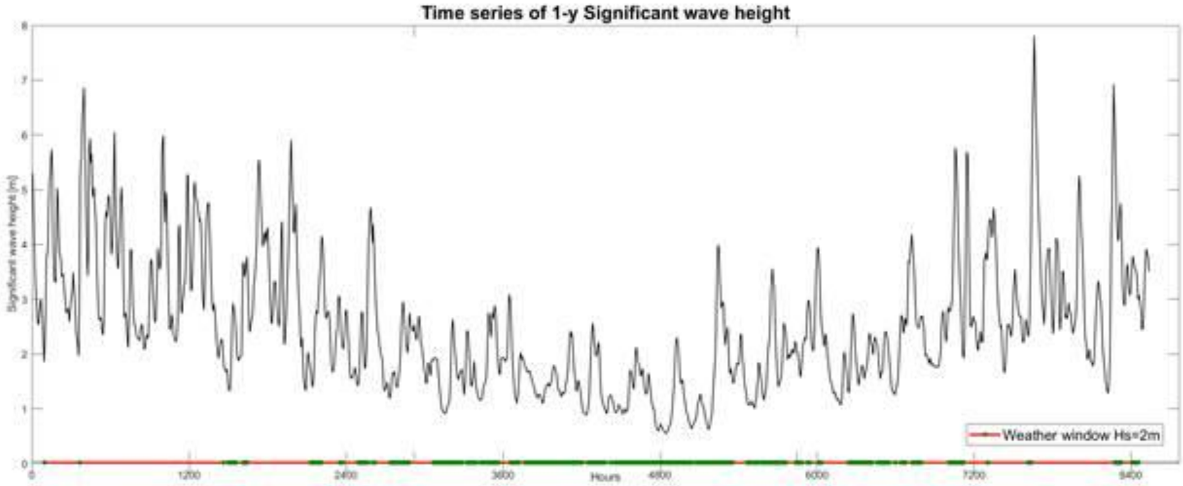


Figure 4: Time series significant wave height for the Norwegian Sea year 2017. An arbitrary design threshold of Hs=2m is shown in the bottom line. Data from (ECMWF 2018).

The figure shows the number of times the waves are below and above an arbitrary threshold of Hs=2 meters for illustration. It shows that the lower wave heights are found during the summer months, and seasonal production might be expected. The mining vessel will then need to obtain other missions the rest of the year to avoid idleness.

Market availability is important to consider when deciding upon the capacity of the bulk vessels, see Figure 5. This applies both when the field operator wants to own or lease the transportation vessels. A high number of vessels means higher bargaining power for the mining contractor.

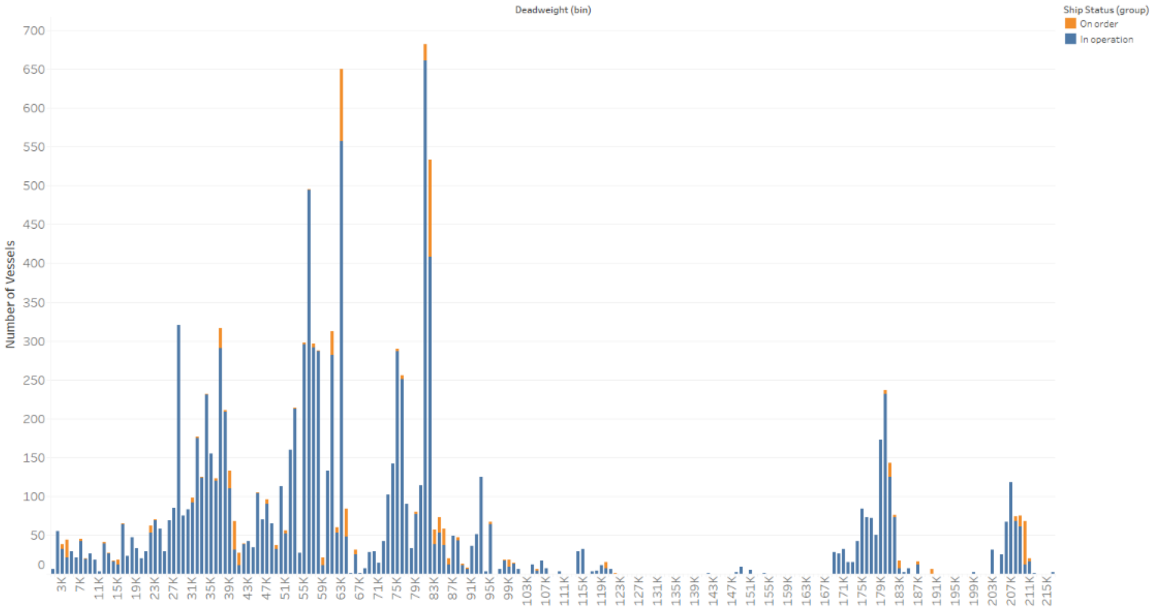


Figure 5: Number of bulk carriers in market sorted by deadweight capacity, from IHS Fairplay.

As can be seen from the figure, there exists a high number of vessels around 12,000 tons, 28,000 tons, 37,000 tons, 56,000 tons, 63,000 tons, and 82,000 tons deadweight. For case 3, a 7,000 tons per day production in two weeks would mean that 98,000 tons storage capacity is needed on board the mining support vessels. As seen in Figure 5 there exists next to zero such vessels. Only a few around 114,000 tons. It is difficult to get hold of such vessels, and it is therefore better to go down in size to a pickup interval of 7 days with two bulk shuttle vessels. With two bulk vessels, we only need production rate x7 days of ore storage. The required bulk capacity onboard the transport vessels is found as the daily production times the interval days of arrival. A margin is added and then Figure 5 is used to pick a standard, highly available bulk vessel from this source to reduce the overall mining system LCOM. The necessary bulk vessel carrying capacity for the different production scenarios are found in Table 4.

Table 4: Bulk carrier size for the three cases.

	Case 1	Case 2	Case 3
Min. req. payload	7,000 t	24,500 t	49,000 t
Replenishment	837 t	837 t	837 t
Final capacity with margin and availability	12,000 t	37,000	63,000

Supplies, fuel (bunkering), spares, and crew will need to be transferred to and from the mining support vessel by the ERRV. The arrival interval is 7 days. Freshwater is made onboard the mining vessel.

Revenue and Cost Drivers

The vessel design objectives are materialised in the design strategy and engineering tactics as described in figures below. This can be technical, operational, and commercial aspects. To identify the areas of improvement, the revenue and cost drivers are mapped in Figure 6 and Figure 7 respectively, and should be carefully scrutinised and considered when finalising the better solution alternative.

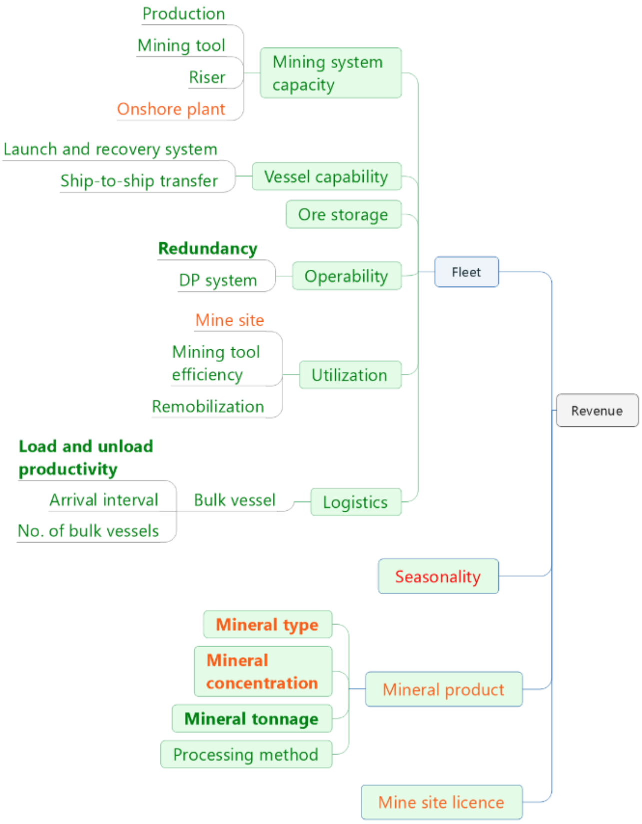


Figure 6: Contribution margin model – Revenue. Green-orange-red according to degree of influence by ship owner on the factors, the most important factors in bold.

The categories influencing revenue show that seasonality, mine site licence, and mineral product are the most difficult to influence. The seasonality is related to the weather conditions at site. These will put restrictions on the production and being far north indicates that seasonal production might be necessary. In that case, it will be important to assure missions for the vessel throughout the rest of the year to avoid unnecessary idleness. Mine site licence can be influenced to some extent – the first movers will be the ones getting access to the most attractive licences. Also, if a company has several licences, they will go to the most valuable deposit first, given by the highest NPV. Licences can be sold if the company is not interested in the area. The mineral product can be influenced to some extent through processing methods and the amount of tonnage to extract. However, the intrinsic characteristics of the deposit, such as concentration and mineral type it contains, are more difficult to influence. The earlier phases of the value chain, exploration activity and resource assessment, will estimate the resource, but the true contents of the deposit will be known once extracted. The mineral type, mineral concentration, and mineral tonnage are listed as important factors. The mineral type and – later – the metals that are extracted are crucial to the price the company can take for the product. Mineral concentration will determine how valuable each tons extracted are – the company will set a cut-off policy here for the accepted cut-off grade per mined block. Mineral tonnage is important as well, especially looking from an economies of scale viewpoint. Depending on the stakeholders' performance yield expectations to such a mining system the different revenue drivers will be given different emphasis and catered for in the final searching for the better total deep seabed mining system.

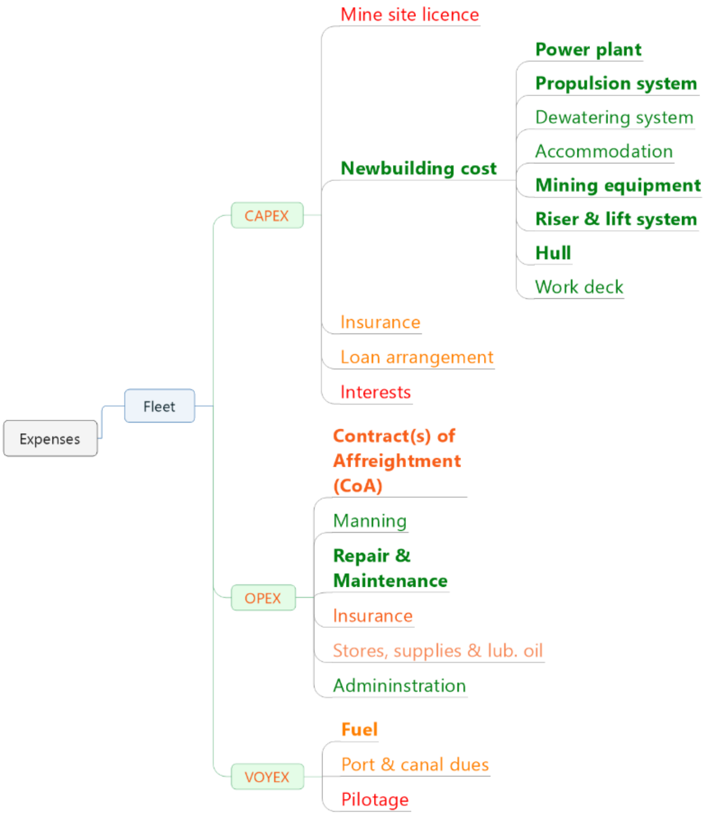


Figure 7: Contribution margin model – Expenses. Green-orange-red according to degree of influence by ship owner on the factors, and the most important factors in bold.

The categories influencing expenses show that the vessel newbuilding cost is the category on the CAPEX side which can be influenced the most. It shows that careful thought should be placed on the choice of marine system, as it can quickly drive up the CAPEX. Additionally, repair and maintenance can be influenced on the OPEX side, which is likely a big contributor. Equipment in the offshore oil and gas industry are maintained constantly to avoid unexpected downtime and keep production running, and it is likely that this will be the case for a deep seabed mining system as well. It might be worthwhile the investment to add redundancy to critical systems, particularly the subsea equipment to avoid a full stop in production if something fails. Fuel will be the biggest contributor to VOYEX and can be influenced to some extent through smart utilization of machinery system. The most difficult to influence are mine site licence, interests, and pilotage expenses. Mine site licence and interests are unavoidable, while the frequency of required pilotage serves is probably low as the mining vessel will rarely go to port. The expenses contribution margin shows that there is a lot to gain from being smart about the choice of marine systems design and logistics scheme to manage and limit the expenses.

Project Design Strategy and Engineering Tactics

The revenue contribution margin model showed that the most important and influential factors are the mineral tonnage, load/unload productivity of the bulk vessel, as well as redundancy. This is to keep a steady and efficient production with a sufficient magnitude. To secure revenue, the mining vessel will stay on site producing as much as possible – it will essentially be an offshore work platform. The expenses contribution margin model showed that the newbuilding cost and repair and maintenance costs are the most important and most influential. Because of these models, we aim to make a special mining ship and have standard ships for the support services. The design strategy is to put special functions on one vessel and keep the other vessels simple and cheap. The idea is that acquiring simpler and cheaper bulk vessels is better. The engineering tactics will then be a consequence of this strategy, see Table 5.

Table 5: Design strategy versus Design tactics

Design Strategy	Design Tactics
Ensure production continuity	Spare collectors Reliable station-keeping system
Special equipment on mining vessel	Self-unloading conveyor belts with high production rate
Stable work platform (Compact design)	High beam (low L/B) Large deck area Safe house for crew High draft

CONCEPTUAL DESIGN

The FTCDA tool was adapted to include the equipment and systems that were specific to a deep seabed mining mission. The design process started with Offshore Construction Vessels (OCVs) as a basis. The operational region was specified to the Norwegian Sea with a desired DP capability of Hs=4,85 meters giving a 90% probability of wind-wave occurrence lower than this limit. The block coefficient (Cb) was manually edited to get a rounded hull shape which allows for more storage. A diesel-electric propulsion system was chosen with an engine room setup of two engine rooms and two switchboards. The systems that were added to the revised and upgraded FTCDA tool was the mining-specific equipment: crushing/dewatering plant, pipe/riser storage, self-offloading system, and collector system. The crushing/dewatering plant has a choice of small, medium, and large depending on the size. The size of the riser storage is dependent on number of joints which in turn is determined by the water depth. The options in the riser module varies from a 1,000 to 5,000 meters. The self-offloading system is divided into small, medium, and large depending on the size. Finally, the collector system is separated into two subsystems: the collectors themselves and the launch and recovery support system. Number and type of collector/LARS can be specified. See Appendix A for an overview of the new FTCDA user interface. The resulting mining vessel features, consisting of the mining ship systems and its mission equipment, are found in Table 6.

Table 6: Technical data related to ship systems and mission-related equipment of the mining vessel.

Ship systems		Technical data
	Hull	Cb=0.8
	Engine room	50 MW
	Accommodation	150 POB
	Station-keeping	DP 3, 6x5,000 kW thrusters
	Deck area	Riser joint storage 20mx30m workshops Safehouse
Mission equipment		
	Seabed collectors	3 collectors + 2 spare collectors
	Launch and recovery system	3x A-frames á 210t, 260t, 310 t
	Crushing and dewatering	
	Ship-to-ship ore transfer	2x self-unloaders
	Ore storage	
	Riser assembly	2x AHC Offshore cranes á 350 t 14m w 3,000m wire
	Riser deployment	8,0mx8,0m moonpool Derrick
	Riser storage	Pipe racks
	ROV	2x work ROVs (hangar and work deck). Overside system with 3,000-meter reach
Other data		
MDO density		9 t/m3
Contingency factor		1.3
Fuel capacity		820 tons
Ore density		3.5 t/m3

RESULTS

Three vessels were created in the FTCDA tool. The technical specifications are found in Table 7.

Table 7: Technical specification of the three mining vessel design solutions.

Parameter	Small vessel	Medium vessel	Large vessel
Length over all (LoA)	150 m	175 m	225 m
Length between perpendiculars (LPP)	142 m	165 m	215 m
Beam	30 m	32 m	40 m
Depth	13 m	18 m	20 m
Max draft	10	14 m	15 m
Cb @ max draft	0.84	0.82	0.81
Design draft	9 m	13 m	14 m
Free deck area	1972 m2	2,811 m2	5,395 m2
Power installed	39,775 kW	43,307 kW	47,231 kW
Design deadweight	17,303 t	36,710 t	69,669 t
Max deadweight	22,604 t	42,299 t	78,392 t
Max deadweight w/o moonpool and topside eq.	24,557 t	44,508 t	80,665 t
Length/beam ratio	5.0	5.47	5.63
Length/draft ratio	15-16.7	12.5-13.5	15.0-16.0
Beam/draft ratio	3.0-3.3	2.3-2.5	2.7-2.9
Deck load – initial	23,917 t	31,228 t	69,199 t
Deck load – final	5,569 t	5,784 t	34,348 t
Steel weight	6,850 t	9,596 t	14,627 t
Light weight	11,416 t	15,993 t	24,378 t

The three vessels presented differ in size. The medium-sized vessel is 25 meters longer than the small vessel and it has twice as much deadweight. The largest vessel is 50 meters longer, 8 meters wider and has almost twice as much deck area and deadweight compared to the medium-sized vessel. The final deck load describes how much extra deck load the vessel can take before the stability is jeopardized, and the biggest vessels outperforms the other two in this respect, as the stability calculations show a much higher allowed extra deck load for the large vessel. The medium-sized vessel has a smaller beam/draft ratio, which is generally associated with increased heave motions (Faltinsen 1990, 84). The larger vessel is longer, and generally, increasing vessel length is linked to decreasing vertical ship motions (Faltinsen 1990, 85). It is therefore expected that the large vessel will have better heave characteristics than the others. Of course, accurate calculations will be needed to determine this with complete certainty. A visual representation of the ship systems is shown in Figure 8.

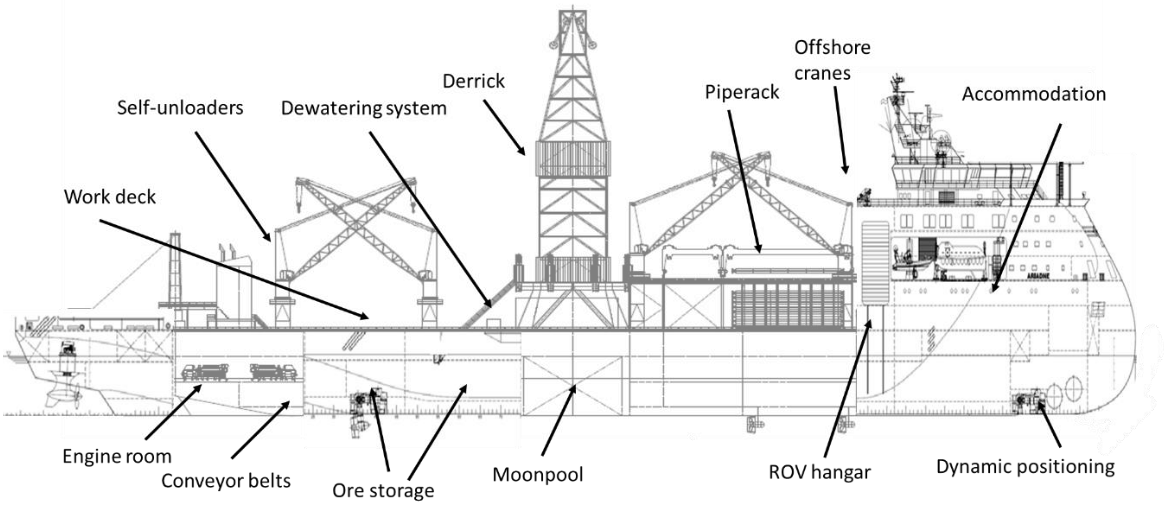


Figure 8: A functional profile of the vessel including the functions using an Ulstein deepwater drilling vessel design.

The various mission equipment is placed onboard. As can be seen, the vessel has many familiar technologies from the offshore oil and gas industry – a pick and mix from different vessels combined into a deep seabed mining vessel. To see how the new designs are positioned compared to proven vessels, a comparison is made to FPSOs, which have a comparable operational pattern of a future deep seabed mining vessel. The main dimensions of the three designs are plotted towards the deadweight in Figure 9.

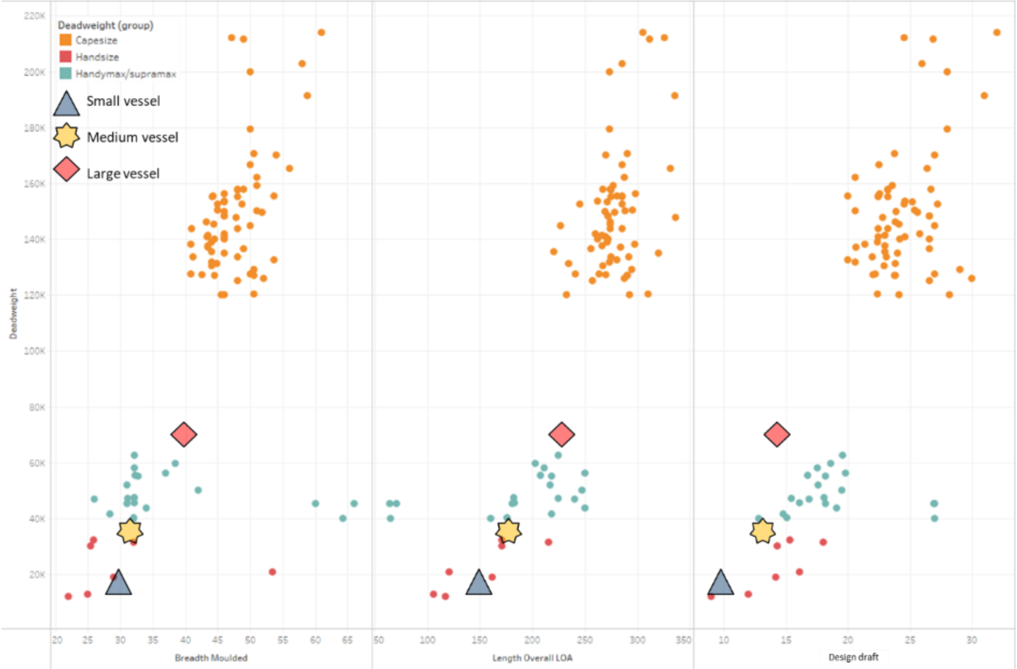


Figure 9: Hull characteristics of vessels compared to various FPSOs. Reference vessel data from IHS Fairplay.

The small vessel is positioned in the handysize segment of vessels, while the medium-sized vessel is between handysize and supramax for all parameters. The large vessel is positioned higher than most supramax FPSOs, which is as expected, considering that more space, payload, and deck load than a traditional FPSO would need. The value of the design draft is smaller than that of the FPSOs – which is surprising, since one would think that more room below deck is necessary. To investigate the main dimensions further, we map out the results compared with bulk carrier solutions, where the length/beam ratio and length/depth ratio is plotted towards the deadweight, see Figure 10.

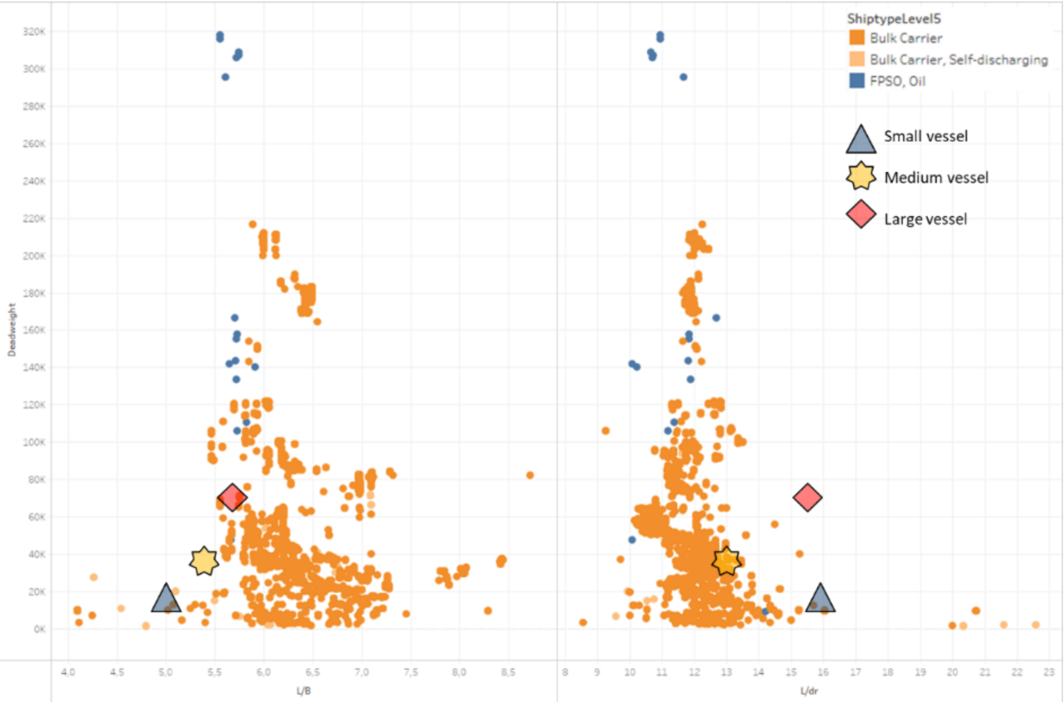


Figure 10: Length/beam ratio and length/draft ratio of the three designs compared to bulk carriers, self-discharging bulk carriers, and FPSOs. Reference vessel data from IHS Fairplay.

Mining vessels are relatively low in length/beam ratio compared to most bulk carriers. This fits well with the compact design strategy of our mining ship solution. The vessels do however have a high length/draft ratio which might indicate that the vessel should in fact go deeper into the water than they do.

With the information from FTCDA, the commercial performance by means of LCOM can be calculated for each vessel. A hypothetical project of 20 years production was assumed, with a discount rate of 12% (Ellefmo 2022). Any investments (CAPEX) along the 20-year lifecycle, such as new equipment or purchase of spares, is assumed to add to 10% of the initial total CAPEX during the 20-year lifetime. Maintenance costs of 60 MUSD/y is assumed based on a max estimation of a deep seabed mining project (Vrij and Boel 2020). Days of operation on a yearly basis is set to 200. LCOM is plotted toward the mining vessel design solutions' newbuild costs in Figure 11.

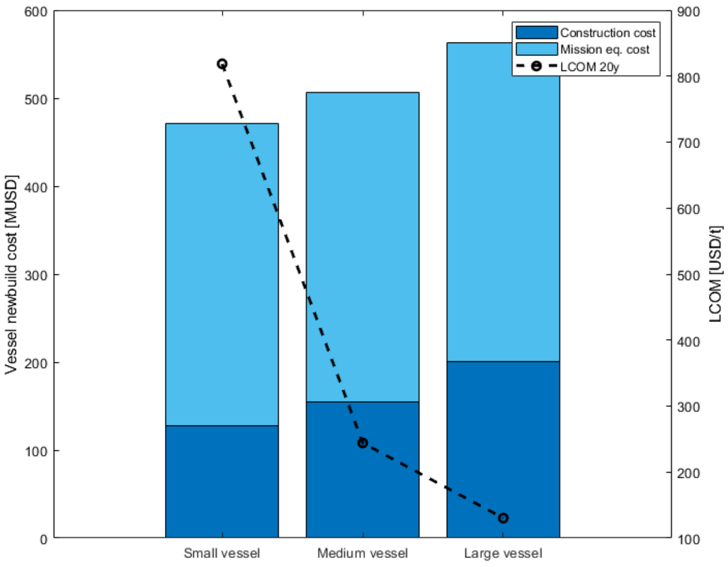


Figure 11: Newbuild cost versus a simplified LCOM for the three vessels.

The vessel newbuilding cost is lower for the smaller vessels than the larger vessels, and this difference is mostly reflected in the added construction costs when increasing size. The mission equipment cost is fairly similar for all vessels, and it is by far the highest portion of the newbuild cost. The vessels do have different production rates, and this is seen in the LCOM. The LCOM of the small vessel is notably higher for the small vessel than for the medium and large vessels. This is an indication that the production rate just does not keep up with the incurred costs. This economies of scale effect must be utilized if the mineral resources and mine site allows.

DISCUSSION

This paper has presented the design process of a novel ship design for deep seabed mining operations. Technology from offshore oil and gas was used to create three mining vessels which contributes to the literature arguing that technology transfer from offshore oil and gas to deep seabed mining is promising. The results give a picture of the relative differences of various vessel design solutions.

The larger vessel has the highest CAPEX, but it turned out to be favourable in terms of stability and production rates. To a ship owner, the added cost might be worthwhile the investment to achieve a more robust ship with more workspace on deck and space under deck for equipment. This is not surprising, as it is often the case that a bigger ship costs relatively less than a small one measure by its performance. In all cases the total mission equipment cost is significantly higher than the construction cost, which also justifies a bigger vessel from the ship owner/operator’s perspective.

Some costs were not reflected in the LCOM calculation. This includes the processing costs after reaching shore, as well as waste handling offshore. Larger vessel will have bigger processing cost and bigger production. Processing comes with additional costs, but also maybe additional revenues – depending on the attractiveness of the product. The processing regime is essentially a trade-off between the cost of processing and net smelter return. To retrieve ‘everything’ will cost a lot. The complete set of costs must be included in order to get the true LCOM. Furthermore, a higher discount rate might be considered in order to truly reflect the risks of such ventures (Ellefmo 2022).

Another discussion point is economies of scale mentioned above. The 20-year lifecycle was chosen to assess the LCOM on a project basis. However, this is only possible if the resource potential at the site is abundant and available to extract economically for several years’ time. The characteristics of these deep sea deposits, such as their metal contents and grade, is still very uncertain as of today. The results show that it is still important to keep a certain throughput through the system – otherwise investment into a full-scale deep seabed mining venture is difficult to justify.

CONCLUSION

This paper reflects and discusses some of the more critically important aspects of the ship design process of a novel vessel for deep seabed mining operations. The business case for such operations is outlined, and a fast-track conceptual design approach arriving at three alternative mining vessel design solutions was carried out. The results show that a larger vessel has favourable stability and capacities, allowing a higher production rate and contrasted strong effect on the levelized cost of mining.

This paper has shown that when examples of reference basis vessels are short or non-existing, it is very important to identify the most relevant reference vessel segment and explore supporting documentation for a novel ship design concept coming from that segment. The ABD and FTCDA approach and design method proved to be very effective in conceptualizing vessel design solutions for the ocean space, in this case particularly a deep seabed mining system and its complimentary logistics solutions. Ship functional models are imperative to use and explore before final design solutions are worked out.

The steps of the business case identified factors that are critical to the project’s commercial viability. Above all, economies of scale, resource availability, and seasonality influence the vessel’s revenue-making capabilities to a great extent. These are just some of the factors that must be accounted for when designing the vessel. The resulting strategy – to keep the special equipment on the mining vessel and keep it producing – had a direct effect on the engineering tactics and marine systems design configuration. This paper shows how important it is to carefully think through the business case before embarking the marine systems design process.

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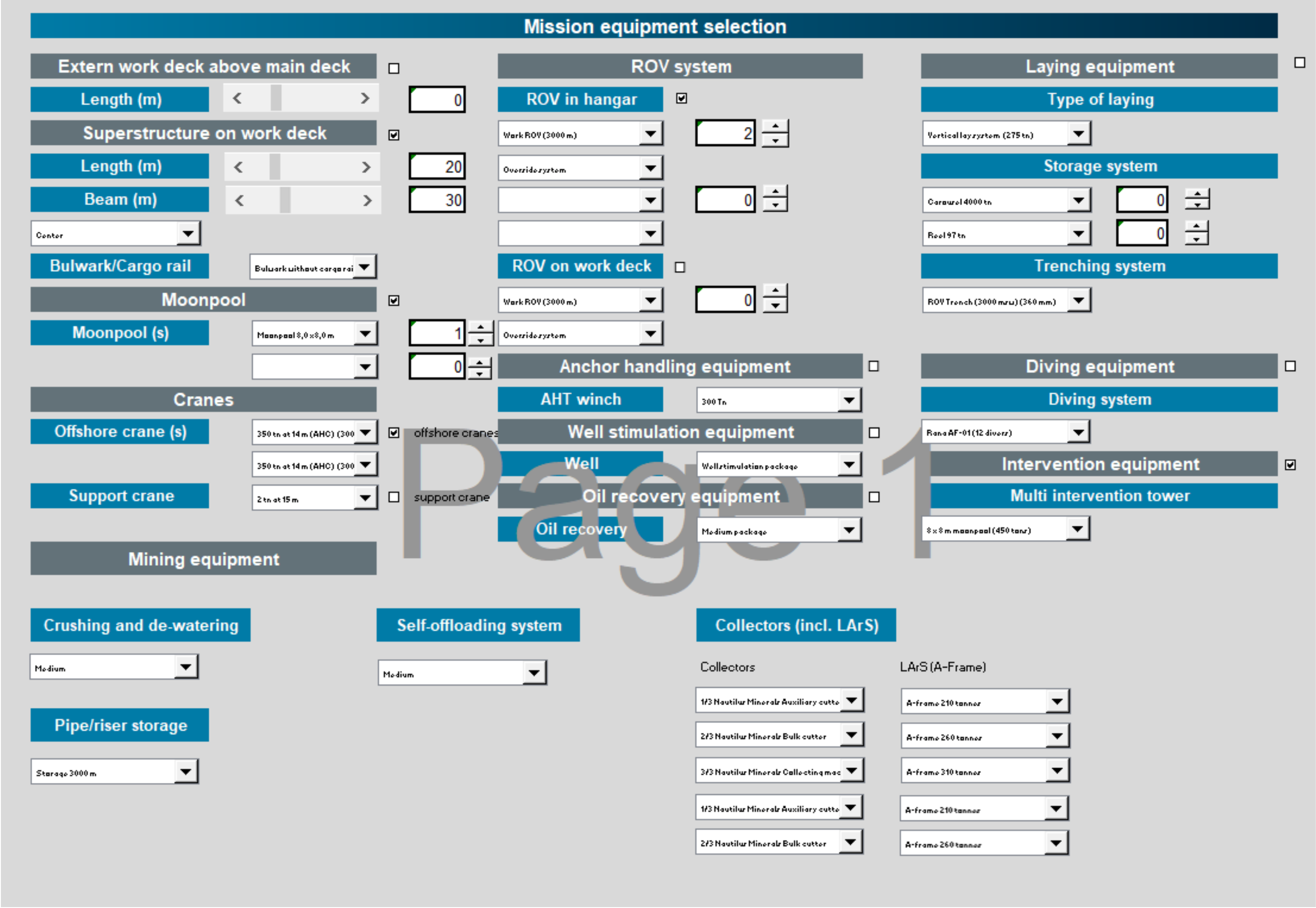
APPENDIX A



Mission equipment selection

Extern work deck above main deck ☐
Length (m): 0

Superstructure on work deck ☑
Length (m): 20
Beam (m): 30
Center

Bulwark/Cargo rail: Bulwark without cargo rai

Moonpool ☑
Moonpool (s): Moonpool 8,0 x 8,0 m — 1
0

Cranes
Offshore crane (s): 350 tn at 14 m (AHC) (300 ☑ offshore cranes
350 tn at 14 m (AHC) (300
Support crane: 2 tn at 15 m ☐ support crane

Mining equipment

Crushing and de-watering: Medium

Pipe/riser storage: Storage 3000 m

Self-offloading system: Medium

Collectors (incl. LArS)

Collectors	LArS (A-Frame)
1/3 Nautilus Minerals Auxiliary cutte	A-frame 210 tonnes
2/3 Nautilus Minerals Bulk cutter	A-frame 260 tonnes
3/3 Nautilus Minerals Collecting mac	A-frame 310 tonnes
1/3 Nautilus Minerals Auxiliary cutte	A-frame 210 tonnes
2/3 Nautilus Minerals Bulk cutter	A-frame 260 tonnes

ROV system
ROV in hangar ☑
Work ROV (3000 m) — 2
Override system
0

ROV on work deck ☐
Work ROV (3000 m) — 0
Override system

Anchor handling equipment ☐
AHT winch: 300 Tn

Well stimulation equipment ☐
Well: Well stimulation package

Oil recovery equipment ☐
Oil recovery: Medium package

Laying equipment ☐
Type of laying: Vertical lay system (275 tn)
Storage system: Carousel 4000 tn — 0
Reel 97 tn — 0
Trenching system: ROV Trench (3000 msw) (360 mm)

Diving equipment ☐
Diving system: Rana AF-01 (12 divers)

Intervention equipment ☑
Multi intervention tower: 8 x 8 m moonpool (450 tons)

Figure 12: The adapted and expanded FTCDA tool.