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REGULAR ARTICLE

Assessment of expected production of a deep-sea mining system: An integrated model-based systems engineering and discrete event simulation approach

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Abstract

In this paper, model-based systems engineering (MBSE) and discrete event simulation (DES) are combined to assess the performance of an offshore production system at an early stage. Various systems engineering tools are applied to an industrial case concerning the retrieval of deep-sea minerals, and a simulation engine is developed to calculate the annual production output. A mean production of 1 Million tonnes of ore per year is estimated for an operation in the Norwegian Sea using Monte Carlo simulation. Depending on the limiting design wave height of the marine operations, the estimated production output ranges from 280,000 tonnes to 1.8 Million tonnes per year. The constrained parameter of the production system is particularly the wave height operational limit of the ship-to-ship transfer operation. We present the learning outcome from applying MBSE and DES to this case and discuss important aspects for improved performance.

KEYWORDS

deep-sea mining, discrete event simulation, expected production, model-based systems engineering, Monte Carlo

1 | INTRODUCTION

An offshore production system requires a sequence of operations to achieve the desired performance.[1] Marine systems design of emerging, industrial systems may be challenging as there is limited operational experience and limited information to draw from similar systems. Production systems in offshore industries, such as oil and gas, aquaculture, and offshore wind, are typically large-scale, cost-intensive, and involve many stakeholders. Increasing the knowledge about such systems at an early stage is important in order to identify constraining parameters and potentially reduce costs and improve performance.

One emerging offshore industry is deep-sea mining: a potential provider of raw materials to the global mineral supply chain. Deep-sea mining concerns the extraction of minerals from a deep marine subsea deposit and making them available for further processing and refining to obtain saleable products.[2] There is no known deep-sea mining system in operation yet, although several concepts have been proposed. One of the companies that has been closest to a commercial realization of a full-scale deep-sea mining operation is Nautilus Minerals. They intended to commence production of seafloor massive sulphides in the Bismarck Sea near Papua New Guinea at 1600 m water depth, but the project came to a halt before deployment.

This article aims to understand and assess the annual expected production of a virtual industrial deep-sea mining system. The approach combines model-based systems engineering (MBSE) and discrete event simulation (DES). MBSE is applied to understand the behavior of the system and its requirements, while DES is conducted to understand how well these requirements are met. To examine the effect of uncertainty, Monte Carlo simulation is performed - a common method to assess the behavior and value of systems.[3] The philosophy of this study may be applicable to many marine system designs of the deep-sea mining system, but the focus here will be on the Nautilus Minerals case as it is the most publicly disclosed system but applied in another ocean region.[4–7] The chosen location is the Norwegian extended continental shelf, where the Norwegian Government has initiated a regional environmental impact assessment as part of an opening process for potential exploration and mining activities.[8]

2 | METHODOLOGY

The economic performance of a deep-sea mining system is linked to its ability to produce continually, which in turn is determined by the capacities of each sub-system, how they relate, and also the negative influence of any downtime.[2] The complexity of this topic, along with the limited information, turns the attention to relevant methods for developing models to design offshore production systems and how well they provide insight. Traditional systems design methods, where requirements are decided upon early in the design process, are increasingly regarded as too rigid. According to the editorial of *Systems engineering 20th-anniversary special issue*[9]: "Systems are no longer just conceived, designed, implemented, and operated in a linear fashion to satisfy stakeholder needs. They are ever-changing, coalescing into systems-of-systems driven by dynamic technological, economic and political forces, and they require us to constantly reassess, upgrade, and evolve them over time". When dealing with complex industrial systems, it is necessary to carefully think through the modeling process.[10] Bringing a modeling framework into the engineering process means that the entire engineering problem is considered while keeping an efficient and consistent process from the start.[11]

Models of technical systems have two distinct purposes: (1) support learning and communication among stakeholders (pragmatic models), and (2) support computer-based simulations and calculate performance indicators (formal models). Both developing pragmatic models and formal models are essential parts of a systems design process.[10] The traits of MBSE make it a major advantage when solving systems design problems.[11] MBSE supports the development of pragmatic models, while formal models are needed for calculation and simulation. Describing the behavior of a system by means of discrete events is the most suitable mathematical framework due to its appropriate level of abstraction. A discrete event system can be interpreted as a representation of a system which is in a certain state and only changes state when a significant event occurs.[10] Change of state is caused by a triggering condition, which may be comprised of one or several circumstances that must take place. If the triggering condition does not take place, the system stays in its current state, and such behaviors might identify weak links or bottlenecks which need further improvement. For marine systems design applications, DES has been found to be a favorable technique with its low computational cost and flexibility in terms of fidelity level.[12] Our two-fold approach starts with the MBSE tool used to support the building of the model, and then the simulation engine used to execute the model.

The model of the Nautilus system has been designed in Sigma language and in the WorldLab Wizard environment. Sigma is an object-oriented modeling language dedicated to system modeling and simulation. It belongs to the S2ML+X family.[10] The central idea of languages of this family is that any behavioral modeling language consists of two parts: a mathematical framework in which the behavior of the system under study is described, the X, and a set of constructs to structure the model, S2ML. S2ML stands for Systems Structure Modeling Language.[13] It gathers object-oriented and prototype-oriented primitives that make it possible to structure models and to reflect into the model the architecture of systems. Several modeling languages entering the S2ML+X paradigm have been developed, notably S2ML+SBE[14] that aims at providing a unified framework for combinatorial probabilistic safety analyzes, and AltaRica 3.0 which is probably the most widely used modeling language implementing the model-based approach in reliability engineering.[15] At the time we write these lines, the Sigma language and its associated assessment tools are still under development by Systemic Intelligence® as a joint effort between academia and industry. The mathematical framework of Sigma is the notion of activity algebra. The WorldLab Wizard environment embeds a dedicated text editor, a compiler of Sigma model into executable interactive and stochastic simulators as well as some peripherical tools. It uses also the WIDL (WorldLab Interface Description Language), which is a domain-specific language dedicated to the description of graphical user interfaces. WorldLab Wizard also makes it possible to generate systemic digital twins from Sigma models.[16]

2.1 | Design of model using MBSE

The system architecture framework consists of the following parts[17]:

- System sketch: Describes the key features of the system to communicate to stakeholders the general idea of the technical system.
- Environment diagram: The environment diagram shows the elements which the technical system interacts with. Some interactions might impact the performance of the system more than others.
- Functional architecture: Description of capacities provided by the system, and functions required to provide these capacities.
- Physical architecture: Description of technical components of the system which are the physical objects that exercise the functions.
- Operation modes: Modes of operation during a system's life cycle are identified to help define what services and functions are needed from external systems in different phases. The triggers that cause the system to switch from one mode to another should also be described.
- Use cases: Scenarios for which the system's functioning is analyzed.

2.2 | Executing model using DES

The information from the physical architecture, the functional architecture, the operation modes, and rates and capacities are integrated, and simulation is conducted to evaluate how the system meets these requirements. The simulation framework is a step-by-step algorithm describing the processes of the deep-sea mining operation.

During the planning stage of marine operations, the workable weather window is useful to estimate operability. Important early-stage information may be obtained, such as planning of logistics, process optimization, equipment selection, and input to feasibility studies.[18] A deep-sea mining operation is affected by downtime due to waiting-on-weather (WoW). Thus, the planning of weather-restricted marine operations means taking weather uncertainty into consideration. The planned duration of a marine operation, T_R, can be defined as[19]:

$$T_R = T_{POP} + T_C \tag{1}$$

T_{POP} represents the scheduled operation period and should be based on a detailed, planned schedule for the marine operation. The weather window must include the estimated contingency time, T_C. The weather window, that is, the time period during which it is safe to safely carry out an operation, should be below the maximum or allowable operational criterion, OP_{WF}:

$$OP_{WF} = \alpha \cdot OP_{LIM} \quad , \quad 0 < \alpha < 1 \tag{2}$$

The OP_{LIM} represents the design criterion for load effects like vessel motions and accelerations. The alpha factor, α, represents the relation between the design criterion and operational criterion, estimated based on the weather uncertainty for the site and the planned length of operation.

3 | DESIGN OF MODEL

3.1 | System sketch and environment diagram

The system sketch and environment diagram of Nautilus Minerals can be found in Figure 1.[20] The system sketch shows the many parts of the system that have to function together in order to produce ore. The environment diagram shows some intersecting factors, for example, waves, benthic fauna of the seabed, and wastewater. The diagram is not exhaustive.

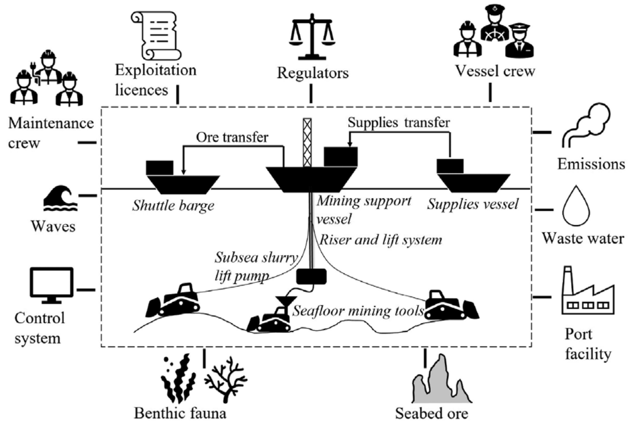

FIGURE 1 The system sketch and environment diagram of Nautilus Minerals. The technical system under study is found inside the dashed lines.[21]

3.2 | Functional architecture

The functional architecture for Nautilus Minerals is shown in Figure 2. Ore extraction is the first activity in a steady state production. The type of resource found on the Norwegian extended continental shelf requires cutting, as the resources are lithified (solid rock). With

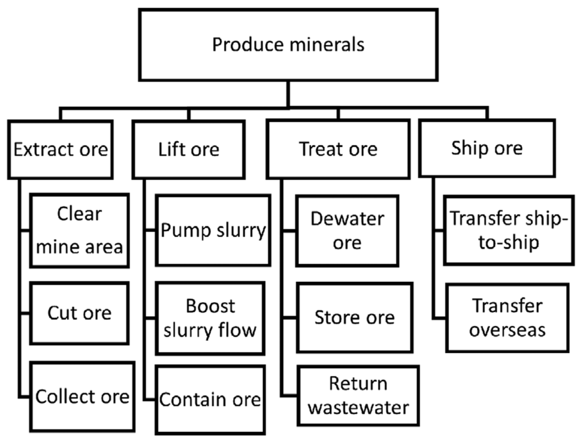

FIGURE 2 Functional architecture of the material flow in offshore operations during exploitation.

chimney-like formations, it might also be necessary to clear and level out the mine area before bulk production. Finally, it is necessary to collect the stock. The Nautilus Minerals concept had two seafloor-going machines doing the cutting and another machine doing the collecting work. The collecting operation is critical as it requires integration with the submersed pumps. Given sufficient feed from the collector, the ore is lifted as a slurry (water/rock mix). Onboard the mining vessel, the ore is dewatered to get rid of the excess water. These tailings (or wastewater) need to be returned in the water column. Regulations are not yet in place regarding how deep this should take place, but return pipes will be needed. Due to the remoteness of the mineral deposits and offshore sites, ship-to-ship (STS) transfer of ore was chosen by Nautilus Minerals to maximize the operational hours of the mining vessel.

3.3 | Physical architecture

The physical architecture for Nautilus Minerals is shown in Figure 3. The seabed production tools are track-mounted cutting tools. The

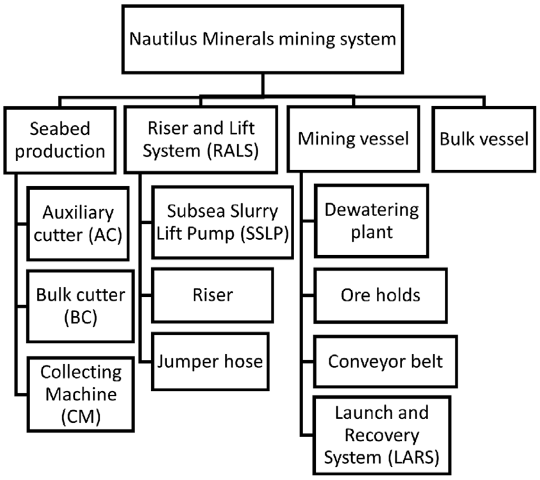

FIGURE 3 Physical architecture of Nautilus Minerals.

primary purpose of the auxiliary cutter (AC) is to prepare suitable platforms for the bulk cutter (BC) by removing chimneys and sediments as well as cutting benches and stockpile areas.[22] The BC serves as the main production unit on the seabed. The auxiliary BC and the main BC deliver fragmented rock to a stockpile simultaneously. The collecting machine (CM) collects from the stockpile and delivers a slurry mix to the subsea slurry lift pump (SSLP). The SSLP, along with the riser and jumper hose, are part of what is referred to as the riser & lift system (RALS). Power and control come from an umbilical cable from the mining vessel. Onboard the mining vessel, the slurry is dewatered, stored, and later transferred to a transportation ship using a conveyor belt. Further, Nautilus Minerals' mining vessel was designed for a maximum storage capacity of 39,000 tonnes. The slurry mix was going to contain 12% solids and 88% seawater. After dewatering, the wastewater is returned close to the seafloor via tubes clamped to the riser (auxiliary pipes).[22] The jumper hose is a flexible hose connecting mining vehicles with the riser-based vertical transport system. The launch and recovery system (LARS) was intended to be used to recover seafloor mining tools by using three A-frames mounted on deck. The decomposed physical architecture elements do not match decomposed functional architecture elements one-to-one. The functional and physical architecture mapping is provided in Table 2.

3.4 | Operation modes

The deep-sea mining operation covers steady state production (useful life period), meaning that mine ramp-up and end-of-life activities, such as levelling chimneys, are not included. The implication of this is that increased failure rates due to undiscovered defects (early phase) and wear-out (late phase) are not accounted for [23]. The following operation modes are included:

- Mode: {Launching; Operation; Recovery; Maintenance}
- State: {Operation; Standby }
- Location: {Port; Transit; Site}

TABLE 1 A use case for ship-to-ship transfer.

	Description
Pre-condition	Continuous production; Mining vessel signals need for ship-to-ship transfer
Post-condition	Collecting machine is forced to stop production
Trigger	Fully loaded cargo holds on mining vessel
Story	1. Cargo holds are filling up at the mining vessel, and it is time for unloading of ore to bulk vessels
	2. Bulk vessel arrives at the offshore location, and crew onboard mining vessel prepares for mooring
	3. Mooring is delayed due to waiting for acceptable weather conditions
	4. Cargo hold onboard the mining vessel has reached the maximum limit
	5. The capacity constraint onboard the mining vessel forces the riser & lift system to stop its flow output
	6. The collecting machine must stop its flow output to the riser & lift system

The duration of the mining operations is determined by each sub-system's mean time between maintenance (MTBM). The recovery and launching are events triggering the maintenance and operation, respectively. If the maintenance or operation cannot start due to weather conditions, they will serve as standby modes - updating the weather forecast every 6 h in this simulation. The standby mode occurs with any sub-system waiting for permission to start its operation. This could be a sub-system waiting for the previous sub-system to finish its operation, or waiting for the next sub-system to have the required capacity to accept the ore. It may also be linked to waiting for acceptable weather conditions (WoW).

Some systems are assumed to be maintained when they are not operational, and as such, their maintenance does not represent any additional downtime. This includes the conveyor belt and the dewatering system. The conveyor belt is only used sporadically and is usually on standby and operational on demand. The dewatering system is maintained when the plant is not utilized, such as when the CM or RALS are not operating. The RALS is maintained four times a year with a maintenance time of 24 h, where the riser string is raised through the moonpool of mining vessel.[22]

3.5 | Use case

The CM, STS transfer and RALS have previously been identified as particularly sensitive sub-systems regarding yearly ore production.[24] In this paper, we describe a use case related to the STS transfer. A challenge for STS transfer is that it must be realized in less time than the mining vessel is being loaded, and preferably significantly less as a practical requirement so that one does not need a vessel always connected. The proximity of vessels during the transfer is challenging, and an acceptable weather window is needed during the transfer. This leads to the use case found in Table 1.

TABLE 2 Production rates by the various systems. The performance characteristics of systems with an asterisk (*) are not known, but have been estimated based on [22, 25]. All outputs, except auxiliary pipes, are stated in the *dry* ore form.

Functions	Physical Systems	Operation Mode	Output
Clear mine area; cut ore	Auxiliary cutter (AC)	Continuous operation	470 t/h
Cut ore	Bulk cutter (BC)	Continuous operation	470 t/h
Collect ore	Collecting machine (CM)*	Continuous operation	470 t/h
Pump & boost slurry	Riser & lift system	Continuous operation	330 t/h
Dewater ore	Dewatering system	Continuous operation	2,840 t/h
Return wastewater	Auxiliary pipes	Continuous operation	2,500 t/h
In-hold storage	Mining vessel ore holds	-	-
Ship-to-ship transfer	Conveyor belts*	On demand	5,000 t/h
Oversea transfer	Bulk vessel x2	On demand	25,000 t/batch
Launch/recover SMTs	Launch & recover system (A-frames)	On demand	-

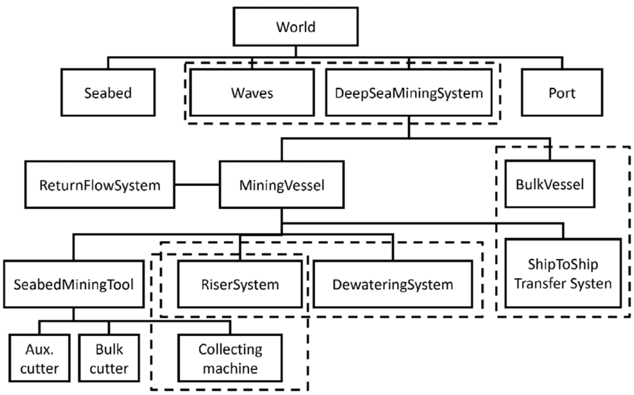

FIGURE 4 The formalized model used for simulations. The systems with boundaries have significant dependencies.

4 | SIMULATION ENGINE

The systems engineering tools were integrated with the output data to form the simulation engine, see Table 2. The variation of the mean production is shown by the standard deviation (σ). To ensure both randomness in executions and reproducibility in Monte Carlo simulations, the analyst can set up the seed of the random number generator at the beginning of simulations: two simulations starting with the same seed unwind in the exact same way and consequently give identical results. The resulting architecture of the simulator is found in Figure 4. The surrounding environment is the seabed, waves, and home port for discharging the minerals cargo, while the technical systems are divided into two main elements: mining vessel and bulk vessel. The physical architecture is reorganized accordingly, with the seabed mining tool further decomposed into AC, BC, and CM.

Every action, or event, has a discrete duration triggered by some condition, see Table 3. These events relate to the transportation or consumption of the ore in the production system, see flowchart of material flow in Appendix: Figure A1. The parts of the system that are modeled stochastically are the mining efficiencies, transit times, and the mean time between maintenance. The weather also constitutes a stochastic parameter, but its input to the simulator is deterministic in the form of binary decision variables to start up weather-restricted operations. The wave modeling is explained in the third subsection of this chapter.

4.1 | Seabed and home port

The seabed and home port constitute two important interfaces for the technical system: the starting point and end point of the ore stock. The port is assumed to have the capacity to retrieve all ore, any amount at any time. In other words, no limitations in any land-based facilities. The seabed is assumed to be abundant and available for extraction in a 1-year production cycle. Also, modeling the seabed topography, slope, and other inherent qualities is deemed outside the scope of this paper. However, these characteristics do affect the production efficiency of the seabed mining tools, and the modeling of this efficiency is explained next.

4.2 | Deep-sea mining system

The maximum performance production rates of the seabed mining tools are set to 470 tonnes per hour. The productivity of the AC and BC are stated to vary between 30% and 100%, including planned maintenance schemes and bad weather.[22] As no further information is given, we have assumed that the uncertainty in the extraction efficiency for the AC is uniformly distributed between 40% and 60%, and for the BC is uniformly distributed between 75% and 100%. Further, the tonnage of cut ore, T_{cut}, is calculated as:

$$T_{cut} = \eta_{cut}[-] \cdot r_{cut}[t/h] \cdot t_{cut}[h] \tag{3}$$

where η_{cut} is the individual extraction efficiency of the two individual BCs, r_{cut} is the extraction rate, and t_{cut} is the extraction duration per event. All other sub-systems follow a pattern of calculating the ore stock from the production rate of that system and its duration per event, constrained by their maximum capacities.

TABLE 3 A comprised list of events, triggering conditions, and duration of the simulator.

Events	Triggering Conditions	Duration
AC/BC operation	AC/BC launch is complete	240 hrs (mean)
CM operates	CM launch is complete AND *if* RALS is available AND *while* cut ore stock ≥ 0	240 hrs (mean)
AC/BC/CM launch/recovery	*If* AC/BC/CM operation/maintenance complete AND waves ≤ threshold during $T_{R,SMT}$	4.5 hrs
AC/BC/CM maintenance	AC/BC/CM recovery complete	8 hrs
RALS lifts ore	*If* CM ore stock ≥ 0 AND *while* available MV storage	2,190 hrs
RALS launch/recovery	*If* RALS operation is complete AND waves ≤ threshold during $T_{R,RALS}$	34 hrs
RALS maintenance	RALS recovery complete	24 hrs
DW dewaters raw ore	*If* RALS ore stock ≥ 0	24 hrs
Wastewater return from DW	*If* water from DW ≥ 0	24 hrs
BV transits from port to site	*If* dewatered ore onboard MV ≥ 1,000 t AND *if* BV cargo hold == 0	$\frac{400[Nm]}{vessel\ speed[kn]}$
Ship-to-ship transfer	*If* waves ≤ threshold during $T_{R,STS}$ AND *while* dewatered ore ≥ 0 AND *while* ore transferred ≤ BV capacity	4.5 hrs
BV transits from site to port	*If* BV reached storage capacity	$\frac{400[Nm]}{vessel\ speed[kn]}$
BV unloads ore at port	*While* BV cargo hold ≥ 0	4.5 hrs

Abbreviations: AC, Auxiliary Cutter; BC, Bulk Cutter; BV, Bulk vessel; CM, Collecting Machine; DW, dewatering system; MV, Mining vessel; RALS, Riser & lift system.

Limitations of the storage capacity might be an issue, as seen in the use case in Table 1. Storage limitations also apply to the shuttle bulk vessel, which had a storage capacity of 25,000 tons in the Nautilus Minerals case. Therefore, a buffer is desirable, and a capacity utilization factor is added in the code. The mining vessel has a storage capacity of 80% of the real capacity. The bulk vessels have a storage capacity of 90% of the maximum capacity. Two shuttle bulk vessels will be used.[26] They have a speed uniformly distributed between 12 and 14 kn.

4.3 | Wave modeling

The system is exposed to weather conditions from the Norwegian Sea. Time series for significant wave height of 3 h interval is found in Figure 5.

The limiting wave height of a marine operation is determined by the motions that can be handled. The significant wave height of the specific mine site is the design criterion in this paper, based on Equation (2):

$$H_{s,op} = \alpha \cdot H_{s,d} \tag{4}$$

There is no available information about the maximum design wave heights of the Nautilus Minerals' equipment, so these are both estimated from literature and scenario-tested. The capability to perform a task depends on the vessel - it could be $H_{s,d} = 2.5$ m for one vessel and $H_{s,d} = 4.0$ m for another.[28] The duration of the quarterly retrieval of the RALS, including contingency time of $T_C = 2 \cdot T_{POP}$, has been set to 68 h.[24] Since our wave data set has a resolution of 3 h, we test a reference time of $T_{R,RALS} = 23 \times 3\text{ h} = 69$ h. The design wave height of this operation is not stated, but similar types of operations have stated a design criterion of $H_{s,d} = 3.7$ m.[29] In this paper, we test $H_{s,d,RALS} = 3.5$ m and $H_{s,d,RALS} = 4.5$ m.

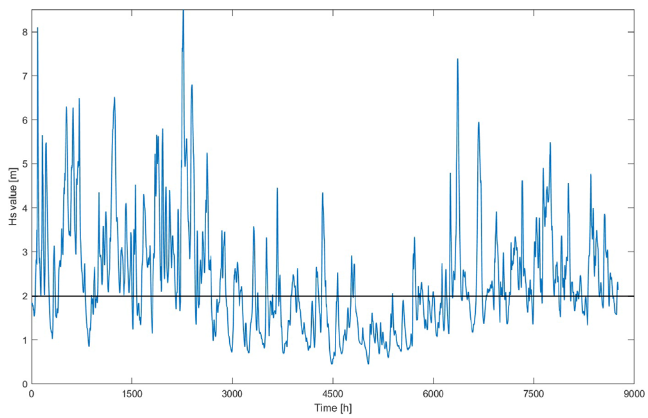

FIGURE 5 Hindcast time series for significant wave height (Hs) in the Norwegian Sea during the year 2021. A 2 m maximum threshold is included for illustration purposes. Generated using Copernicus Climate Data,[27] accessed 2022-08-19.

There is limited information about the STS transfer operation of Nautilus Minerals. The total duration of this type of operation depends on the amount of dewatered ore to be discharged, the unloading rate, and the duration of additional activities related to the start-up and finalization of the operation. A side-by-side STS transfer operation may start by preparation of equipment (1 h), approach (1–2 h), mooring (1 h), and connecting (1–2 h). In an example of liquid cargo transfer, the transfer operation itself may take 10–12 h. The disconnecting, unmooring, and departure take about 2 h. From this example, it is seen that one can expect about 6–10 h of related activities apart from the transfer itself, which must be accounted for literature[30]. Previous work on preliminary ship design of a mining vessel has identified an unloading rate of 5000 t/h to 8000 t/h for a system producing around 3 Million tonnes per year. This gives a duration of 12–18 h total.[31] The amount

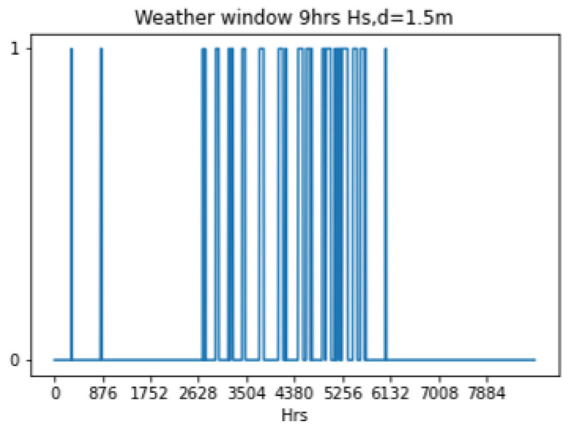

FIGURE 6 A 9 h weather window with $H_{s,OP} = 1.1$ m for 2021. Generated using Copernicus Climate Data,[27] accessed 2022-08-19.

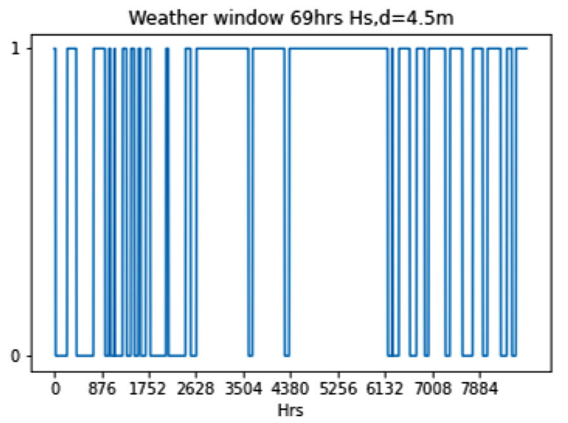

FIGURE 7 A 69 h weather window with $H_{s,OP} = 3.8$ m for 2021. Generated using Copernicus Climate Data.[27].

to be transferred per operation is constrained by the vessel with lowest capacity, in our case the bulk vessel. We set the unloading rate of 5000 t/h and $T_{POP,STS} = 16$ h. With a contingency time of 50%, this gives $T_{R,STS} = 24$ h.

The launch and recovery time of mining tools is calculated assuming a descent and lift speed of $v = 0.5$ m/s.[25] For a water depth of 2400 m,[32] the duration becomes 1.33 h. Additional activities are set to take 3 h, we set $T_{POP,SMT} = 4.5$ h. With a 50% contingency time, we get $T_{R,SMT} = 6.8$ h. The available wave height data set has intervals of 3 h, so we check for a 3×3 h $= 9$ h window for the launch and recovery of mining vehicles, respectively.

The information about hindcast wave heights, design wave heights, and duration pave the ground for the wave modeling, which is done as follows: The weather window is calculated based on the design wave height for the marine operations with a predefined duration. This is checked towards the wave data set, and a new data set with decision information is made based on the criteria in Equation (4). A binary value tells whether the operation may start or not. Whenever the marine operation is triggered, the simulator calls this data set at the corresponding time of year, and the event may begin if the element has a value 1. A separate data set is made for each design wave for each weather-sensitive event, with the events being the mining tool maintenance, STS transfer, and RALS maintenance. In total, this becomes eight data sets. Examples of the data sets are found in Figure 6 and Figure 7.

A binary value (yes/no) informs whether an operation has permission to start, given the significant wave height (Hs) at the site, the design criteria of the technology, and the duration of the marine operation. If there is a request for start-up of an operation, it will proceed if the value at the specific time of the request is 1. Should, for instance, the launch of the BC take place at 1752 h (= 73 days) into the year, it will *not* be allowed to start up this operation as there is no available weather windows at that time. Similarly, if the quarterly retrieval of the riser and lift system takes place at 5256 h (= 219 days) into the year, it will have permission to start this operation. It is assumed that the vessels will not operate in extreme weather conditions. This represents a source of downtime which must be accounted for. The simulator checks every 6 h whether the next 48 h fulfil $H_s \leq 6$ m. If this condition is not fulfilled, the mining vessel will not operate, and in practice, it will have at least 42 h for emergency relocation. Similarly, the bulk vessel will not leave port when this condition is not fulfilled.

5 | SIMULATION RESULTS

The simulations are conducted for one year at a time (8760 h), and we run $N = 10,000$ Monte Carlo simulations for each scenario. The annual mean production of the deep-sea mining system given various likely design wave heights is shown in Table 4. The data on the base case is found in Table 2, and in addition we have: $H_{s,d,SMT} = 2.5$ m, $H_{s,d,STS} = 2.5$ m, $H_{s,d,RALS} = 4.5$ m, and $MTBM = 240$ h for all seabed miners. In this base case, the mean production of the mining system of Nautilus Minerals is just over 1 Million tonnes per year. If there were no weather restrictions on marine operations, the highest theoretical production would be just under 2.5 Mt per year. This shows that deep-sea mining production is, in fact, significantly constrained by waves in the Norwegian Sea.

Case 1 studies the effect of reducing allowable design wave heights. A reduction in design wave height to 3.5 m for maintenance of the RALS in case 1*a* did not affect the annual production. When studying cases 1*b*/*c*/*d*, it is seen that various combinations of design wave heights of $H_{s,d} = 1.5$ m ($H_{s,OP} = 1.1$ m) reduce the mean annual production by up to 74%. This is not surprising since, looking back at Figure 6, there are hardly any weather windows in Q1 of that year. This means that the seabed mining tools cannot be launched or recovered, and STS transfer is delayed for more than 100 days into the year. Similarly, the last day of any 9-h weather window is mid-August, which would only be acceptable if aiming for seasonal production. The variable that points out is the $H_{s,d,STS} = 1.5$ m, which seems to worsen the production significantly. Case 1*b* shows that the production might suffer less if the design wave height of STS transfer is increased to $H_{s,d,STS} = 2.5$ m. The results indicate that design wave heights for STS transfer should be $H_{s,d} = 2.5$ m as a minimum requirement for a continuous all-year operation in the Norwegian Sea.

TABLE 4 Simulation results for different wave height criteria. A case with no weather restrictions shows the highest theoretical yearly production.

	SMT maint.	STS transfer	RALS maint.	Mean prod. p.a.	σ	σ [%]
$H_{s,d}$ Ideal case	-	-	-	2,460,333 t	51,902 t	2.1%
$H_{s,d}$ Base case	2.5 m	2.5 m	4.5 m	1,064,378 t	34,575 t	3.2%
$H_{s,d}$ Case 1a	2.5 m	2.5 m	3.5 m	1,028,225 t	49,733 t	4.8%
$H_{s,d}$ Case 1b	1.5 m	2.5 m	3.5 m	691,217 t	99,377 t	14.4%
$H_{s,d}$ Case 1c	2.5 m	1.5 m	3.5 m	284,083 t	11,124 t	4.0%
$H_{s,d}$ Case 1d	1.5 m	1.5 m	3.5 m	279,595 t	13,897 t	5.0%
$H_{s,d}$ Case 2a	3.5 m	3.5 m	3.5 m	1,627,107 t	154,956 t	9.5%
$H_{s,d}$ Case 2b	3.5 m	2.5 m	4.5 m	1,070,719 t	33,518 t	3.1%
$H_{s,d}$ Case 2c	2.5 m	3.5 m	4.5 m	1,648,588 t	86,314 t	5.2%
$H_{s,d}$ Case 2d	3.5 m	3.5 m	4.5m	1,799,782 t	57,716 t	3.2%
$H_{s,d}$ Case 3a	1.5 m	3.5 m	4.5 m	847,922 t	139,589 t	16.5%
$H_{s,d}$ Case 3b	3.5 m	1.5 m	4.5 m	284,060 t	11,214 t	4.0%

Note: σ is the standard deviation.
Abbreviations: RALS, riser and lift system, SMT, seabed mining tools, STS, ship-to-ship.

Cases $2a/d$ examine the effect of increased maximum allowable design wave heights of seabed mining tool maintenance and STS transfer. Case 2*b* shows no effect in increasing the design wave height of mining tools maintenance compared to the base case. However, increasing the design wave height of the STS transfer shows immediate effects in the other cases: Adjustments may increase production by up to 60%.

In cases 3*a*/*b*, we wish to study the effect of low/high combinations of design wave heights closer. In case 3*a*, the production does not suffer as much even though the design wave height of seabed mining tool maintenance is $H_{s,d,SMT} = 1.5$ m. This might be explained by the fact that the launch and recovery of seabed mining tools require a relatively short weather window, which allows for a higher number of possible weather windows throughout the year. Case 3*b* confirms the previous tendencies that the design wave height of the STS transfer is a critical parameter.

6 DISCUSSION

This paper has presented the modeling and simulation of an offshore system in an early-stage industry. Scenario-testing of allowable design criteria showed how the application context of technologies affects the producibility. Changes in design criteria of one technology can largely affect the entire sequence of operations, and - ultimately - the annual production and profitability.

The allowable wave limit for STS transfer clearly stands out as a critical parameter for the annual production. When the wave limit is low, the bulk vessels have to spend much time waiting for acceptable weather conditions. The use case in Table 1 was found to be relevant in the DES. When the mining vessel storage fills up, and a shuttle bulk vessel is at the site waiting, the STS transfer operation might be postponed. A backwards cascading effect is that the RALS and CM cannot produce. On the seabed, the auxiliary BC and BC might still be cutting, but then there is a risk of ore stock piling up. Another effect that was seen is that once the STS transfer operation started, the bulk vessel could not always collect all material onboard the mining vessel due to lower storage capacity. This indicates that the bulk vessels were under-specified. Since transportation vessels are the cheaper asset, they should have a higher ore storage capacity than the mining vessel to allow a complete emptying of the mining vessel once STS transfer operation is initiated.

The success of STS transfer is not just a question of allowable wave limits but also the operation and vessel arrangements. Nautilus Minerals opted for using a conveyor belt for this purpose. However, it is uncertain whether this is the ideal technology in the Norwegian Sea due to the waves and the risk of losing the valuable cargo during the transfer. Another suggestion that has been put forward is the tandem offloading using a floating hose - favorable due to its similarities with existing practices in the offshore oil and gas industry.[33] The pros and cons of side-by-side versus tandem transfer were studied in a liquid cargo transfer setting. There is a good proven track record of side-by-side transfer, but tandem offloading can be used in harsher weather conditions because of the larger distance between vessels and easier disconnection and departure in case of emergency.[30] In a deep-sea mining setting, the floating hose technology option would require pumping of the slurry mixture from the mining vessel to the bulk vessel. Again, this requires a dewatering unit onboard the shuttle bulk vessel (or dewatering interface connecting with the bulk vessel) and a watering unit onboard the mining vessel since slurry storage is unlikely. Then water has to be taken from the riser or dewatering plant, and free water must be supplied to the auxiliary pipe. A downside from a commercial standpoint is that an onboard dewatering system requirement means that shuttle bulk vessels would need to be converted, and making them more specialized. This would decrease the vessels' second-hand value in the market.

Another technology choice that can be discussed is the seabed mining tools. A concern in the development of this industry is how to keep the ecologic connectivity intact when humans intervene with industrial systems. It is questionable whether three seabed-going bulldozers is the most gentle approach for the seabed. Others have proposed one miner to cover the three excavation functionalities from Figure 2.[33,34] A wide search for technology options is still needed to ensure that good solutions are found. The use of known or mature technology in a new setting has lead to incidents in the past. Generally, it is necessary to carry out a technology qualification process when introducing new technologies in the offshore oil and gas industry.[35] Even if known technologies from the offshore oil and gas industry are used, deep-sea mining is still a new setting requiring technology development efforts.

The real number of available weather windows varies from year to year. The duration of weather windows is a conservative estimate accounting for uncertainties in marine operations. The alpha factor works by reducing the operational limit, while the contingency factor, T_C, works as a safety factor by adding buffer time for unexpected events. Another conservative estimate was used: the design wave height of the governing activity during the marine operation, that is, the activity with lowest design wave height, has been used to calculate the weather window. This might result in unnecessary downtime if the activities are non-continuous, that is, can be interrupted. This would not have been done in the actual execution of the marine operation, where forecasts are used and tested towards a sequence of activities requiring different operability limits.

There is limited operational experience with deep-sea mining systems and significant uncertainty in the production output presented. In addition to the uncertainty in the underlying assumptions presented previously in the paper, there is also uncertainty in the material losses during the different stages of production. How much material that will be lost is not known yet. The excavation process is influenced by particle size distribution. For vertical transportation, there is the extent of damage to particles during transportation, as well as the amount of water involved. During dewatering, the material losses depend on the choice of dewatering system. The free water can be separated easily, but extracting the valuable finer material from this water is more expensive and depends on the economics of the project. Put differently; there is a risk that valuable metals are sent down with the wastewater.

This simulator is intended as a screening tool during the planning of a deep-sea mining operation. If the results from this early-stage screening are satisfactory, further analyses of the operability and response of the vessel would be needed. The allowable limits of sea states need to include not only H_s but also the wave period, T_p, as it is an essential parameter for floating vessels.[18] Other central environmental parameters are wave direction, wind speed, and wind direction.

7 | CONCLUSION

We have shown in this paper that MBSE and DES can be combined to assess the performance of deep-sea mining systems at an early concept design development stage. The benefits of applying MBSE and DES to the case study was that the system could be properly and systematically understood before building a more detailed model for the simulator. By testing various scenarios, we have shown the versatility of the simulator. The expected production of the deep-sea mining system of Nautilus Minerals was assessed given different scenarios, and results show that the design wave height of the STS transfer operation was critical to the overall production. This analysis is based on yearly production, but such an analysis could also be executed for cost scenarios by including CAPEX and OPEX.

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CONFLICT OF INTEREST STATEMENT

There is no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The wave data of this study are available from Copernicus Climate Data Store. Restrictions apply to the availability of these data, which were used under license for this study. Data are available at https://cds.climate.copernicus.eu/ with the permission of European Centre for Medium-Range Weather Forecasts (ECMWF). The European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains.

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APPENDIX

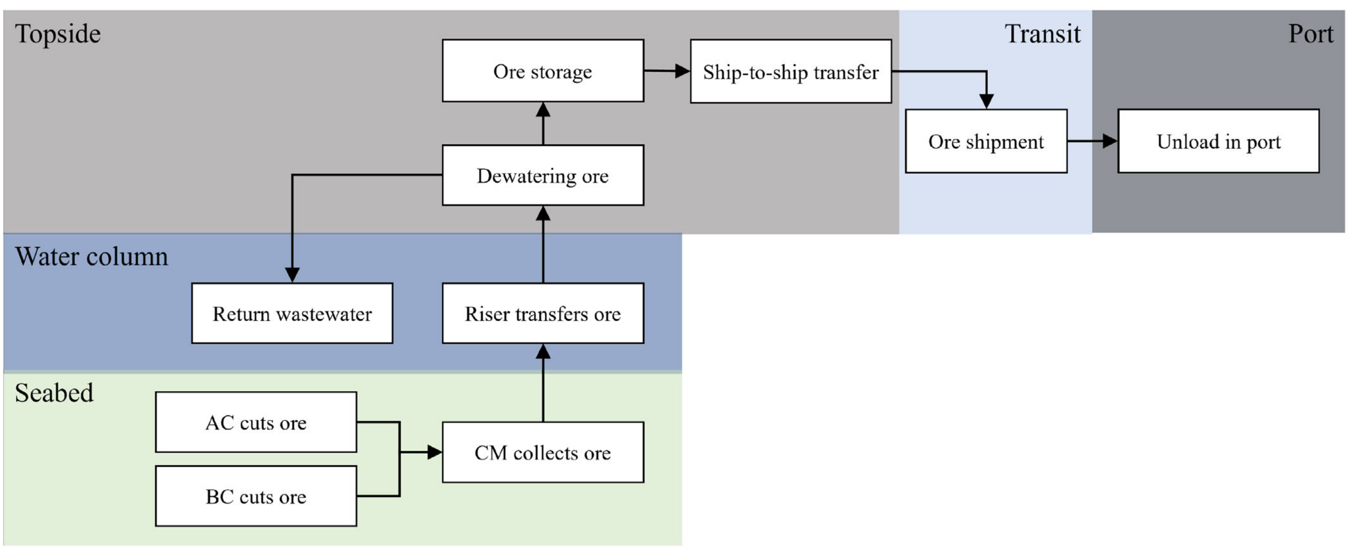

FIGURE A1 Flowchart showing material flows.

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