Exploring Deep-Sea Minerals

Systems modeling for an emerging industry and unknown futures

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Thesis for the degree of Philosophiae Doctor (PhD)
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Scientific environment

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Abstract

Deep-sea mining sparks heated debate. In response to population- and economic growth, as well as to the demands of electrification, technological shifts, and geopolitical turmoil, the world is projected to require a substantially increased and diversified supply of critical minerals. Deep-sea minerals and deep-sea mining have long been considered an alternative resource to established and asymmetrically distributed terrestrial identified mineral resources. However, deep-sea mining entails industrial-scale intervention in a poorly understood environment with equally opaque consequences. This Thesis explores how deep-sea mining may unfold and contributes a basis for qualified decisions and sound policy design in the very uncertain and very urgent realm of deep-sea mining. This is done by first providing a multidimensional problem definition for deep-sea mining. Then, with analysis drawn from stochastic dynamic optimization, underlying reasons deep-sea mining may emerge as an industry are discussed. Finally, based on stochastic System Dynamics modeling and simulation, the Thesis considers how such an industry may unfold on the Norwegian continental shelf and how such an industry may innovate to become robust in an uncertain environment. The Thesis contributes an aggregated, multidimensional, systems-based deep-sea mining problem definition. It contributes models and analysis deciphering the potency of different economic factors that may drive or inhibit a transition towards deep-sea mining. It further contributes a synthesis of the emerging deep-sea mining industry in Norwegian waters, its potential economic framework, and its most auspicious room for innovation and development. The Thesis concludes that deep-sea mining may indeed be encouraged to emerge despite epistemic uncertainty and that there are valid reasons for such emergence. The Thesis further concludes that the emergence of deep-sea mining could prove either profitable or not, depending on innovation policies, geopolitical climatic and environmental priorities, and, most importantly, the qualified navigation of epistemic uncertainty.

Abstrakt

Dyphavsmineraler er et omdiskutert tema. I tilsvar til befolknings- og økonomisk vekst, i tillegg til etterspørselen fra elektrifisering, teknologisk revolusjon og geopolitisk urolighet, er verden forventet å etterspørre en betydelig større, og betydelig mer diversifisert tilgang til kritiske mineraler. Dyphavs mineraler har lenge blitt sett på som en alternativ kilde til veletablerte, men ujevnt geografisk fordelte mineralressurser på land. Samtidig vil uthenting av mineraler i dyphavet kunne bety en industrielt skalert forstyrrelse av et miljø man i varierende grad forstår, og fullt ut kan vurdere konsekvensene av. Denne avhandlingen utforsker og belyser hvordan en mineral-industri på dyphavet vil kunne foregå og bidrar med en basis for kvalifiserte beslutninger og fornuftig politikk-utvikling i den veldig usikre, og veldig tidskritiske sfæren som utgjør dyphavsmineraler. Dette gjøres ved først å fremlegge en flerdimensjonal problem-definisjon for dyphavsmineralindustri, og dernest, med utgangspunkt i stokastisk dynamisk optimering, diskuteres underliggende årsaker for hvorfor dyphavsmineraler kan vokse frem som industri. Avslutningsvis, med utgangspunkt i stokastisk System Dynamikk modellering og simulering av tilfellet «dyphavsmineraler i norsk farvann», vurderer denne avhandlingen hvordan slik aktivitet vil utarte i Norskehavet, og hvor innovasjon og utvikling bør fokuseres for å danne grunnlag for en robust industri i en usikker virkelighet. Denne avhandlingen bidrar med en aggregert, multidimensional, og system orientert problemdefinisjon for dyphavsmineralindustri. Den bidrar modeller og analyse som avkoder effekten av ulike økonomiske faktorer som kan akselerere, eller bremse, en overgang til dyphavs mineraler. Videre bidrar denne avhandlingen med en syntese for mineral industri i Norsk farvann, så vel som et mulig økonomisk rammeverk, og det mest lovende området for innovasjon og utvikling for denne industrien. Avhandlingen konkluderer videre med, på tross av epistemisk usikkerhet, at det er det er tydelige underliggende årsaker for at en mineralindustri på dyphavet vil kunne vokse frem, og at det er rasjonelle argumenter for å understøtte en slik utvikling. Avhandlingen konkluderer videre at dyphavsmineraler kan vise seg både profitabelt eller ikke, og at dette avhenger av innovasjonsstrategi, geopolitiske,

miljømessige og klimamessige hensyn, men først og fremst av evnen til å navigere innen epistemisk usikkerhet.

List of Publications

Title	**Authorship**	**Publication**
Sustainability-oriented innovation: Improving problem definition through combined design thinking and systems mapping approaches *Included as Appendix I	*Lars-Kristian Trellevik (50%)* *Brooke Wilkerson (50%)*	Thinking Skills and Creativity, (2021)
Reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations in mineral industry transition *Included as Appendix II	*Lars-Kristian Trellevik (50%)* *Rasmus Noss Bang (50%)*	Mineral Economics (2022)
Perspectives on exploration and extraction of seafloor massive sulfide deposits in Norwegian waters *Included as Appendix III	*Lars-Kristian Trellevik (50%)* *Rasmus Noss Bang (50%)*	Mineral Economics (2022)
Exploring exploration — how to look for deep - sea minerals *Included as Appendix IV	*Lars-Kristian Trellevik*	Mineral Economics (2023)
The Many Challenges of Deep-Sea Mining *Included as Appendix V	*Lars-Kristian Trellevik*	Systems Research and Behavioral Science (Under Review)

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Contents

1. Background: High-Seas, Deep Waters, Critical Minerals

"In the depths of the ocean, there are mines of zinc, iron, silver, and gold that would be quite easy to exploit."

Captain Nemo, 20,000 Leagues Under the Sea

Our planet is blue. The continuous saltwater bodies of Earth cover more than two-thirds of our planet. The ocean holds 97 % of Earth's water and has an average depth of 3700 meters (Charette & Smith, 2010). Although the oceans constitute our planet's largest geographic feature, they could be better explored. With ocean exploration ongoing, at least since the HMS Challenger expedition in the 1870s, only about 10 percent of the ocean floor has been mapped with a data resolution of 100 square meters (Lusty & Murton, 2018; Toro et al., 2020). The ocean is the Earth's final frontier of exploration (Lusty & Murton, 2018; Sparenberg, 2019). Yet, this is not to say that we have no knowledge of the global seabed.

The "deep ocean" is not a rigorously defined term but can be conceived as ocean depths greater than 200 meters, where little light penetrates, prohibiting photosynthesis. The deep ocean covers about 60 percent of our planet's surface and is home to significant variance of geologies, geomorphologies, and ecosystems. As on land, diversity, along with a dynamic geological and biological history, makes the seafloor a realm of mineral deposition (Hallgren & Hansson, 2021; Lusty & Murton, 2018; Sparenberg, 2019; Toro et al., 2020). This realm, the deep sea, is the part of the ocean most poorly explored and poorly understood. It is, as such, a space on our planet ridden with scientific uncertainty. Yet since the *HMS Challenger* trawled up ferro-manganese nodules from the seabed in the 1870s, the existence of marine minerals has been well established (Bang & Trellevik, 2022b; Lusty & Murton, 2018; Sparenberg, 2019).

Mineral deposits occur on the seabed and are either a result of hydrothermal activity along converging tectonic ocean ridge systems or from slow deposition and accumulation of minerals from seawater on abyssal plains. Different subsea landscapes and oceanographic conditions dictate different depositional environments and, thereby, different depositional categories. There are three main categories of marine mineral deposits: Polymetallic nodules, ferro-manganese crusts, and sulfide massive seamounts (SMS)(Bang & Trellevik, 2022a; Murton et al., 2019; Pedersen et al., 2010; Petersen et al., 2016; Toro et al., 2020).

Polymetallic Nodules are potato-sized and shaped concretions with diameters between 1 and 12 cm spread out over vast areas on abyssal plains and in all oceans. Substantial deposits are found in the Pacific Clarion-Clipperton Zone, the Peru Basin near the Cook Islands, and the Central Indian Ocean Basin. Different nodule fields have different mineral compositions and concentrations, but elements such as copper, cobalt, manganese, nickel, and rear-earth elements are common (James et al., 2013; Hyman et al., 2022). Nodules form and develop over long periods on sedimented seabed where elements propagate on biological or other agents such as shark teeth, bone fragments, shells, or other hard surfaces (Toro et al., 2020). The metal content in the known polymetallic nodule fields is substantial. Hein et al. (2020) postulate that the known marine resources contain more nickel, manganese, and cobalt than all known resources on land, in addition to significant amounts of copper.

Ferro-manganese crusts are hard layers of metallic deposition on hard rockfaces such as ridges, seamounts, and plateaus where currents or slope angles have prohibited deposition of loose sediment (James et al. et al., 2013; Toro et al., 2020). These deposits occur in all oceans and can span several kilometers, varying thicknesses between millimeters and as much as 26 centimeters. Ferro-manganese crusts present at depths between 400 and 7000 meters, but the most significant thickness of such crusts is found in the depth range between 800 and 2500 meters (Petersen et al., 2016; Toro et al., 2020). The ferromanganese crusts contain many elements identified as critical for hi-tech industries and renewable energy generation, such as cobalt, vanadium, cadmium, tellurium, barium, nickel, rear-earth elements, yttrium, and all elements of the platinum group (Haugan & Levin, 2019; Toro et al., 2020).

Sulfide Massive Seamounts (SMS) are mineral deposition in close proximity to hydrothermal vent systems. These deposits are typically relatively small in geographic expanse with geographic expanse of about 200 x 200 meters. Unlike nodule fields and ferromanganese crusts, SMS deposits are three-dimensional deposits where minerals are deposited via and during hydrothermal liquid flow through the seabed and into chimneys protruding on the seabed. This fluid flow is enabled by seawater percolating through porous seabed and then exposed to magmatic heat and mineral enrichment and propelled back towards the seabed (Murton et al., 2019; Pedersen et al., 2021). SMS deposits contain elements such as copper, zinc, gold, silver, gallium, cobalt, barium, rear earth elements, and more, depending on location (Murton et al., 2019; Pedersen et al., 2021; Pedersen et al., 2016; Sahlström et al., 2023).

Although first discovered in the 19th century, serious thought and initiatives towards extraction of deep-sea minerals only date back to the 1960s. J. L Mero's book "*The Mineral Resources of the Sea*" (1965) sparked a veritable gold rush for deep-sea minerals. In this publication, Mero suggested that the sea held practically limitless manganese, copper, nickel, and cobalt deposits in polymetallic nodule fields. Although the calculations were based on merely 101 data points, the resource estimate was widely accepted. In turn, a triple-digit number of research cruises set out to locate the minerals. Mero later, in 1977, expanded the database and suggested both substantial resources in the North Pacific and further predicted that marine mineral extraction could reach industrial maturity in as little as five years (Glasby, 2000, 2002).

Plummeting metal prices and regulatory obstacles imposed by the U.N. Convention on the Law of the Sea (UNCLOS) abruptly halted these initial and ambitious nodule extraction plans. In the mid-1980s, new stakeholders joined the fray, this time with long-term commitment programs and seeking significant subsidies from sponsoring states (Glasby, 2002). In the 1990s, focus also emerged on hydrothermal SMS and crust deposits in converging tectonic ridge areas. Most notable are the efforts and investments made by the private company Nautilus Minerals Inc., which set out to mine the Solwara 1 SMS deposit in Papua New Guinea (PNG). Nautilus obtained a license to prospect and extract minerals within the exclusive economic zone of PNG and invested heavily in exploration, advanced robotic machinery, and surface platforms, and ultimately went bankrupt in 2019 before successfully extracting minerals at an industrial scale (Glasby, 2002; Toro et al., 2020; Trellevik, 2023a)

As mineral resources in international waters do not befall any one state, UNCLOS dictates that wealth from international resources must also befall states not partaking in deep-sea mining (Oyarce, 2018; Rona, 2003). Although UNCLOS was signed in 1982 and went into effect in 1994, the International Seabed Authority (ISA) has yet to establish clear regulations for extraction licenses, as well as a scheme for international redistribution (Glasby, 2000, 2002; Hallgren & Hansson, 2021; Hoagland et al., 2010; International Seabed Authority, 2023).

To date, there has been no successful industrial-scale extraction of deep-sea minerals (Hallgren & Hansson, 2021; Hyman et al., 2022; Trellevik, 2023a). This may, however, change in the not-so-distant future with both ISA and several nation-states advancing regulatory efforts, consequence assessments, and research initiatives in parallel with several private companies investing and developing technology and organizations for deep-sea mining. In Norway the process of opening the Exclusive Economic Zone (EEZ) for mineral exploration and extraction is advancing and the Norwegian parliament is expected to vote on a governmental proposition for an opening-process during the fall session of 2023 (Bang & Trellevik, 2022a; Hvinden, 2023; International Seabed Authority, 2023; Ministry of Petroleum and Energy, 2022a; Oyarce, 2018; Trellevik, 2023a).

1.1 The Epistemic Uncertainty of Deep-Sea Mining

Epistemic uncertainty may be defined as uncertainty arising from a *"…a lack of knowledge about the appropriate values to use for quantities that are assumed to have fixed but poorly known values in the context of a specific study"*(Helton et al., 2010). This Thesis is a deep dive into epistemic uncertainty. It explores how deep-sea mining may unfold, thereby providing a basis for qualified decisions and sound policy design.

As with any study of the future, this Thesis is, therefore, inherently exposed to deep uncertainty.

The deep sea is poorly explored, and there are considerable knowledge gaps pertaining to mineral resources, deep-sea biology and ecosystems, oceanography, ocean-ridge tectonics, and hydrothermal activity (Hyman et al., 2022; Lusty & Murton, 2018; Pedersen et al., 2021). As the knowledge of the deep sea and its various resources, inhabitants, and functions is limited, unknown, and possibly unknowable – any scientific endeavor to understand what the consequences of human intervention might be must be considered to be uncertain (Hyman et al., 2022; Kaikkonen et al., 2018; Ma, Zhang, Du, Liu, & Shen, 2022). The same can be said for the prospect of success of such intervention (Bang & Trellevik, 2022a).

As there is yet no established industrial scale deep-sea mining to study, there is also considerable uncertainty related to understanding the technology, cost-efficiency, material output, as well as profitability of an emerging deep-sea mining industry (Bang & Trellevik, 2022a; ISA, 2022). To assess the prospective future of such an industry is henceforth also an uncertain undertaking.

The International Energy Agency (IEA) forecasts that there will be a tremendous increase in demand for critical minerals on account of economic growth, electrification renewable energy production, and high-tech production in the immediate future. The IEA furthermore suggests that known mineral reserves and recycling will not be able to accommodate the increasing demand (International Energy Agency (IEA), 2021; Kaluza et al., 2018; Watzel et al., 2020). The geopolitical situation is also likely to affect the demand and supply of critical minerals. Existing mines and processing plants are unevenly distributed geographically across different, potentially conflicting, interest spheres (Kalantzakos, 2020; Trellevik, 2023b). It is not an uncertain assumption to ascertain that climate change will be a driver for increased demand for critical minerals – and that deep-sea minerals may become a resource for meeting this demand (Hammond & Brady, 2022; International Energy Agency (IEA), 2021; Kaluza et al., 2018; U.N. Environment Programme, 2022; Volkmann & Lehnen, 2018; Watzel et al., 2020) On the other hand, the demand for minerals for, essentially high-tech manufacturing and energy solutions, is inherently tied to innovation and technological development. If, for example, the prevailing battery chemistry for the world's electric vehicles were to change radically – so would the demand for certain minerals (Simas et al., 2022). Both supply and demand, and thereby the price of critical minerals in the future, is thus uncertain. As such, the rationale for embarking on deep-sea mining to accommodate future demand may be considered equally uncertain.

As Nautilus Minerals went bankrupt, it was primarily accredited to unforeseen regulatory obstacles delaying income and investment. This, in turn, has been linked to a lack of a *"social license to operate,"* where local communities in Papua New Guinea (PNG) expressed stark opposition, calling for state intervention (Filer & Gabriel, 2018; Gross, 2022). A *"social license to operate"* is a concept known in the mining industry since the mid-1990s; it does not have a robust definition but can loosely be understood to be a level of approval, report, and common interest between miners, regulatory bodies and communities affected by the mining activity (Filer & Gabriel, 2018). Although the Secretary General of the International Seabed Authority famously expressed that: *"It must be stressed, however, that it is useless and counter-productive to argue that an a priori condition for deep-sea mining is an existential debate about whether it should be permitted to go ahead or not. The international community passed that point already many years ago "* (Lodge & Verlaan, 2018, p2); the social license to operate for deep-sea mining (DSM) remains a highly contested topic. The debate around whether DSM is ethically, socially, and environmentally sound and acceptable is indeed heated. NGOs such as the World Wildlife Foundation (WWF) have launched substantial campaigns favoring a moratorium on deep-sea mining, while other stakeholders are loudly in favor of the commencement of DSM (Boomsma & Warnaars, 2015; Filer & Gabriel, 2018; WWF, 2020; Zhang et al., 2015). Therefore, there may be uncertainty about the basic foundation for DSM as an emerging industry. Whether, when, where, and under what regulatory regime this potential industry will be able to obtain a social license to operate is not clear.

In summary, deep-sea mining is a domain of deep and epistemic uncertainty. The future cannot be known, and DSM is merely a prospective industry – still residing in the future. However, there is a notable push toward the industry's emergence; investments are made, regulatory code is being written, referendums are approaching, technology is developed, and geopolitical turmoil is ever present (Bang & Trellevik, 2022a, 2022b; Trellevik, 2023b). Simultaneously, all the above are subject to deep uncertainty; the abyss is poorly understood, deep-sea mining is industrially in its infancy, technology evolves concomitantly, as do markets, and public opinion is fluid. Epistemic uncertainty must, therefore, be recognized as a central property of any discourse on the emergence of deep-sea mining.

1.2 Theoretical Framework and Research Philosophy

Deep-sea mining is a topic of discourse framed by epistemic uncertainty across a swath of dimensions, disciplines, perspectives, and unknown futures. As the commencement of industrial deep-sea mining appears to be fast approaching both internationally and in Norway, predicated by projected mineral demand, geopolitical turmoil, and governing bodies at national and international levels verging on opening seabed for deep-sea mining, it is also a discourse of urgency. The theoretical framework must be carefully considered for appropriately addressing such a complex, uncertain, and urgent topic.

System Dynamics and its underlying theory is an appropriate departure point for establishing a theoretical framework, as it is focused on development over time, feedback loops, accumulations and potentially nonlinearities that work together to create policy resistance and unanticipated behavior. A common theoretical heuristic within the System Dynamics tradition and literature postulates that "structure generates behavior”. The theory embedded in this heuristic suggests that the fixed relational connection between variables in a system and the nature of variables dictates how the outcomes produced by this system will unfold (Forrester, 1987; Lane & Oliva, 1998; Sterman, 2002). By abstracting real-world phenomena or hypotheses and reproducing system structure in computer models, the subsequently generated behavior can be explored, and hypothesis can be tested (Forrester, 1987; Sterman, 2002). System Dynamics theory also engages with uncertainty. As System Dynamics is the study of complex dynamic systems and their behavior over time, uncertainty is understood as a lack of knowledge about the past, the present, and the future (Pruyt & Kwakkel, 2014). This lack of knowledge resonates with the epistemic uncertainty framing deep-sea mining. As this Thesis explores how deep-sea may unfold, it implicitly explores development over time. With knowledge gaps about the past, present, and future, System Dynamics theory complements the theoretical framework for this research. It should be noted that although System Dynamics regularly engage with uncertainty, it may not be ideal as a stand-alone approach for such analysis and benefits from being complemented by other approaches (Pruyt, 2007). Assuming this position, System Dynamics theory may also require complementation.

This Thesis is, therefore, also informed by Post-Normal Science (PNS), as this concept was defined and developed by Funtowicz and Ravetz in the early 1990s (Funtowicz & Ravetz, 1990). It should be underlined that this Thesis does not treat PNS orthodoxically but is informed and inspired by Post Normal Science and thus supplements the theoretical framework of System Dynamics with complementary ideas.

Post-normal science suggests that a new scientific method is needed to appropriately address complex political and technical challenges arising on the scientific horizon. Funtowicz and Ravetz argue that new methodology is imperative since *[science] "..is being called upon to reach conclusions on problems before all the data are to hand"* (1990). Funtowicz and Ravetz contend, *"The trouble is that on the basis of uncertain inputs, decisions must be made under conditions of some urgency. In such conditions, science cannot proceed based on accurate predictions but only on forecasts influenced by values and policy. Typically, in such issues, the facts are uncertain, values in dispute, stakes high, and decisions urgent. In this way, it is "soft" scientific information which serves as inputs to the "hard" policy decisions on many important environmental issues*." (Funtowicz & Ravetz, 1990; Trellevik, 2023b).

In essence, Post-Normal Science suggests that in complex challenges where the data is uncertain and decisions must be made, there is a need for making uncertain forecasts to have at the very least, some footing for decision-making. This is very much what is presented in several of the articles included in this Thesis; the Thesis follows this prerogative by presenting analysis and decision-support tools in the form of formal and quantitative optimization and simulation models built upon data from a plurality of sources associated with a plurality of uncertainties.

Post Normal Science thus complements the theoretical framework found within System Dynamics by anchoring System Dynamics to a realm of application within this Thesis. While System Dynamics provides a stand-alone theory, it also operationalizes Post Normal Science by expanding this theory with actionable ideas and methods.

The theoretical framework for this Thesis is further informed and complemented by the ideas put forward by Zeckhauser in the essay *"Investing in the Unknown and Unknowable"* (2010). Although never alluding to either Post-Normal Science or System Dynamics as guiding theories, Zeckhauser's essay aligns with certain principles of Post-Normal Science and System Dynamics. Zeckhauser discusses investments where future states are unknown or unknowable. The essay points out that such investments may yield phenomenal profits or losses. Where great fortunes have been made in successful investments in the unknown or unknowable, this is attributable to repeatable clear thinking about unknown or unknowable situations over time. Zeckhauser concludes that: *"..clear thinking about U.U. [uncertain and unknowable] situations, which includes prior diagnosis of their elements, and relevant practice with simulated situations, may vastly improve investment decisions where U.U. events are involved. If they improve, such clear thinking will yield substantial benefits.".*

Although applied in a considerably different setting and for a different purpose than that addressed by Post Normal Science, this conclusion echoes the principles offered by Funtowicz and Ravetz where *[science] "..is being called upon to reach conclusions on problems before all the data are to hand"* (1990). In the world of investments, a conclusion may translate into a bet, and in this world, uncertainty is ever present. According to Zeckhauser, clear thinking, or "prior diagnosis of elements and practice with simulated situations," will vastly improve such decisions.

This Thesis aims to facilitate such clear thinking on uncertain assumptions and a world of incomplete control when called upon to make urgent decisions. Furthermore, this Thesis is practicing Zeckhauser's advice to "practice with simulated situations" and does so through three optimization and simulation-based articles.

Finally, this Thesis recognizes and applies a "plurality of legitimate perspectives." The inclusion of a plurality of perspectives is prevalent throughout this Thesis and its associated series of articles. This demonstrates yet another dimension in which this Thesis is informed by Funtowicz and Ravetz's requirements for "appropriate science," where: *"The science appropriate to this new condition will be based on the assumptions of unpredictability, incomplete control, and a plurality of legitimate perspectives" (1993).* The optimization and simulation-based articles present non-exhaustive quantitative models where aspects of deep-sea mining are explored, clearly based on unpredictability and incomplete control assumptions.

1.3 Research Questions

This Thesis sets out to answer four research questions. These questions are raised to explore how deep-sea mining may unfold and thereby contribute a basis for qualified decisions and sound policy design. These questions partially address the global context of deep-sea mining and the case of deep-sea mining on the Norwegian continental shelf. The reasoning for studying the Norwegian case is that Norway has documented resources on its continental shelf, is advancing legislative and regulatory premises, and has a firmly established offshore and subsea industry presumably equipped and evidently prepared to take on the challenge of deep-sea mining (Bang & Trellevik, 2022a; Ministry of Petroleum and Energy, 2021, 2022b; Trellevik, 2023a).

The research questions are:

1. How can a multidimensional problem definition for deep-sea mining be framed?
2. Why would deep-sea minerals emerge as an industry?
3. In the case of Norway, how would deep-sea mining unfold, and to what avail?
4. What is the techno-operational gap for robust SMS mining in Norwegian waters?

These research questions straddle a swath of different perspectives, dimensions, scales, uncertainties, and data sources. To appropriately address the research questions, this Thesis employs a poly-methodological approach.

2. Methods

This Thesis is framed by epistemic uncertainty along several axes of inquiry. As outlined in the theoretical framework above, such uncertainty requires a multi-perspective, multi-method, and multi-source approach for effectively exploring the topic. This plurality is further reflected in the research questions. These span a wide array of dimensions and disciplines. Addressing these questions thus requires a multi-methods approach. Any singular methodology would not possibly address the different research questions neither appropriately nor adequately.

This, at its core, is as prescribed by the Post Normal Science paradigm where urgent conclusions are required under multivariate uncertainty, and furthermore aligned with the overarching scientific remit of this Thesis: to explore the possible futures of deep-sea mining. As such, this Thesis is scaffolded on three different methodological approaches: systems thinking, (stochastic) dynamic optimization, and (stochastic) System Dynamics modeling.

2.1 Systems Thinking

Systems thinking is a loosely defined methodology, and any one rigours and universally accepted characterization lacks in the literature. Systems thinking is a set of thoughts and techniques for holistically describing and analyzing the complexity of interrelated systems of many variables, perhaps across many sectors, disciplines, or perspectives. This is achieved by considering whole entities of interrelated elements rather than by considering constituent system parts in isolation (Anderson & Johnson, 1997; Ramage & Shipp, 2009; Sydelko et al., 2020).

Systems thinking focuses on the exchanges or interactions between system components and the patterns that emerge from those interactions (York et al., 2019). Systems thinking may further be described as a method for exploring and developing actual impact policies within complex systems or challenges as a strategy for enabling systemic change (Government Operational Research Service, 2012). A central concept for Systems Thinking is the focus on system behavior arising from endogenous relationships and activity of components within the system rather than considering system change as a property or effect of exogenous impact (Meadows & Wright, 2008).

This Thesis applies Systems Thinking and operationalizes this method by developing causal loop diagrams (CLDs) based on a variety of data sources. These data sources include literature review, quantitative data elicitation, and qualitative methodologies such as participatory systems mapping workshops, semi-structured interviews with stakeholders and experts, as well as iterative disconfirmatory interviews. Rooted in Systems Thinking and Participatory Systems Mapping, I develop a methodology for framing inclusive, holistic, and multidimensional problem definitions. This methodology is then applied to the case of deep-sea mining, where a multidimensional and multi-perspective problem definition, including trade-offs and synergies across a swath of different disciplines, sectors, and interest spheres, is suggested (Trellevik, 2023b; Wilkerson & Trellevik, 2021).

2.2 Dynamic Optimization

Dynamic optimization is a set of techniques of the calculus of variations and of optimal control theory. Dynamic optimization seeks solutions to continuous time dynamic problems as a continuous function or a set of functions where the optimal result is indicated (Kamien & Schwartz, 1991).

Dynamic optimization is in this Thesis applied to four dynamic problems, and these are solved by the application of the GAMS Knitro Software. Dynamic optimization is computationally intensive, and the application of dynamic programming, compared to System Dynamics software, offers some computational advantages affording solutions to multivariate and stochastic models over a series of Monte Carlo sensitivity Monte Carlo simulations (Bang & Trellevik, 2022b). The problems, as they are defined, draw inspiration from Herfindahl (1967), Solow and Wan (1976), Amigues et al. (1998), Holland (2003), and Meier and Quaas (2021), who are all working on problems where the optimal order to extract different deposits is the focus. The problems are also inspired by Campbell (1980) and Cairns (2001), who focus on extraction under restrained investments and capacities. Finally, the problems are informed by Hotelling (1931), Salant (1976), Reinganum and Stokey (1985), Lewis and Schmalensee (1980), Loury (1986), Hartwick and Sadorsky (1990), and Salo and Tahvonen (2001) who are all partly discussing and partly focusing on oligopoly models of nonrenewable resources (Bang & Trellevik, 2022b).

Stochastic dynamic optimization and sensitivity analysis are employed to explore the impact of various influences catalyzing or inhibiting the emergence of deep-sea mining. This exercise aims to divulge and ascertain plausible market dynamics in mining with the emergence of deep-sea mining as an alternative source of manganese. The optimization problems are considering a conceptual case rather than a specific one to reveal underlying dynamics governing the possible transition towards deep-sea mining rather than exploring a given mineral market or industrial example. The use of a conceptual case is also based on the nature of the available data and the associated uncertainties within deep-sea mining. The dynamic optimization in this Thesis employs a plethora of data points that are highly uncertain, yet drawn from, qualified assumptions. While such data and analysis contribute to conceptual analysis in support of "Clear Thinking," as prompted by Zechauser, for potentially urgent decision making and policy design, it can hardly be employed in any reasonable predictions or forecasting of real-world scenarios for any particular mineral case. Using dynamic optimization on purely conceptual cases removes any such potential confusion (Bang & Trellevik, 2022b).

2.3 System Dynamics

System Dynamics (S.D.) studies complex issues or challenges developing over time. It is also commonly used for studying decisions made under such conditions. When dealing with complexities, uncertainty is also common (Pruyt & Kwakkel, 2014). System Dynamics may be seen as an application of Systems thinking based on control theory and theory of nonlinear dynamics, where computer models allow for simulation and analysis of complex systems behavior over time (Spector et al., 2001; Sterman, 2000, 2002).

Within System Dynamics, complex systems are abstracted into computerized simulation models where system components are represented as stocks and flows and where the link or relationships between variables and the dynamic nature of these relationships govern the simulated systems' behavior over time. (Forrester, 1987; Sterman, 2002)

System Dynamics commonly employs a wide variety of quantitative as well as qualitative data in the modeling process. In the System Dynamics literature, it is encouraged to elicit knowledge from written, numerical, and "mental" databases . "Mental databases" refer to the expert, often tacit knowledge held by experts and stakeholders. (Forrester, 1987, 2007; Forrester JW, 1992; Luna-Reyes & Andersen, 2003a; Sterman, 2002). Mental databases include expert knowledge, experience, perceptions, and expectations. Such information can be of merit, especially when numerical and written databases are limited or incomplete. The latter is symptomatic for any emerging industry and, indeed, the case for deep-sea mining. Such data can only be retrieved through rigorous qualitative methodology. In many cases, such data is critical for establishing feedback loops in dynamic simulation models (Luna-Reyes & Andersen, 2003b). In the case of this Thesis, mental databases constitute a pivotal data source for developing an exploratory System Dynamics model, as the industry structure the models digitally mimic, is still being forged and are constructs yet of the future. The perspectives and expectations of involved stakeholders are important for modeling a system of this nature (Bang & Trellevik, 2022a; Trellevik, 2023a).

Repenning (2002) and subsequently, Kopainsky and Luna-Reyes (2008) establish that the system dynamics modeling process parallels the theory-building concept. In this perspective, the methodology and modeling process applied in this Thesis can thus be seen as a contribution towards a theory about the emerging exploration and extraction industry tied to SMS deposits on the Norwegian continental shelf. This theory is then formulated as a System Dynamics model and allows for exploration through simulation (Bang & Trellevik, 2022a).

The System Dynamics modeling process employed in this Thesis draws upon a variety of quantitative and qualitative methodologies. The process commences with studies of numerical and written databases by way of data canvassing and literature reviews. Observation is widely employed throughout the Ph. D project. I have participated in conferences, workshops, meetings, and other formal and informal events with representatives from industrial, public policy, and academic stakeholders and experts, involved in some capacity, with deep-sea mining. Through a series of participatory modeling workshops, I have elicited several mental models at various levels of aggregation and various levels of granularity. These have since formed the basis for establishing first-draft system dynamic models. The system dynamic models have then been through an iterative process of semi-structured disconfirmatory interviews. The evolving model and its parameterization have been presented to and challenged by a broad panel of experts and stakeholders from industry, government bodies, and academia. Through the iterative process, the model scope has become focused, parameters have been justified or had reasonable ranges defined, validity and utility have been established as a level of saturation has been reached through the iterative and disconfirmatory approach. The modeling process, as it relates to modeling stages, validity and utility, model scope, and saturation, is graphically portrayed in Fig 1.

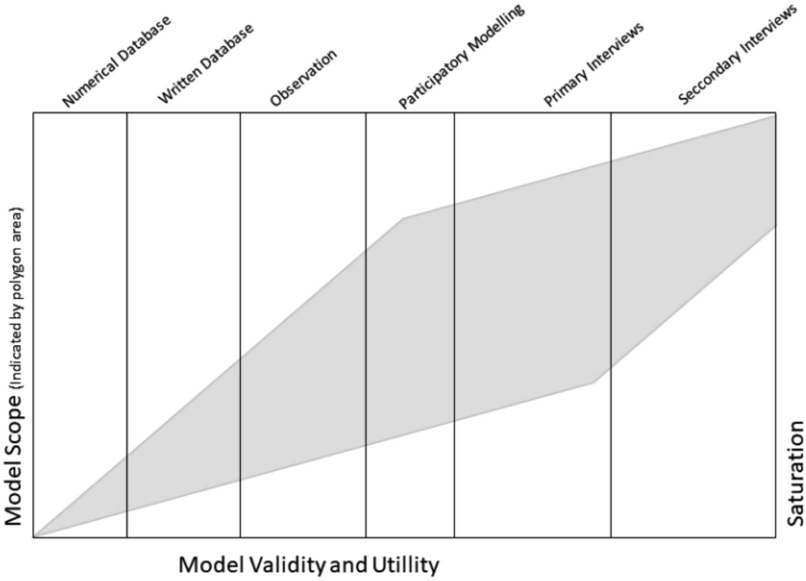


Fig. 1 Illustration of the model development process and how it relates to model scope, saturation, and model validity and utility (Bang & Trellevik, 2022a).

The resulting system dynamics models in this Thesis present a likely structure of an emerging deep-sea mining industry in Norway and allow for exploring its possible behavior and possible outcomes. The system dynamics models also enable inquiry about the budding industry's most auspicious areas of innovation and focused future performance improvement. To appropriately account for the epistemic uncertainty embedded in deep-sea mining, the system dynamics models are simulated with several stochastic variables and apply Monte-Carlo sensitivity simulations over a considerable number of simulation runs for every policy scenario included in the analysis. The model structure and its parameterization, as well as the stochastic parameter ranges, are qualified by expert and stakeholder engagement through the qualitative data elicitation process.

3. Summary of Articles

This Thesis includes five articles. These five articles are based on research adopting a wide array of methodologies. This, in turn, is necessitated by epistemic uncertainty and the theoretical framework established for working with this level of uncertainty. This guides the methodological approach to appropriately addressing the four research questions, straddling a wide array of dimensions and scientific disciplines. In sum and convergence, these articles illuminate the overarching goal of this Thesis through the application of a multifaceted methodological toolbox and the array of insight such a toolbox affords the wide range of research questions raised.

3.1 Sustainability-oriented innovation: Improving problem definition through combined design thinking and systems mapping approaches

This article is co-authored with Brooke Wilkerson (University of Bergen). The article departs from an observation recognizing that sustainability-oriented innovation (SOI) is a topic currently drawing considerable attention on account of an increased sustainability focus within arenas of development, business, and education (Wilkerson & Trellevik, 2021).

The article discusses how SOI processes are typically modeled upon design thinking toolkits, with a pronounced emphasis on empathy with user experience and user needs. While this effectively ensures innovation processes converge on tangible and definable needs or requirements, it may restrict its capacity to position the challenge in an encompassing systemic or societal framework. This, in turn, may produce narrow or incomplete problem definitions, inapt for sustainability-oriented innovation processes (Wilkerson & Trellevik, 2021).

The article presents, and qualifies through testing, a novel methodology developed by the authors for eliciting and defining problems for SOI. The article demonstrates that introducing systems mapping in the problem definition phase of sustainability-oriented innovation processes allows for adequate boundaries for defining the problem space. This, in turn, raises awareness of how the system may dynamically self-influence (Wilkerson & Trellevik, 2021).

When considering the concept of sustainability as a system's property, the article suggests that an elevated viewpoint, afforded by systems mapping, complements the design thinking approach with its focus on empathy with the user, enables a robust problem definition where system properties, and thus, sustainability considerations may be included. The article details this mixed methodology and provides case studies of its application. The example cases demonstrate how design thinking and systems mapping can be combined to improve problem definitions within sustainability-oriented innovation processes. The article also suggests directions for further discourse and future research within this domain (Wilkerson & Trellevik, 2021).

This article forms a methodological point of departure for establishing a multidimensional problem definition for deep-sea mining, as proposed in *"The many challenges of deep-sea mining"*(Trellevik, 2023b).

3.2 The Many Challenges of Deep-Sea Mining

This article employs the methodology suggested by Wilkerson and myself (2021), for developing multidimensional and inclusive problem definitions for complex challenges, such as sustainability-oriented innovation processes, towards developing a multidimensional problem definition for the emergence of deep-sea mining (Trellevik, 2023b).

This article is motivated and informed by Hallgren and Hansson (2021). They have studied conflicting narratives of deep-sea mining and suggest that although there are conflicting narratives, the policy paths currently dominating the debate encourage industrial deep-sea mining in the imminent future. They implore that the preponderance of the emerging industry narrative disregards the wider discourse in the literature and that these alternative narratives should be included in regulatory processes and discussions. *"The many challenges of deep-sea mining"* constitute an effort to bridge this gap in the literature and contribute a framework for the inclusion of multiple perspectives (Trellevik, 2023b).

The article is furthermore motivated by initiatives by multiple countries and the international community, rapidly approaching decision gates, potentially allowing the industrial commencement of deep-sea mining. The article registers that the public debate on deep-sea mining is accelerating in temperature of discourse, considering both volume and level of polarization. As such, and as proposed and encouraged by Hallgren and Hansson, this article contributes a more encompassing problem definition.

The article presents a causal loop diagram, constituting a problem definition, including the multiple perspectives, considerations, trade-offs, and synergies across a swath of dimensions, sectors, and disciplines embedded in the potential emergence of deep-sea mining. This problem definition is effectively a boundary object and, thus, an encompassing and holistic launch pad for systemic discourse on deep-sea mining. This is a contribution, as such a problem definition, or multidimensional and cross-disciplinary departure point for discussion, appears lacking in the literature (Trellevik, 2023b).

The problem definition, presented as a model, includes, and interrelates the dynamics of realms such as global warming, environmental degradation, global mineral markets, socio-ethical practice, and geopolitics. The problem definition is aggregated and conceptual and may, with merit, be expanded in both scope and granularity. Nevertheless, the problem definition presented in the article reduces complexity and positions complex dynamics in a relational structure where pivotal trade-offs and synergies are revealed in the many challenges of deep-sea mining. This, in turn, contributes a framework for qualified and perspective-inclusive discussion and consideration of deep-sea mining. Thus, it also contributes a framework for policy design within this contested domain (Trellevik, 2023b).

The article is based on data aggregated from findings and observations from literature review, participatory systems mapping workshops, and semi-structured interviews with experts and stakeholders (Trellevik, 2023b).

3.3 Reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations in mineral industry transition

This article is co-authored with Rasmus Noss Bang (Norwegian School of Economics). The method on which the article and its model, optimization, and analysis are based is dynamic optimization.

This article identifies three present factors that may be significant in a potential transition towards including deep-sea mining in the global supply chain for minerals. As suggested by the article's title, these factors are reserve-dependent capital efficiency, cross-sector competition, and asymmetric mineral security considerations. In the article, “reserve-dependent capital efficiency” is defined as *"accessibility and grade-dependent output per unit capital*," “reserve-dependent capital efficiency” is defined as *“competition between two separate mining sectors*," and “asymmetric mineral security considerations” is explained as situations where for example resource owners and/or governments are heavily reliant on a given mining sector, possibly outside their control, for profit or security considerations (Bang & Trellevik, 2022b).

The article presents four conceptual optimization problems. These are explored to identify the impact of the different factors on the possible transition towards the inclusion of deep-sea mining in aggregated mineral supply. The first problem assumes a hypothetical principal agent who executes the decisions of resource owners, governments, and producers. The principal-agent invests and extracts minerals to maximize the net present value of extraction from terrestrial and marine mineral reserves in a reserve-independent capital efficiency scenario. The second problem considers the same problem as the first, with the variation that in this problem, the principal agents are subjected to reserve-dependent capital efficiency. The third problem considers a duopoly of two competing principal agents, both executing decisions on behalf of resource owners, governments, and producers committed to a sector, building capital and mining to maximize the net present value of extracted minerals from the remaining reserves, and under the influence of the decisions of the other principal agent. The fourth and final problem considers a duopoly scenario where a marine principal agent appreciates mineral security and profits. The mineral security considerations are contextualized by the ongoing geopolitical turmoil and energy security considerations arising in Europe in the wake of Russia's invasion of Ukraine (Bang & Trellevik, 2022b).

The optimization and sensitivity results and the associated analysis of these demonstrate that reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations all can, in various fashions, catalyze a possible transition towards the inclusion of deep-sea mining in the global mineral supply mix. However, a number of caveats and considerations beyond the boundaries of this study may thwart the conceptual results presented in the article. The dynamic optimization problems do not consider externalities, such as the environmental impact of mining, either onshore or offshore. The article furthermore does not consider potential technological shifts affecting the demand for minerals. The article also simplifies the implicit timeline for developing deep-sea mining, assuming that deep-sea minerals are readily available for extraction. There is a requirement for significant deep-sea exploration to locate reserves and develop extraction concepts for deep-sea minerals. As the article highlights discounting as a major contributor to guiding investment decisions, the latter merits further research (Bang & Trellevik, 2022b). Dynamic or time-sensitive considerations affecting discounting and thus the net present value of reserves are, to a much greater extent, included in the articles *"Perspectives on exploration and extraction of seafloor massive sulfide deposits in Norwegian waters"* and *"Exploring exploration — how to look for deep - sea minerals*."

The article does, however, conceptually demonstrate how several essential factors, all very identifiable and documented phenomena in the real world, such as conflicting geopolitical interest-spheres, depleting ore grade of identified resources, and market dynamics, may encourage and enable the emergence of deep-sea mining (Bang & Trellevik, 2022b).

3.4 Perspectives on exploration and extraction of seafloor massive sulfide deposits in Norwegian waters

This article is Co-Authored with Rasmus Noss Bang (Norwegian School of Economics). The article contributes a stochastic system dynamics model, considering deep-sea mining of seafloor massive sulfide (SMS) mineral deposits in Norwegian waters.

The model presented in the article is synthesized on the foundation of industry perceptions, perspectives, expectations, and knowledge, elicited through a participatory systems mapping session with 82 participants as well as 20 in-depth interviews with experts and stakeholders from industry, academia, and the public policy sector (Bang & Trellevik, 2022a).

The article presents simulation results capturing the anticipated ranges of resource- and economic potential as conceived by the qualified participating contributors to the study. The simulation results imply an expected commercial resource base of 1.8 to 3 million tons of copper, zinc, and cobalt. Copper accounts for the most substantial component of this mineral mix (Bang & Trellevik, 2022a).

Related to the expected commercial resource base, the article draws attention to a disagreement between academic- and industry-conceived prospects, where the academic contributions predicate a more conservative estimate than what is prevalent amongst the industry stakeholders. The associated net present values reside in the range of a net present loss of 970 million USD and up toward a net present profit of 2.53 billion USD. The academic expectations are projected to produce a negative net present value, whereas the industry-conceived prospects are projected to yield a profit in net present value (Bang & Trellevik, 2022a).

Upon closer investigation, the results show that one of the foremost challenges of SMS mining is the initial exploration costs, dominated by the cost associated with coring deep-sea SMS deposits to verify ore-grade and mineral content. Coring costs are expected to remain high with today's exploration technology, considering the relatively low efficiency associated with these operations (Bang & Trellevik, 2022a).

Exploration costs are also accrued early on the timeline of exploration and extraction of deep-sea minerals. This is a challenge, as the revenue-generating activity of actual mineral extraction occurs years later. This constitutes a significant negative impact on the net present value of the industry on account of discounting (Bang & Trellevik, 2022a).

The article, therefore, contributes that an area of attention for the budding industry should be to identify technologies and operational concepts to reduce the costs associated with coring operations, as well as methods to limit the time passing between initial exploration and extraction of minerals and thus the generation of revenue (Bang & Trellevik, 2022a).

This article is based on surveys of numerical and written databases, qualitative data elicitation through participatory modeling, and iterative semi-structured, disconfirmatory interviews with stakeholders and experts. The article is further built upon stochastic simulation and employs Monte Carlo sensitivity runs across a substantial number of simulation runs to account for uncertainty. The article contributes, beyond the analysis of the simulated behavior, a synthesis of how a possible SMS mining industry is likely to evolve in Norwegian waters (Bang & Trellevik, 2022a).

3.5 Exploring exploration - how to look for deep - sea minerals

This article further develops the model presented in *"Perspectives on Exploration and Extraction of Seafloor Massive Sulfide Deposits in Norwegian Waters"* to explore the potential innovation space embedded in the possibly emerging SMS mining industry in Norwegian waters. "Innovation space" is here understood as the sectors, or functionalities, of the system where innovation, development, or performance improvement would yield the most significant impact towards establishing a robust industry (Trellevik, 2023a).

The article builds on my earlier research, indicating that the profitability of deep-sea mining with established technology heavily depends on high ore grades, cost of exploration, and time between initial exploration and extraction of minerals. This study explores the potential impact of emerging techno-operational concepts on the possible profitability of SMS mining within the Norwegian exclusive economic zone. This is done to understand how the reliance on high ore grades, which is a variable of considerable uncertainty, may be reduced by increasing the cost-efficiency of exploration through techno-operational innovation, thus rendering the emerging industry more robust towards uncertain ore grades (Trellevik, 2023a). This is aligned with the recommendations presented in *"Perspectives on Exploration and Extraction of Seafloor Massive Sulfide Deposits in Norwegian Waters*"

The article and the model developments on which it is based implement and analyze techno-operational concepts projected to enter the subsea services market in the near future. The article considers the advantages or disadvantages of applying these techno-operational concepts within the framework of SMS-mining in Norwegian waters. The techno-operational concepts explored in the article as they are implemented in the model are Unmanned Surface Vessels (USVs), fleet operated Autonomous Underwater Vehicles (AUVs), and geophysical methodology for enhancing the geographical footprint of conventional coring operations on the seabed, to ascertain the volume and ore-grade of SMS deposits. These techno-operational concepts are recognized as budding tecno-operational concepts of innovation presently pursued by the subsea survey and exploration industry (Argeo, 2022; ECA Group, 2022; Fugro, 2022; Konberg Maritime, 2022; Malehmir et al., 2012; Ocean Infinity, 2022; Sahoo et al., 2019; Stove et al., 2013; Yu et al., 2019; Trellevik, 2023a).

The article is based on stochastic simulation of policy scenarios testing all three techno-operational concepts individually and all possible combinations of the different concepts. The analysis also includes stochastic Monte Carlo sensitivity analysis. It isolates the relative effectiveness of the techno-operational concepts to render the potential SMS industry robust towards the uncertainties associated with ore grade (Trellevik, 2023a).

The article finds a substantial benefit in developing and qualifying geophysical sampling methodology for enhancing the area covered by conventional coring, thus ascertaining mineral resources with greater cost-efficiency. The article further indicates a moderate benefit of launching unmanned surface vessels for regional surveys. Somewhat counterintuitively, it is further demonstrated that fleet-operated autonomous underwater vehicle concepts for high-resolution surveys may be either inefficient or directly counterproductive. Through this analysis, the article contributes an understanding of techno-operational concepts that are of value not only to industrial stakeholders engaged in innovation but also to policy- and government bodies currently evaluating the prospectivity of SMS-mining in Norwegian waters. The latter group is informed by this article demonstrating that tecno-operational concepts already emerging on the horizon will likely render SMS-mining on the NCS a robust endeavour as the reliance on high ore grade is diminished (Trellevik, 2023a).

4. Answering the Research Questions

As stated earlier, the overarching ambition of this Thesis is to explore how deep-sea mining may unfold and thus contribute a basis for qualified decision-making and sound policy design. The five articles included in this Thesis, through the four research questions and through different methods, angles, and approaches, sets out to illuminate this overarching ambition. The following sections will address the research questions and identify how these questions have been answered through the series of articles.

4.1 How can a multidimensional problem definition for deep-sea mining be framed?

This question is raised and addressed in my two articles: "*Sustainability-oriented innovation: Improving problem definition through combined design thinking and systems mapping approaches*" (Wilkerson & Trellevik, 2021) and "*The Many Challenges of Deep-Sea Mining*" (Trellevik, 2023b). While the 2021 article is a methodological contribution, the 2023 article applies the ideas put forth in the 2021 article towards deep-sea mining at an aggregated level.

"*Sustainability-oriented innovation: Improving problem definition through combined design thinking and systems mapping approaches*" (Wilkerson & Trellevik, 2021) departs from what is identified as a shortcoming within the Design Thinking tradition in addressing multidimensional problems for Sustainability Oriented Innovation (SOI). As "Sustainability" is a system's property, the article suggests that the Design Thinking school of thought's strong focus on empathizing with one stakeholder or challenge is not well suited for SOI, as sustainability, by definition, requires multiple perspectives to be included. In this, it is predicted that sustainability-oriented innovation cannot take place in a vacuum. While solving a challenge for any one stakeholder, the challenges of other stakeholders may be dramatically worsened. Furthermore, by finding solutions to reduce the environmental footprint of one business, that solution may increase the overall footprint of the society or context of that business, depending on what this solution is. The methodology contributed suggests applying systems mapping to increase the scope of the problem definition prior to seeking solutions. This, in turn, enables an iterative design process where more than one target is under consideration and, as such, is better suited to accommodate sustainability innovation processes (Wilkerson & Trellevik, 2021).

Although this article focuses on sustainability-oriented innovation, the methodology also applies in other contexts. Sustainability-oriented innovation (SOI) has defined characteristics that separate it from other types of innovation processes, including the need to include a long time horizon, examine the problem in a larger context, and consider multidimensional targets such as environmental, social, and economic impacts) (Buhl et al., 2019; Wilkerson & Trellevik, 2021). This is how deep-sea mining is contextualized in *"The Many Challenges of Deep-Sea Mining* ."As noted in the article, the literature on deep-sea mining is fragmented and primarily arranged along fault lines of academic disciplines (Trellevik, 2023b). To bridge the gap between different academic disciplines and perspectives and to provide a more cross-disciplinary and aggregated synthesis and problem definition, the article applies the systems mapping methodology as suggested in the 2021 article. In this application, the 2023 article contributes an inclusive and intuitively available representation of the multidimensional targets, trade-offs, and synergies embedded in deep-sea mining. As such, the problem definition provided may be utilized for sustainability-oriented innovation processes, policy design, or further exploration, at higher granularity, the problem definition itself.

The problem definition is presented as a Causal Loop Diagram:

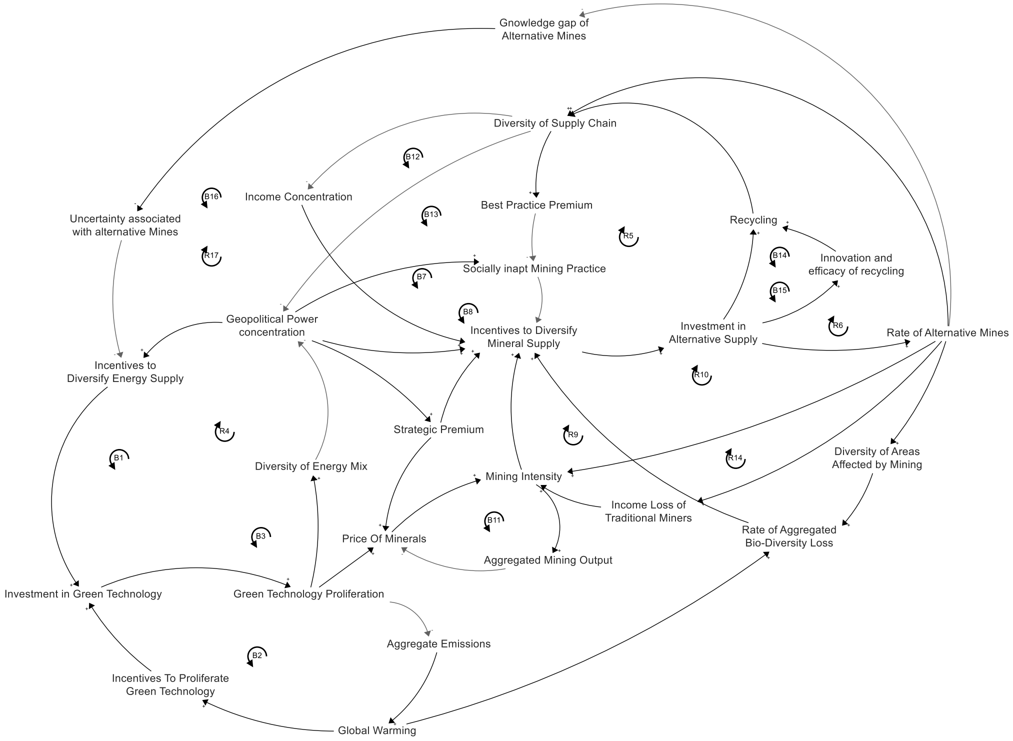


Fig 2: CLD: The Many Challenges of Deep-Sea Mining (Trellevik, 2023b)

The model consists of 19 connected feedback loops. Seven of these are reinforcing loops, while twelve are balancing feedback loops. Reinforcing feedback loops further accelerates effects within the feedback loop as any variable is initially increased or reduced. Balancing loops are dynamic feedback loops where the causal relational dynamics generate a waning effect to either an initial increase or reduction of a variable in the feedback loop. The dominance dynamics between various feedback loops generate the aggregated system behavior, but that can only be ascertained through simulation (Spector et al., 2001; Sterman, 2000; Trellevik, 2023b).

This problem definition straddles various sectors, including climate change, biodiversity loss, geopolitical power dynamics, green technology, socio-ethical dimensions, mineral recycling, and mining at different locales. It contributes an intuitive way of seeing these in relation to each other for better grasping how deep-sea mining can be envisioned or further explored. *All* dimensions are not explored in further detail within this Thesis, yet *some* certainly are.

4.2 Why would deep-sea minerals emerge as an industry?

As elaborated in more detail in preceding chapters, there is a projected increase in demand for minerals, partly due to population and economic growth in general and partially due to the proliferation of green- and high-tech (Haugan & Levin, 2019; International Energy Agency (IEA), 2021; Kaluza et al., 2018). Simultaneously, ore grades in terrestrial mines are in decline, and established mine sites are being depleted at increasing rates; unit cost of production is increasing, and recycling technology is still not mature (Golroudbary et al., 2019; Henckens, 2021; Petersen et al., 2016; Ragnarsdóttir, 2008). There are also concerns related to supply security as certain geopolitical interest spheres are dominating supply chains of critical minerals (Bang & Trellevik, 2022a, 2022b; Hao & Liu, 2011; Kalantzakos, 2020; Trellevik, 2023b). Deep-sea minerals may partially solve the above challenges as they present a vast resource of critical minerals independent of existing mining and supply-chain conditions and distribution.

To further investigate how different drivers promoting the emergence of deep-sea mining may manifest, the article *"Reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations in mineral industry transition"* employs a conceptual model, dynamic optimization problems, and sensitivity analysis to test the efficacy of different factors innate to mineral-market evolution (Bang & Trellevik, 2022b). This article demonstrates that reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations play essential and catalyzing roles in driving a transition towards a global mineral commodity market where deep-sea mining is included. The article presents several scenarios, and analysis of these scenarios reveals dynamics to be expected over time assuming the introduction of different factors. It is interesting to review the final dynamic problem presented in the article as it demonstrates how and why marine deep-sea mining may emerge, coupled with the knowledge of supply concerns and demand projections in global mineral markets.

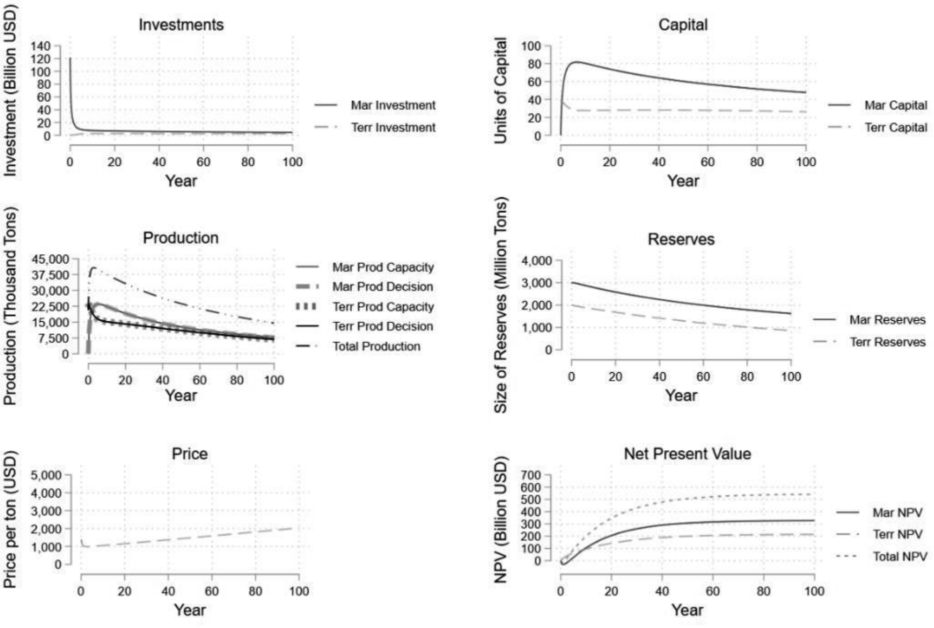


Fig 3: Reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations, Sensitivity to doubling of m_2 (Bang & Trellevik, 2022b).

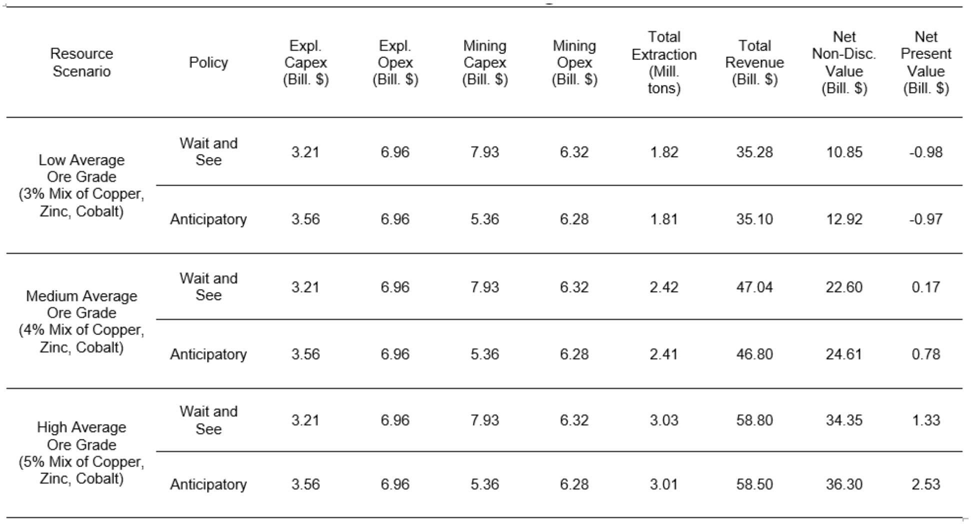
Fig. 3 shows the development of terrestrial and marine mineral production in a scenario where a doubling of the marine factor productivity turns the marine sector into the dominant producer despite its initiation with no capital and requirement for substantial investment costs to establish production capital. This further demonstrates that the marine mining sector could be leveraged to benefit from the advantage of abundant resources, assuming a reasonable approach to extraction. A doubling of m2 also turns the marine sector into the dominant producer (Bang & Trellevik, 2022b).

The consequence of the above analysis is that deep-sea mining may indeed emerge due to dwindling resources on land, growing demand, and the willingness to accept a premium for secure supply. Although this may be an intuitively available conclusion, it is still of value to simulate and understand how such development would unfold. It is furthermore of value if any particular outcome were to be defined as a policy goal. As such, this conceptual study affords some clear thinking, as postulated by Zeckhauser (2010), on how future states may play out and what policy space may be available.

Also, the articles *“Perspectives on exploration and extraction of seafloor massive sulfide deposits in Norwegian waters”* and *“Exploring exploration — how to look for deep - sea minerals”* shed light on the question of why deep-sea mining may emerge as an industry (Bang & Trellevik, 2022a; Trellevik, 2023a). These articles demonstrate the possibilities for profitable national industrial enterprise in the case of deep-sea mining of SMS deposits in Norwegian waters; this partly answers why industrial deep-sea mining may arise. The prospective profits do not, however, come without caveats.

“Perspectives on exploration and extraction of seafloor massive sulfide deposits in Norwegian waters” shows that it is not given that extraction of deep-sea minerals from SMS deposits will be profitable. This depends on the actual average aggregated ore grade of the mineral mix in SMS deposits and the investment policies assumed. The article tests numerous scenarios where stochastic variables are given different ranges and constraints.

Table 1. Overview of Baseline Simulation Results. Average Values Across 1000 Monte Carlo Runs (Bang & Trellevik, 2022a).



Resource Scenario	Policy	Expl. Capex (Bill. $)	Expl. Opex (Bill. $)	Mining Capex (Bill. $)	Mining Opex (Bill. $)	Total Extraction (Mill. tons)	Total Revenue (Bill. $)	Net Non-Disc. Value (Bill. $)	Net Present Value (Bill. $)
Low Average Ore Grade (3% Mix of Copper, Zinc, Cobalt)	Wait and See	3.21	6.96	7.93	6.32	1.82	35.28	10.85	-0.98
	Anticipatory	3.56	6.96	5.36	6.28	1.81	35.10	12.92	-0.97
Medium Average Ore Grade (4% Mix of Copper, Zinc, Cobalt)	Wait and See	3.21	6.96	7.93	6.32	2.42	47.04	22.60	0.17
	Anticipatory	3.56	6.96	5.36	6.28	2.41	46.80	24.61	0.78
High Average Ore Grade (5% Mix of Copper, Zinc, Cobalt)	Wait and See	3.21	6.96	7.93	6.32	3.03	58.80	34.35	1.33
	Anticipatory	3.56	6.96	5.36	6.28	3.01	58.50	36.30	2.53

The simulation results summarized in Table 1 reveal a substantial range of total mineral extraction. The lowest estimate is 1.8 million tons of copper, zinc, and cobalt; the highest is more than 3 million tons. This further implicates a range of net present values between a negative value of 970 million USD and a positive value of 2.53 billion USD (Bang & Trellevik, 2022a). This can be accredited to both ore grade and investment policy. The ore grade is subject to uncertainty; there is no comprehensive empirical data on which an average ore grade can be established with any certainty for the Norwegian SMS deposits (Bang & Trellevik, 2022a; Pedersen et al., 2021). Should the lower ore grade of 3 percent prove to be accurate, the investment policy would not be able to generate a profitable national endeavor into SMS mining. On the other hand, should the average ore grade of the mineral mix prove to be 4 percent or more, SMS mining is likely to be profitable regardless of policy – and considerably more so with an anticipatory investment policy (Bang & Trellevik, 2022a).

In other words, depending on the ore grade of the Norwegian case, possible and reasonable financial arguments for why deep-sea mining may be established. This is, however, not necessarily true in other locations. Nautilus Metals Inc. where close to establishing commercial mining on the Solwara 1 prospect in the Bismarck Sea – but went bankrupt prior to full-scale commencement (Glasby, 2002; Toro et al., 2020; Trellevik, 2023a).

It should in this regard be noted, as this is integral to the simulation model on which the analysis is based, that the Norwegian case is both (A) modeling an aggregated, national level, industry complex, and (B) that the model assumes an existing fleet and competence pool able to partake in the simulated industry. Considering the concept of ecological fallacies, that things being true on an aggregated level does not necessarily make them true on the disaggregated level, this aggregation level is critical (Woodruff et al., 2018). There is no reason to make predictions of any one enterprise based on the aggregated analysis results – or vice versa. Furthermore, a company rigging to embark on commercial mineral extraction in the Bismarck Sea does so far from any hub of subsea capital and competence. The opposite is true in Norwegian waters, where a substantial offshore industry is established servicing oil and gas-related activity (Bang & Trellevik, 2022a; Trellevik, 2023a). The failed case of Nautilus Minerals Inc. henceforth is of little application as a case study relative to the aggregated, national-level SMS case in Norway. Of note, however, one may be justified in concluding that the presence of an already established subsea industry may be necessary for the profitable establishment of an SMS industry. The latter finds support in that an anticipatory investment policy yields greater returns in the simulated scenarios. This can be accredited to a reduced period of depreciation, which in turn boosts net present value; this effect is substantial across all scenarios. From this, it can be deduced that the pre-existence of capital and competence will be of importance for the profitable establishment of an industry. In turn, this may lead to, at the very least, qualified speculation related to which geographic regions may be equipped to pursue deep-sea mining.

4.3 In the case of Norway, how would deep-sea mining unfold, and to what avail?

The preceding chapter discussed how Norway may claim profitability within SMS exploration and extraction if the ore grade of deposits exceeds 3 percent. The articles *"Perspectives on exploration and extraction of seafloor massive sulfide deposits in Norwegian waters"* and *"Exploring exploration — how to look for deep - sea minerals"* do, however, present more elaborate insight into how such an industry may materialize (Bang & Trellevik, 2022a; Trellevik, 2023a).

Based on an iterative and extensive qualitative research process, *"Perspectives on exploration and extraction of seafloor massive sulfide deposits in Norwegian waters"* presents a model-based synthesis of an aggregated SMS deep-sea mining industry, as shown in Figure 2.

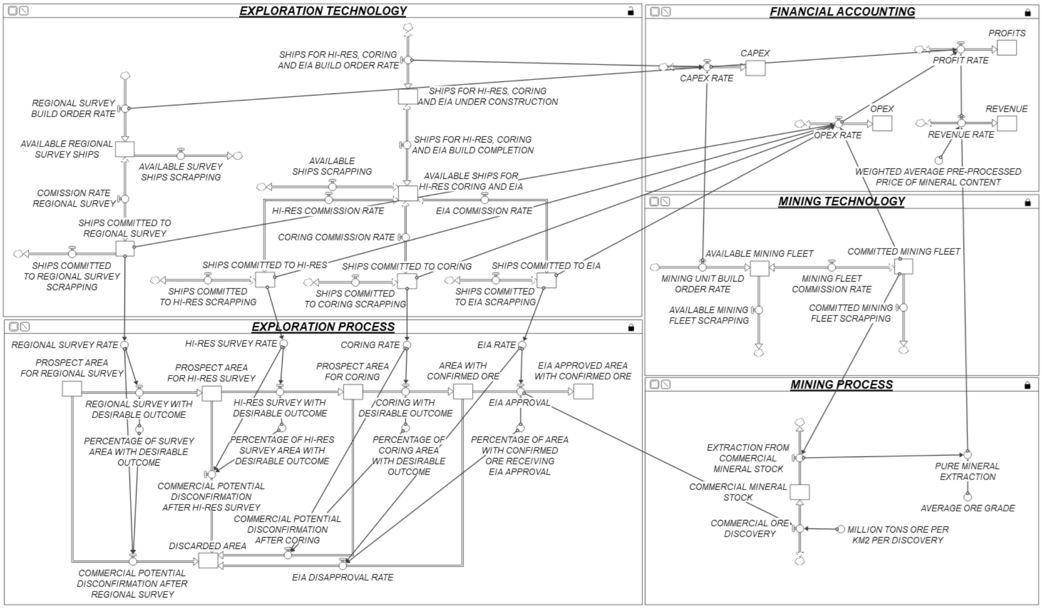


Fig 4: Simplified High-level Model Overview (Bang & Trellevik, 2022a).

The model has five sectors. The first sector, in the lower left corner of Fig. 4, presents an overview of the exploration process. The second sector describes the exploration technology in the upper left corner. In the lower right corner, the third sector outlines the mining process, while the fourth, the middle right sector, captures the mining technology. Finally, the fifth sector tracks financial accounting. This synthesis arises from qualitative data eliciting how an array of stakeholders and experts envision that a Norwegian SMS mining industry will likely be organized and operating. As a stand-alone model, this is a contribution in its own right; as such, a synthesis has yet to be presented prior to this article's publication (Bang & Trellevik, 2022a). Thus, it also partially answers the research question discussed in this chapter.

The model demonstrates that there are likely to be two categories of vessels engaged in SMS exploration. Relatively small and cost-efficient vessels conducting regional surveys and a fleet of larger multipurpose subsea vessels dividing their time between hi-resolution surveys, coring operations, and environmental impact assessments. There is a priority of fleet utilization embedded in the model where exploration phases are given priority depending on their proximity to the exploration stage. This means that environmental impact assessments are prioritized over coring, and coring operations are, in turn, prioritized over hi-resolution surveys. The logic behind this is risk management and maturity of prospects. Depreciation is a major challenge throughout an industry with a long lead time between early exploration and minerals entering the commodity markets; it is essential to expedite cash flow by carrying mature prospects through to the extraction phase (Bang & Trellevik, 2022a).

The synthesis further describes the development and commissioning of extraction capital. This is the techno-operational concept included in the model with the least conceptual detail. The experts and stakeholders contributing to the study are unclear on how and what this technology and fleet would look like. There are, however, analogies of interest from the oil and gas industry – and these dictate cost frames and capacities. This sector does, regardless, infer considerable uncertainties and is, as with any future technological innovation concept, dependent on a number of currently semi-qualified assumptions with wide confidence bands (Bang & Trellevik, 2022a).

This article further indicates a substantial market to be considered for vessel owners and contractors engaging in the potential SMS exploration process. Over the simulation horizon, a significant number of vessels, particularly the larger and more advanced multipurpose subsea vessels, are committed to exploration activities. The same is valid for operators of mining fleet assets.

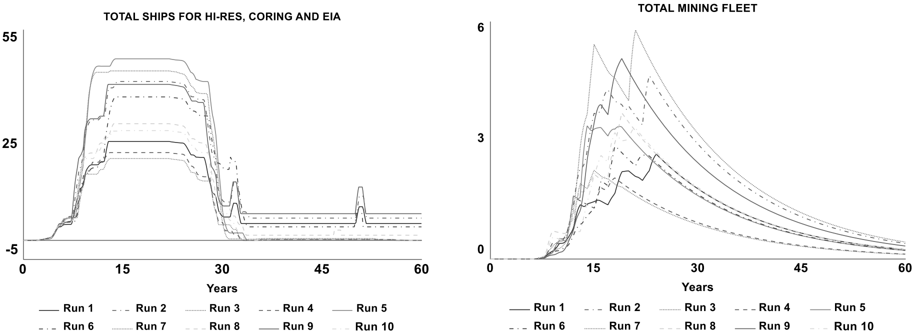


Fig. 5. Total Ships and Mining Units Trajectories over a Random Selection of Monte Carlo Runs in the Medium Average Ore Grade Scenario with the 'Anticipatory' policy (Bang & Trellevik, 2022a).

Figure 3 shows the multipurpose vessel and mining units employed at randomly chosen Monte Carlo simulations. In these selected simulation runs, approximately between 20 and 50 multipurpose vessels are consistently utilized over approximately 20 years. This is an encouraging market perspective for Norwegian vessel owners and subsea contractors. Simultaneously, the requirement for mining units, conceived as complete units including subsea assets, surface platforms, and logistic vessels, is more restricted. There is, in other words, no indication in this simulation calling for a massive mining fleet to be built; these selected simulation runs indicate a requirement for between approximately two and six complete mining units, with a waning requirement from about year 25 (Bang & Trellevik, 2022a).

This model and its model boundary exclude any onshore processing of marine minerals. This is an element to consider when analyzing the possible development of deep-sea mining in Norway. Onshore processing could infer jobs, logistics, infrastructure, and considerable value added. As the model excludes this, the price of minerals is significantly reduced as a constant fraction of the market value of refined minerals in the financial accounting sector of the model. Any onshore activity henceforth lies beyond the scope of this Thesis and is not be discussed further (Bang & Trellevik, 2022a).

Also beyond the scope of this model is any externality introduced by deep-sea mining on SMS deposits. Externalities in this context refer to phenomena such as environmental degradation, competition with other industries, or shifts in mineral demand due to new technologies or economic growth. This study can, therefore, only be applied to the analysis of the possible industry itself and little beyond that (Bang & Trellevik, 2022a).

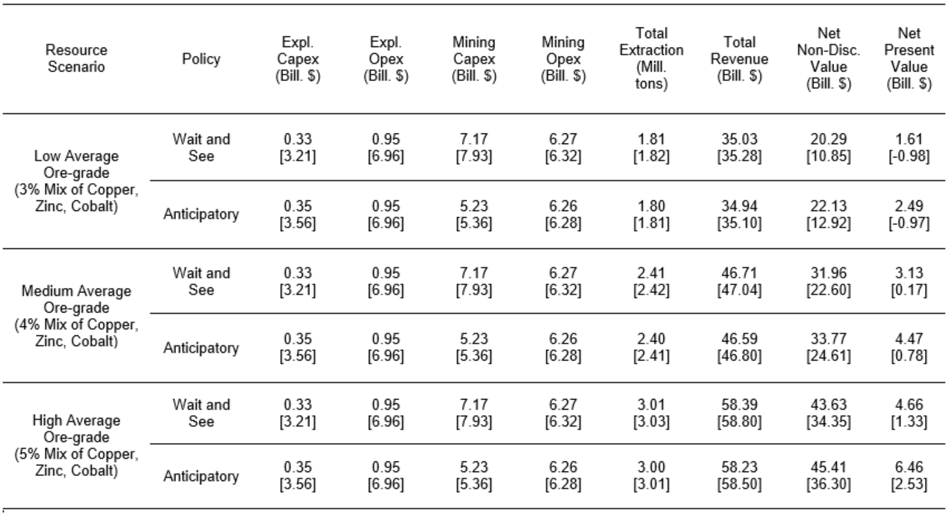
4.4 What is the techno-operational gap for robust SMS mining on the NCS?

The article *"Exploring exploration — how to look for deep - sea minerals"* explores the innovation space within SMS mining in Norwegian waters. This article employs the same simulation model but introduces emerging techno-operational concepts that can alter the projected trajectories of the potential aggregated industry. These techno-operational concepts are all focused on the SMS deep-sea mining exploration phase.

This article introduces and analyzes three techno-operational concepts for SMS exploration. The concepts are tested separately and in all possible combinations and subjected to extensive sensitivity analysis.

The three techno-operational concepts in the article are referred to as policies: *(Policy A)* Utilization of remotely operated, unmanned surface vessels (USVs) for regional surveys. *(Policy B)* Utilization of fleet-operated autonomous underwater vehicles (FAUV) for high-resolution surveys. *(Policy C)* Utilization of geophysical methodology to augment the geographical footprint of conventional coring operations. These techno-operational concepts are currently emerging in the industry, also for different offshore segments, and have reached variable maturity levels (Trellevik, 2023a).

Table 2. Overview of Simulation Results with Policy A + C. Average Values Across 1000 Monte Carlo Runs with baseline results in brackets (Trellevik, 2023a).



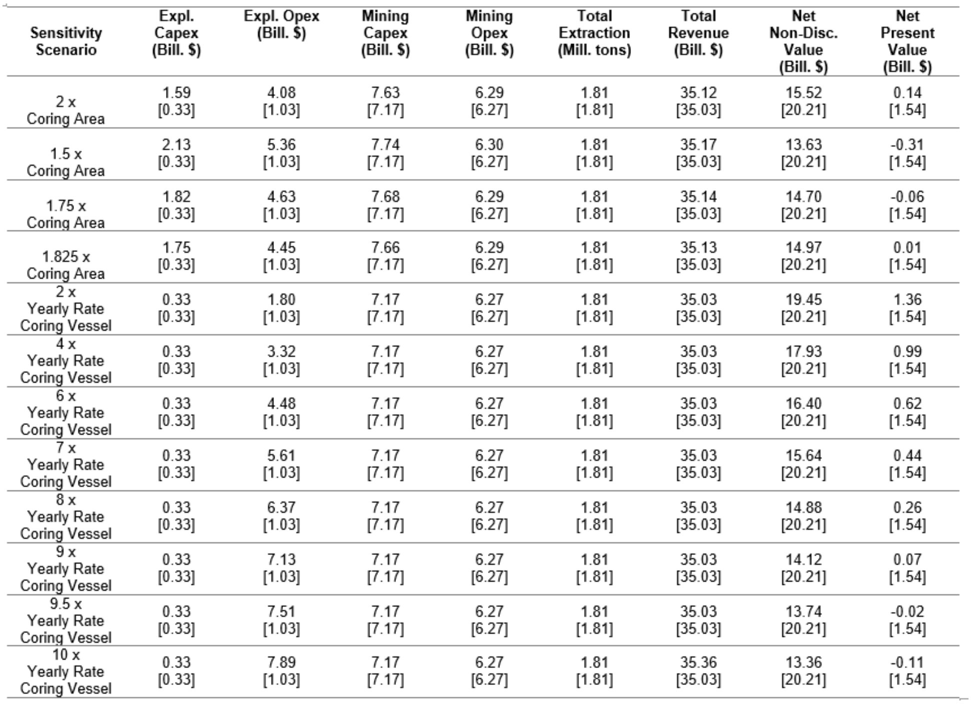
Resource Scenario	Policy	Expl. Capex (Bill. $)	Expl. Opex (Bill. $)	Mining Capex (Bill. $)	Mining Opex (Bill. $)	Total Extraction (Mill. tons)	Total Revenue (Bill. $)	Net Non-Disc. Value (Bill. $)	Net Present Value (Bill. $)
Low Average Ore-grade (3% Mix of Copper, Zinc, Cobalt)	Wait and See	0.33 [3.21]	0.95 [6.96]	7.17 [7.93]	6.27 [6.32]	1.81 [1.82]	35.03 [35.28]	20.29 [10.85]	1.61 [-0.98]
	Anticipatory	0.35 [3.56]	0.95 [6.96]	5.23 [5.36]	6.26 [6.28]	1.80 [1.81]	34.94 [35.10]	22.13 [12.92]	2.49 [-0.97]
Medium Average Ore-grade (4% Mix of Copper, Zinc, Cobalt)	Wait and See	0.33 [3.21]	0.95 [6.96]	7.17 [7.93]	6.27 [6.32]	2.41 [2.42]	46.71 [47.04]	31.96 [22.60]	3.13 [0.17]
	Anticipatory	0.35 [3.56]	0.95 [6.96]	5.23 [5.36]	6.26 [6.28]	2.40 [2.41]	46.59 [46.80]	33.77 [24.61]	4.47 [0.78]
High Average Ore-grade (5% Mix of Copper, Zinc, Cobalt)	Wait and See	0.33 [3.21]	0.95 [6.96]	7.17 [7.93]	6.27 [6.32]	3.01 [3.03]	58.39 [58.80]	43.63 [34.35]	4.66 [1.33]
	Anticipatory	0.35 [3.56]	0.95 [6.96]	5.23 [5.36]	6.26 [6.28]	3.00 [3.01]	58.23 [58.50]	45.41 [36.30]	6.46 [2.53]

Table 2 shows the most successful techno-operational improvement baseline scenario in *"Exploring exploration — how to look for deep - sea minerals"* (Trellevik, 2023a). In this scenario, USVs are utilized for conducting regional surveys (*Policy A*), and geophysical augmentation of coring operations is applied (*Policy C*) alongside conventional physical coring operations. This combined policy generates significantly lower Exploration Capex and Exploration Opex than *Policies A* or *B* or the combination of the two policies. *Policy A +B* generates higher NPV than *Policy C.* Henceforth, combining USVs with geophysical sampling is beneficial.

It is worth noting that applying these two policies generates a positive net present value in every ore-grade and investment scenario. These two techno-operational concepts, in conjunction, are at the most meager average ore-grade scenario and risk-averse investment regime able to generate an NPV of 1.61 Billion USD, which is a more advantageous financial prospect than the negative 970 Million USD under the same conditions, but without these tecno-operational concepts in play. Likewise, at the other end of the scale, lies the high average ore-grade scenario where accumulated NPV can reach as much as 6.46 Billion USD. It is reasonable to conclude that successful implementation of USVs and Geophysical data augmentation may render the SMS prospects significantly more robust on the aggregated level, then what can be expected without these techno-operational concepts in place (Trellevik, 2023a). The main contributor to these results is *Policy C*. While USVs positively affect NPV, the effect is marginal. It is also of interest that *Policy B,* the utilization of fleet-operated AUVs, may have a negative effect on NPV. This techno-operational concept may be counterproductive.

Sensitivity analysis further elaborates how critical a sound geophysical methodology for enhancing the geographic footprint of coring operations is.

Table 3. Overview of Sensitivity Results with Policy C at 3 % Average Ore-grade and “Wait and See” setting, Average Values Across 1000 Monte Carlo Runs with *Policy C* baseline results in brackets (Trellevik, 2023a).



Sensitivity Scenario	Expl. Capex (Bill. $)	Expl. Opex (Bill. $)	Mining Capex (Bill. $)	Mining Opex (Bill. $)	Total Extraction (Mill. tons)	Total Revenue (Bill. $)	Net Non-Disc. Value (Bill. $)	Net Present Value (Bill. $)
2 x Coring Area	1.59 [0.33]	4.08 [1.03]	7.63 [7.17]	6.29 [6.27]	1.81 [1.81]	35.12 [35.03]	15.52 [20.21]	0.14 [1.54]
1.5 x Coring Area	2.13 [0.33]	5.36 [1.03]	7.74 [7.17]	6.30 [6.27]	1.81 [1.81]	35.17 [35.03]	13.63 [20.21]	-0.31 [1.54]
1.75 x Coring Area	1.82 [0.33]	4.63 [1.03]	7.68 [7.17]	6.29 [6.27]	1.81 [1.81]	35.14 [35.03]	14.70 [20.21]	-0.06 [1.54]
1.825 x Coring Area	1.75 [0.33]	4.45 [1.03]	7.66 [7.17]	6.29 [6.27]	1.81 [1.81]	35.13 [35.03]	14.97 [20.21]	0.01 [1.54]
2 x Yearly Rate Coring Vessel	0.33 [0.33]	1.80 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.03 [35.03]	19.45 [20.21]	1.36 [1.54]
4 x Yearly Rate Coring Vessel	0.33 [0.33]	3.32 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.03 [35.03]	17.93 [20.21]	0.99 [1.54]
6 x Yearly Rate Coring Vessel	0.33 [0.33]	4.48 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.03 [35.03]	16.40 [20.21]	0.62 [1.54]
7 x Yearly Rate Coring Vessel	0.33 [0.33]	5.61 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.03 [35.03]	15.64 [20.21]	0.44 [1.54]
8 x Yearly Rate Coring Vessel	0.33 [0.33]	6.37 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.03 [35.03]	14.88 [20.21]	0.26 [1.54]
9 x Yearly Rate Coring Vessel	0.33 [0.33]	7.13 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.03 [35.03]	14.12 [20.21]	0.07 [1.54]
9.5 x Yearly Rate Coring Vessel	0.33 [0.33]	7.51 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.03 [35.03]	13.74 [20.21]	-0.02 [1.54]
10 x Yearly Rate Coring Vessel	0.33 [0.33]	7.89 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.36 [35.03]	13.36 [20.21]	-0.11 [1.54]

Table 3 demonstrates that less than a doubling of the footprint of the area covered by coring, renders a positive NPV in the 3 percent ore-grade and "wait and see" scenario. The sensitivity analysis shows that the yearly vessel rate of multipurpose vessels engaged in coring operations can increase more than nine times and still yield a positive NPV for the aggregated industry. This suggests that the geophysical methodology does not have to be revolutionary in its efficacy to render a robust aggregated national industry (Trellevik, 2023a).

5. Conclusions and Further Research

This Thesis explores and illuminates how deep-sea mining may unfold and thereby contribute a basis for qualified decisions and sound policy design. The Thesis first demonstrates that a multidimensional and inclusive problem definition may be established by applying the qualitative methodology and a broad systems-perspective modeling approach. Having contributed such a problem definition, the Thesis does not explore every facet of that exact definition. However, it focuses on certain constituent parts and invites the scientific and other communities to populate the analysis. The multidimensional problem definition includes geopolitics, climate change, green- and high-tech production growth, environmental degradation, socio-ethical dimensions, and global mineral and mining markets. The Thesis does not exhaustively examine all these arenas but dives deep into exploring several synergies and trade-offs captured in this problem definition (Trellevik, 2023b).

The Thesis postulates that factors present today may encourage or accelerate a process where deep-sea mining is included in the global mineral supply mix. It shows that depleting reserves on land inevitably will favour new and untapped resources, such as deep-sea minerals, regardless of their initial capital requirements (Bang & Trellevik, 2022b). This is reflected also in the Norwegian SMS case. This case, inevitably dominated by uncertainty, may prove profitable on the aggregated level, also at the lowest ore-grade predictions provided by experts, if the industry focuses on targeted innovation of techno-operational concepts (Bang & Trellevik, 2022a; Trellevik, 2023a). The Thesis demonstrates, furthermore, that the obtained advancements in cost-efficiency do not need to be revolutionary to facilitate a robust national business case for embarking on SMS mining (Trellevik, 2023a). Simultaneously, the Thesis exhibits that the development of SMS mining may generate significant activity for the Norwegian offshore fleet and subsea service sector (Bang & Trellevik, 2022a). This suggests employment both onshore and offshore, as well as support activities amongst subcontractors within a plethora of logistical, technical, and administrational fields. Such activity would obviously entail national tax revenue and possible export revenues should these services be required outside of Norwegian waters.

The Thesis does not consider mineral-related activity beyond the activity offshore. Smelting and refinement and such industrial arenas are thus not included. This segment is where considerable value is added and would be relevant for policymakers considering the societal and socio-economic impact of deep sea mining (Bang & Trellevik, 2022a; Trellevik, 2023a, 2023b).

The Thesis demonstrates that geopolitical turmoil and derived supply security considerations are essential for the emergence of deep-sea minerals (Bang & Trellevik, 2022b; Trellevik, 2023b). When considering the Norwegian case, this notion should be included in the considerations. Close allies and trade partners of Norway, The European Union, and the United States have both attached considerable geopolitical risk to the supply of critical minerals (Bang & Trellevik, 2022b; European Council, 2022; Kalantzakos, 2020; United States Geological Survey (USGS), 2020). As this Thesis shows, Norway could become a significant producer of critical minerals such as copper, cobalt, zinc, gold, silver, rear earth minerals, and more, by way of deep-sea mining, without dire economic risk, as deep-sea-mining of SMS resources can be shaped and developed robustly in the Norwegian case (Bang & Trellevik, 2022a; Trellevik, 2023a). This should undoubtedly be of note for Norwegian policymakers engaging with deep-sea mining. During the war in Ukraine and the derived energy crisis in Europe, Norway has profited substantially through exports of natural gas and reaffirmed strategic alliances by supplying this much-needed resource upon urgent request (Norsk Petroleum, 2022). Mineral resources should be considered within the same framework of thinking.

Since the dawn of commercial electrification, the establishment, and proliferation of, electrical power generation and distribution have dictated massive shifts in the demand for various minerals, particularly copper (Radetzki, 2009). The International Energy Agency forecasts a substantial surge in demand for critical minerals utilized for green power generation and transmission (International Energy Agency (IEA), 2021). This, particularly when coupled with the risk associated with asymmetrically distributed mineral supply between different interest spheres and the urgent global requirements for accelerated electrification and technological shift on account of climate change, should be included in the notes of policymakers in Norway and beyond.

This Thesis does not explore the possible negative regional and local consequences for deep-sea ecosystems on account of deep-sea mining to any considerable extent. As suggested in the multidimensional problem definition, this is clearly a topic that merits adequate attention (Trellevik, 2023b). The Thesis simply considers such effects as externalities in the model-based articles included in the study (Bang & Trellevik, 2022a, 2022b). However, this does not suggest in any way or form that these effects are not to be considered but simply that they have been placed beyond the defined modeling boundaries. Moreover, the Thesis draws up a problematic trade-off and conflict line, constituted by the direct biodiversity loss or environmental degradation that may be invoked by deep-sea mining and the biodiversity loss inflicted by global warming (Trellevik, 2023b). All the time, no industrial-scale deep-sea mining has yet been executed, and while the deep-sea ecosystems are still poorly understood and surveyed, this challenge, as with all questions of the deep sea, is subject to epistemic uncertainty. While Post Normal Science may inform decision-makers engaged in uncertain realities under expressed urgency, further modeling and simulation exercises along the methodological lines of those developed and included in this Thesis may be valuable and important for facilitating "Clear Thinking" on these complex decision-gates. As such, this is undoubtedly a domain that calls for further research, modeling, and analysis. This Thesis and the theoretical framework and methods developed and applied could be transferred or inform such modeling, simulation, and exploration initiatives.

6. Positionality

When I started pursuing a Ph.D., I had already spent 15 years in the offshore- and subsea industry. During this time, I worked in technical and managerial positions for several companies. Throughout my career, I had the opportunity to focus on what in the industry is known as "Ultra-Deepwater" operations – loosely defined as subsea operations below 3500 meters. At this depth, there is little or no oil- and gas activity, which is what occupies most of the offshore fleet throughout the year. As such, this specialization on deepwater, afforded me the opportunity to work with deep-water salvage, innovation, survey, and research projects. Through this stint, I gained valuable and rather unique competence that only a minimal segment of the offshore- and subsea industry is entrusted with.

Through my previous career, I also had the opportunity to build a significant network with other deep-sea professionals and the wider offshore- and subsea community. During my tenure as operations and project manager for deep-sea operations, I planned and executed the successful salvage of hundreds of tons of gold and silver, the salvage of the Apollo 11 booster engines, we searched for and found a substantial amount of shipwrecks, airplanes and other objects swallowed by the abyss, and we supported research expeditions—all of this at depths between 3500, and 5700 meters. One of the research expeditions I had the pleasure of working with in 2014 was with the University of Bergen – they were exploring hydrothermal vent systems in the Norwegian Sea. As mentioned above – these systems fuel the deposition of deep-sea minerals on the Norwegian continental shelf (Pedersen et al., 2021, 2010).

My experience and knowledge of the deep sea and operations in this hostile environment taught me two important lessons: (1) We can do incredibly difficult things at incredible depths, and (2) there are resources at these great depths that would be interesting to explore further.

In the hydrothermal vent systems along the mid-Atlantic ridge in the Norwegian Sea, there are mineral deposits, fascinating and unique biology of interest to genetic bioprospecting, and considerable thermal resources. All of these could one day emerge as important resources. As an opportunity for a research grant emerged at the University of Bergen, I was privileged to become a Ph.D. research fellow with the System Dynamics Group and the Center for Deep-Sea Research.

My background and my ties to the industry have allowed me to gain access to an otherwise less-than-transparent industrial complex to conduct qualitative research. This has been a foundational asset and of tremendous value to my work with this Thesis. Having refused to speak to researchers in my professional past, I was fully aware that gaining access to board rooms, ROV hangars, public administration, and tech labs was difficult for any "outsider." Not only is everyone always very busy, but there is, to some extent, also a reluctance to talk to strangers about emerging technology, strategy, and markets. My name and network got me through many of those doors with ease, and I could elicit information at the cutting edge of the offshore- and subsea sector. This has lifted the quality of my work simply by providing better data and has brought me closer to answering my research questions.

However, my background also introduces an array of possible biases that I may or may not carry with me as a former deep-sea professional. This must be handled with care. First and foremost, may be the risk of omittance, as it is difficult to access sources beyond my network in this somewhat candid sector. There may be technologies, strategies, policies, or other insights overlooked in the qualitative work, either because I could not get the interviews set up or because companies or professionals choose to remain opaque for now for strategic or competitive purposes. There may also be a level of confirmation bias innate in my analysis. As a former professional in the field, I may hold several pre-conceptions that may or may not be accurate. Finally, there may be an innate conflict of interest in my work. Once my Ph.D. is submitted, Deep-sea mining is likely to unlock job opportunities for me or my former friends and colleagues in the subsea industry.

I feel confident that I have omitted, or at the very least, significantly reduced, fallacies introduced by biases embedded in my positionality. Three barriers mitigate positionality bias. (1) Rigorous application of the qualitative methodology and several iterations of disconfirmatory interviews, as well as iterative workshops with stakeholders and experts of different perspectives, reduces the risk of bias inflecting into my analysis. (2) Close collaboration and co-authorship with authors with no ties or history with the industry also reduce the effect of my possible biases. (3) Peer review of my articles also serves the purpose of reducing the effect of bias.

This Thesis assumes no normative position. It assumes that deep-sea mining *may* happen. First, it explores approaches to framing problem definitions and synthesizes and simulates why, how, and to what avail some aspects of that potential industry may evolve.

Source of data

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7. Appendix I

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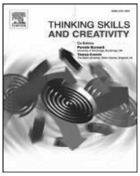

Sustainability-oriented innovation: Improving problem definition through combined design thinking and systems mapping approaches

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ABSTRACT

Sustainability-oriented innovation (SOI) is receiving increased focus, as sustainability takes a more central role in business, development, and education arenas. SOI processes typically draw from design thinking toolkits, with a focus on the user's needs and experiences. While this is an effective way to ensure that the innovation process is grounded in real, definable needs, it's also limited in its ability to place the problem in a larger societal and systemic context. This can lead to a narrow or incomplete problem definition.

We designed and tested a new approach for eliciting and defining problems for SOI. Our work shows that using systems mapping in the problem definition phase of SOI helps set adequate boundaries for the problem space and increases understanding of how the system influences itself over time. As "sustainability" is a systems property, we find that the "helicopter view" provided by systems mapping complements the empathetic design thinking approach to form a more robust problem definition. We present this combined methodology and provide examples of where and how it's been used. These examples illustrate the potential of design thinking and systems mapping to support and enhance problem definition for SOI and provide the basis for discussing future research directions.

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1. Introduction

Adequate and comprehensive problem definition is a key step in any type of innovation process, but it is particularly true when innovating for sustainability. Sustainability-oriented innovation (SOI) has defined characteristics that distinguish it from other types of innovation processes, including the need to include a long time horizon, examine the problem in a larger context, and consider multidimensional targets (ie, environmental, social, and economic impacts) (Buhl et al., 2019).

Innovation processes typically draw from design thinking toolkits. The design thinking approach focuses on the user's needs and experiences, which provide valuable insights that guide innovation development (Carlgren, Rauth, & Elmquist, 2016; Roth, Globocnik, Rau, & Neyer, 2020). While this approach is an effective way to ensure that the innovation process is grounded in real, definable needs, it's also limited in its ability to place the problem in a larger societal and systemic context (Hoolohan & Browne, 2020). This can lead to a narrow or incomplete problem definition. The unique characteristics of SOI heighten the importance of developing a holistic problem definition, yet current SOI development is usually characterized by ill-specified problem statements (Buhl et al., 2019).

Systems mapping is a group model building approach that focuses on empowering participants to create a shared understanding of a complex problem (Hovmand, 2014; Hovmand et al., 2012; Videira, Antunes, Santos, & Lopes, 2010). The approach to and understanding of systems is an outgrowth of systems thinking and system dynamics. The suite of tools implemented in systems mapping are particularly helpful in creating consensus around adequate system boundaries and understanding how the system influences itself over time from an aggregated and cross-disciplinary perspective (Videira et al., 2010). This approach addresses some of the key needs of SOI, but on it's own, systems mapping can lack the specificity and empathetic perspective that design thinking engenders (Buchanan, 2019). We assert that an approach that includes both design thinking and systems mapping can create a more in-depth and richly detailed problem description that includes both individual perspectives and systemic understanding.

Our approach, called systems sustainability-oriented innovation (SSOI), builds on the strengths of design thinking and systems mapping practices to create a more robust problem statement.

We present the theory behind this approach and discuss the practical considerations of employing such an approach. Finally, we provide two empirical examples of a combined approach in problem definition workshops. These examples illustrate the potential of SSOI to support and enhance problem definition for sustainability innovation and provide the basis for discussing future research directions.

1.1. *Sustainability and innovation*

Sustainability is increasingly identified as a key driver of innovation for companies, and environmental and social criteria have been incorporated into default design criteria, in addition to traditional criteria such as profitability, aesthetics, etc. (Gaziulusoy, 2015). Sustainability is a broad and normative concept, with a problem- and process-oriented application that has grown out of a desire to ensure that both current and future generations can meet their own needs without compromising planetary life support systems (Brundtland, 1987; Nagatsu et al., 2020; Shahadu, 2016). Innovation that accounts for sustainability requires explicit consideration of sustainability's defining characteristics.

"Sustainability" is a system property, rather than a property of elements in the system. Only when the system as a whole is sustainable can the individual components of the system be considered sustainable (Gaziulusoy, 2015). This has implications for individuals embedded in a society and what level(s) of society a SOI should target. Innovation for sustainability needs a systems vantage point to evaluate the product/service innovation within the system in which they will be produced and consumed (Gaziulusoy, 2015; Gaziulusoy & Brezet, 2015).

In addition, the emergent qualities of systems mean that the consequences of working towards or achieving sustainability may be different at the individual versus the societal level, raising questions of social justice (Bennett, Blythe, Cisneros-Montemayor, Singh, & Sumaila, 2019). Individuals may need to change their lifestyles and livelihoods in ways that are difficult or uncomfortable in order to move towards sustainability at the societal level. Changes that may be experienced as negative at the individual level may have emergent positive impacts at the societal level, reinforcing the need for SOI to consider both individuals and society in an explicitly systems perspective (Bennett et al., 2019).

"Sustainability" is inherently multidimensional, and working towards sustainability innovation requires consideration of multidimensional targets (Buhl et al., 2019; Videira et al., 2010). Operationalizing sustainability requires a comprehensive consideration of actions and impacts across sectors (such as environment, society, and economy) and a recognition of interrelations and interdependency across spatial and temporal scales (including future generations) (Gibson, 2006; Hjorth & Bagheri, 2006; Videira et al., 2010).

These characteristics of sustainability have consequences for designing an appropriate innovation process. Typical innovation processes are focused on individual products or services. These innovations result in only minor improvements in sustainability terms (Gaziulusoy & Brezet, 2015), yet sustainability-oriented innovation (SOI) will often require solutions that move beyond incremental adjustments on a product or technology level (Buhl et al., 2019). Explicitly incorporating and addressing the distinctive aspects of sustainability, described above, in the innovation process is necessary for SOI. Innovation aimed at sustainability should have a systems and societal scope that accounts for multidimensional targets (Buhl et al., 2019).

In particular, problem definition is an often neglected phase in SOI, and current SOI processes are usually characterized by poorly- specified problem statements (Buhl et al., 2019). Defining the scope of the problem defines the space in which innovative solutions can be developed. A problem defined too narrowly limits the space of available solutions and might therefore lead to solutions that are too confined to have a meaningful impact (Hoolohan & Browne, 2020). Traditional approaches to innovation tend to focus on individual users and their needs when defining the problem. This focus, though valuable, can exclude the broader, cross-sectoral and systems perspectives needed to adequately define a sustainability related problem.

1.2. *Current approaches to problem definition*

The innovation and design fields are characterized by plurality and, as a result, ambiguity in terms and approaches (Buchanan, 2019). While other academic fields typically emphasize convergence on canonical theories, the shifting and distributed nature of social innovation's theoretical foundation is often viewed as an asset for further development (Bijl-Brouwer & Malcolm, 2020). Approaches overlap (and complement) in name and methodology, with some based in theories of constructivist learning and others derived from practice and experience (Buchanan, 2019; Sevaldson, 2018). Rather than defined methodologies, design tools can be better understood as a suite of adaptive practices tailored to the specific needs of the problem being examined (Bijl-Brouwer & Malcolm, 2020).

Among these many adaptive practices, we focus on design thinking as a well-established and widely applied approach within the design practitioner SOI community. Design thinking is a suite of practitioner-based, problem solving approaches that typically emphasizes a user-centered, empathetic process (Buhl et al., 2019). The approach is loosely characterized by a blend of creative and analytic modes of reasoning and various hands-on tools and techniques (Buhl et al., 2019). As a suite of practices, design thinking implementation varies across contexts, with some practices emphasizing iteration and others focused on deep user empathy and understanding (Carlgren et al., 2016). As such, there is no single accepted definition of design thinking (Buhl et al., 2019; Carlgren et al., 2016; Jones, 2014). Most existing literature on design thinking is aimed at practitioners rather than academics, and it tends to emphasize tools and activities rather than theoretical foundations (Buhl et al., 2019).

Design thinking projects typically start with an exploratory phase that seeks to empathetically understand the given problem from the user's perspective. Through observing users in real-life situations in context, the practitioner defines an adequate problem and solution space (Buhl et al., 2019; Carlgren et al., 2016). This focus on immediate users can infuse the design process with empathy and realism, providing valuable insights into what people do, value, and desire (Hoolohan & Browne, 2020).

One common, established expression of design thinking is the “double diamond” (Clune & Lockrey, 2014; Conway, Masters, & Thorold, 2017) (Fig. 1). As a practice, the double diamond is typically defined as having five steps that are iteratively applied. The five steps are divided into diverging and converging phases, where diverging phases widen perspectives and converging phases increase focus.

Within these double diamonds, five steps are typically defined. (1) Empathy: the point of view of the user is elicited.(2) Define: Knowledge about the user is distilled and formulated as specific needs, wants or requirements (problem definition). (3) Ideation: ideas for solutions are formulated based on the specific needs and requirements one is aiming to satisfy.(4) Prototyping: ideas are implemented in first stage products or services.(5) Testing: potential users and other relevant stakeholders test and provide feedback on the prototypes. These five steps are iterative and the process may be partially or completely revisited several times.

We recognize that the double diamond approach is one of many approaches to design thinking, and design thinking is only one of many approaches to innovation. Still, many SOI processes are framed around design thinking methodologies (Buhl et al., 2019). While design thinking tools are commonly used for innovation processes, a user-focused innovation process such as design thinking can limit the innovation scope in ways that exclude multidimensional targets, societal impacts, and systemic understanding, further contributing to poorly defined problems (Buhl et al., 2019; Hoolohan & Browne, 2020). This limitation of design thinking to meet the needs of SOI are well documented in the academic literature, yet there are few studies that propose or implement methodologies to address that gap (Jones, 2014; Pourdehnad, Wexler, & Wilson, 2011). A key research question for SOI is how design thinking can progress beyond its focus on individual users and also engage in reconfiguring social, political, and material systems (Hoolohan & Browne, 2020).

1.3. *The systems mapping intervention in SOI*

Systems approaches to design have long been seen as valuable for placing design processes and products in larger contexts (Buchanan, 2019), and the benefit of combining elements of design thinking with elements of systems methodologies as a path towards robust innovation processes for complex challenges is highlighted in several studies (Bausch, 2002; Conway et al., 2017; Jones, 2014; Pourdehnad et al., 2011).

A number of systems-oriented methodologies have been developed to aid in problem definition, including systems mapping, gigamapping and synthesis maps. These methodologies vary in scope, stakeholder involvement, and required resources and skills (Jones & Bowes, 2017). All three approaches produce a collaborative visual artifact that represents the participants’ learning and understanding of a complex system. Gigamapping demands the most time and expertise, and results in the highest level of detail of the three approaches, while systems mapping, the focus of our research, requires the least time and no expertise and produces a lower level of detail in the resulting map (Jones & Bowes, 2017).

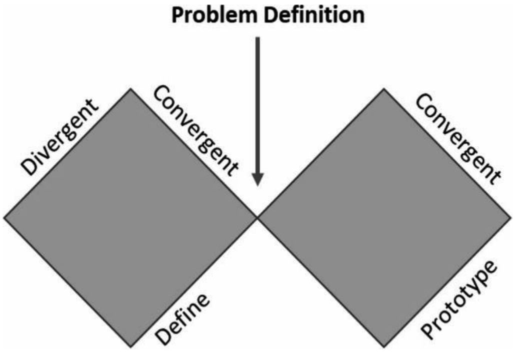

Fig. 1. A typical representation of the design thinking "double diamond" (adapted from Conway et al., (2017)).

Systems mapping, one of a suite of tools for group model building, is a participatory approach to creating a shared understanding of and communication about a complex problem (Videira et al., 2010). Systems mapping can be a stand alone stakeholder engagement process or a starting point for developing a system dynamics model, which is a mathematical model based on differential equations. Systems mapping includes a toolbox of scripts, or activities, that can be implemented in a variety of stakeholder contexts to elicit understanding of a complex problem, identify leverage points for intervention, and more (Hovmand et al., 2011, 2012). Systems mapping is often considered a tool for implementing systems thinking. Though systems thinking is poorly defined in the literature, it's broadly understood as an approach to complexity that emphasizes feedback and an awareness that a system's structure creates its behavior.

Systems mapping's particular strengths include eliciting a shared, visual understanding of a problem and its interconnections across disciplinary and sectoral boundaries. Further, through that process, the systems mapping creates a forum for discussion that can formalize understanding of a complex problem (Scott, Cavana, & Cameron, 2016; Videira et al., 2010; Videira, Antunes, & Santos, 2017). The resulting systems map typically has a focus on feedback within the system and on developing an adequate system boundary. It makes causal relationships explicit and can function as a reference point and boundary object for further discussions of leverage points and interventions in the system. In systems mapping, emphasis is not on the individual's experience but on the aggregated structure of a complex issue. In contrast to design thinking, systems mapping takes an aggregated perspective and can provide a "helicopter view" of a problem.

The systems mapping intervention as implemented in this study is a "quick and dirty" approach, especially when compared with approaches such as gigamapping and synthesis maps. Designers implementing gigamapping or synthesis mapping can use months to create a comprehensive and visually detailed map (Jones & Bowes, 2017; Sevaldson, 2018). Our implementation of systems mapping (outlined in the following section) generally takes less than two hours and requires no formal training for participants. Though less richly detailed than other approaches, the systems mapping intervention is designed to quickly give non-experts an aggregated and dynamic perspective on their sustainability issue.

2. Method: applying systems sustainability-oriented innovation

We propose employing systems mapping in the problem definition phase of design thinking as a way to address the user-focused limitations identified above. We call this approach systems sustainability-oriented innovation (SSOI). We modified the standard five step design thinking approach by adding a systems mapping activity in the first divergent phase of the design thinking process (Fig. 2). By adjusting and adding to the design thinking practitioner process, we were able to enlarge and contextualize the problem scope for SOI.

Our systems mapping activity was based on the open source “Initiating and Elaborating a Causal Loop Diagram” facilitation guide (also called a script) in Scriptapedia (Hovmand et al., 2011). This script is especially valuable for creating consensus and improving communication around a problem. While systems mapping facilitation guides are intended to be implemented in person, in our case, we modified the guide to move the process online due to Covid-19. Online systems mapping is a relatively new practice, but has been shown to provide valuable experiences and insights for participants (Wilkerson et al., 2020).

In the facilitation guide, participants are asked to identify a key problem variable for the specific case they are working on. Once participants agree on the variable, they start tracing causality by asking “what causes this variable to change?” This question helps identify the variable(s) that influence the original variable. As each new variable is added to the map, the group connects it to existing variables with arrows to indicate influence (Fig. 3). This process is informally referred to as “mapping backwards,” as chains of influence are traced back from the key variable.

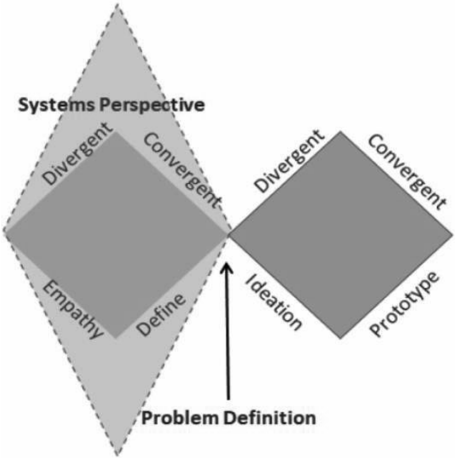

Fig. 2. Elaborating on (Conway et al., 2017) - introducing a systems perspective in the early phase of an innovation process allows for sustainability to be more fully considered throughout the process.

By repeating this process, the systems map evolves. Participants are further challenged to consider polarity of relationships by asking “ if there is an increase in variable A, is that causing an increase or a decrease in variable B?” Through noting variables’ relationships and polarities, participants build the systems map. Towards the end of the process, participants are asked to identify loops, or cyclically chained variables, in the system. Feedback loops are also classified as either “balancing” or “reinforcing,” where balancing loops dampen and reinforcing loops amplify phenomena over time. Identifying loop characteristics helps participants understand how the system influences itself over time.

The output of this SSOI process is a systems map (also known as a causal loop diagram) that illustrates relationships among major variables in the system and clearly delineates the system boundaries (i.e. the problem space) relevant to the key variable. The systems map provides a “helicopter view” of the problem that complements the empathetic, individual perspective in design thinking.

The systems map is one of several inputs into following design thinking exercises, where participants conduct interviews and explore the points of view of people within various parts of their system map. The aim of including systems mapping in design thinking is not to seamlessly integrate the two methodologies. Rather, the systems map participants produce is intended to provide a new perspective that can both enhance and disrupt the standard empathetic, human-centered perspective of design thinking.

3. Examples SSOI in practice

To test the potential of SSOI, we applied the methodology and collected data on the process and results in two settings: a problem- definition workshop for sustainable business innovation and a sustainable innovation course for bachelor degree students. Both cases were run online, using Zoom (zoom.us) for communication and Miro (miro.com) for activities.

3.1. *SSOI in business settings*

The Bergen2030 innovation competition was run by a business incubator that gathered sustainability “headaches” from businesses and a municipality. Examples of headaches included emissions from construction sites, waste material from Omega-3 fish oil production, and electricity management in housing associations. The aim of the competition was to gather and refine the sustainability problems, then allow interdisciplinary teams to compete to solve or improve the problem. The organizations with the headaches first gathered in a workshop to refine their problem description, and then the team competition took place several weeks later. In relation to the double diamond, the problem description workshop corresponded to the first diamond, while the team competition corresponded to the second diamond.

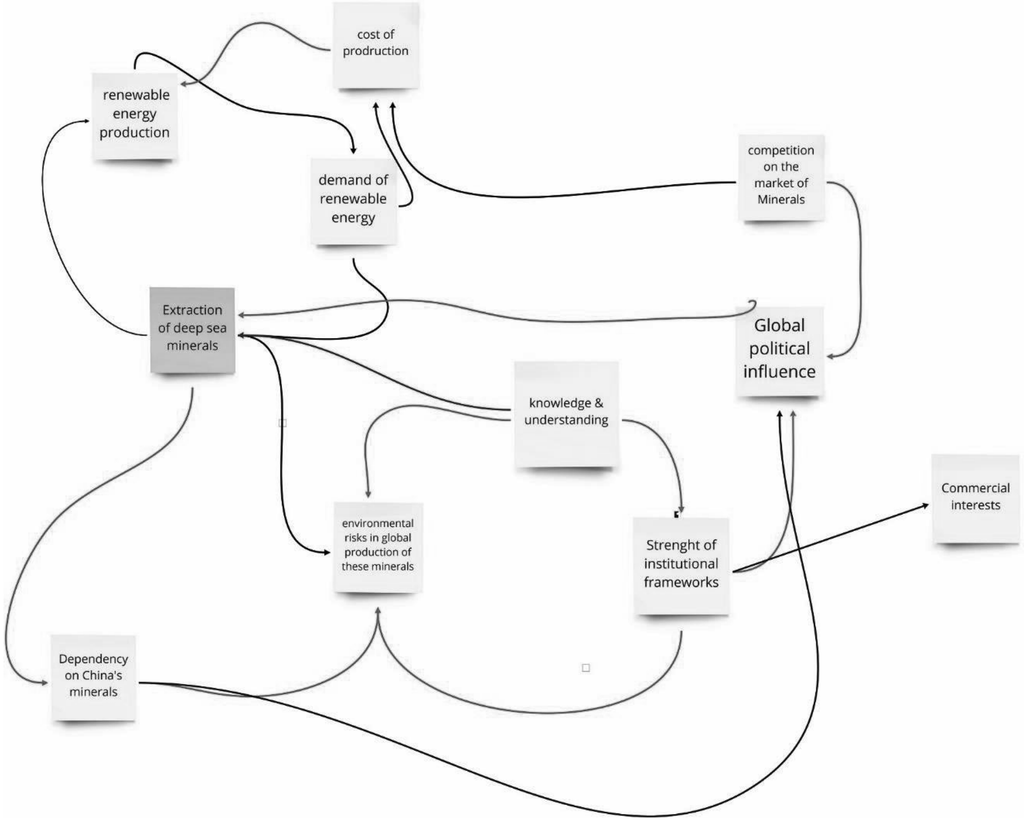

Fig. 3. Example systems map developed by students.

We applied the SSOI methodology in the problem description workshop. The explicit aims of the two day workshop were to 1) Further develop and increase the quality of the organization’s problem description to be used in the following phases of the innovation process; and 2) provide training in a set of activities and tools that participants could use independently in other innovation processes. Each of the five participating organizations (total of 20 participants) had different levels of experience and formal competence in innovation practice. The participating organizations included large corporations with business activities within shipping, aquaculture, real estate, and power-grid services. A municipal public management body also participated. The team members represented a wide array of professions and experience levels within innovation processes. One team consisted of a company's internal innovation department, where all members had both experience and academic training in design thinking and product/services design, while other teams included accountants, marketing-personnel, VPs, engineers and architects – all with widely varying previous training or experience with innovation and product/service design.

The problem definition workshop consisted of a series of exercises that built on each other. At the start of each exercise, participants were given a brief introduction to the activity and its aims and purpose. Participants then worked within their groups with facilitators circulating to provide assistance as needed. Exercises included traditional design thinking activities, such as "empathetic interviews"

Table 1

Workshop Summary.

Activity	Description	Prompts	Time (minutes)
Introduction	Presentation by facilitators. Introduction to systems mapping with two examples of systems maps: one addressing population dynamics and one addressing urban housing development. Focus on understanding: • A Variable as a phenomenon, element, or entity that can be measured and either increase or decrease in magnitude. • A Causal Link as a connection between Variables that indicates how a change in one variable would affect another variable. • A Feedback Loop as a circular arrangement of causally connected variables.		15

Identify a key variable	Facilitated group discussion. Identify key variable as a point of departure for the mapping exercise.	• Business case: Is there anything in the material produced in the previous exercises that you consider a key variable particularly important for your understanding of your challenge? Or can you think of something completely new that would be important for your challenge? • Student case: Can anyone suggest a relevant key variable to start with here? It does not have to be the most critical or most important, but we need a place to start.	5
Causal mapping	Facilitated group discussion. Team members add variables and connect them via causal links; thereby iteratively expanding the systems map in a "mapping backwards" process as described in section 2.	• What causes your variable to change? Or is your variable causing a change in another variable? • Is the change in the same or in the opposite direction? • What else can cause a change in X variable? • What would a change in X cause down the line?	40-50
Identify Feedback Loops	Facilitated group discussion. Participants are challenged to identify closed loops where chains of variables are linked together to form full circles. Facilitator may identify first feedback loop and emphasize the "story" each loop tells (ie, how it relates to the larger system).	• What is the feedback story here? • What is the nature of this feedback loop is it reinforcing or is it balancing?	10
Debrief	Facilitator summary and facilitated group discussion. Facilitator summarize the findings in the Systems Map focusing on identified feedback loops and loose ends. Facilitator highlights that the work is not complete and encourages the participants to keep working to expand the Systems Map to be more comprehensive, and to use it as a boundary object for their further work with the innovation challenge.	• What system behaviors have we found that should be considered when we move forward with our innovation process? • Are there any counter-intuitive or potentially un- desired effect loops we should be aware of?	15

and “points of view,” in addition to the systems mapping exercise. The outcome of the two day workshop was a comprehensive problem description that could be delivered to teams working on the problem in the competition.

3.2. *SSOI in educational settings*

The Sustainable Innovation course at the University of Bergen is an optional course for bachelor level students from all faculties, and students must apply and be accepted into the course. The focus of the course is teaching students innovation methodologies and sustainability concepts. The bulk of the course is a project in which students work in teams with five to seven members to address a “real world” sustainability challenge presented by a client.

In 2021, the course had 30 students from four faculties. Almost none of the students had previous experience or training in systems mapping or design thinking. The systems mapping workshop was the first exercise the students did in their teams and the first activity related to their innovation challenge.

The workshop consisted of a 15 minute introduction to systems mapping by the authors, one hour of facilitator-assisted workshop in the teams, and a 15 minute plenary debrief. In the workshop, the teams agreed on a key variable for their problem, then built a systems map using that variable as a starting point. Though the workshop was short, many teams continued to work on their systems map after the workshop had ended. In class meetings subsequent to our workshop, students received training and facilitation in design thinking.

3.3. *Workshop structure*

The idea of expanding the traditional design thinking approach to include a systems perspective in SOI emerged in discussions between the business workshop organizers and the authors. In preparation for the business workshop, the authors worked closely with the workshop organization team and facilitators. The workshop program was developed over a period of four months and was considered a pilot project for innovation.

The student systems mapping workshop built on the experience, feedback and evaluation of the business workshop. Few adaptations were necessary, though the participants and starting points were different in this setting. In both cases, the systems mapping workshop was based on the “Initiating and Elaborating a Causal Loop Diagram” facilitation guide in Scriptapedia (Hovmand et al., 2011) (Table 1).

After the business workshop the system maps remained available for the participating teams. They were also collated into a more comprehensive insight report (including the results of exercises they did prior to systems mapping) that was delivered to the teams. Teams continued work with the “second diamond,” where solutions to the predefined “headaches” were sought over the course of a 48 hour hackathon.

Students in the academic course maintained access to their systems maps, and many teams continued to work on, and with, the systems maps generated through the workshop.

4. Data collection and analysis

For both cases, we analyzed the systems maps generated by participants for evidence of multidimensional perspectives and inclusion of both individual and societal aspects. We also conducted and analyzed interviews and surveys to better understand the learning process and perceived value of systems mapping for problem definition. The systems maps provide insights into the problem descriptions, while surveys and interviews provide insights into the process.

4.1. *SSOI in business settings*

After the workshop, we conducted semi-structured interviews of five professionals (one from each participating team). The semi- structured interviews were carried out along a predefined interview protocol; all respondents were interviewed by the same protocol. The interview protocol consisted of three main lines of questions: (1) Baseline – assessing the previous experience with innovation, design and systems thinking. (2) Workshop Execution – assessing how the respondents experienced the theory, examples, exercises and facilitation of the workshop. (3) Utility – assessing to what extent components of the workshop were found to be useful by respondents. The protocol also included room for any other remarks or comments observed by the respondents.

Interviews were conducted by both co-authors via video meeting. The interviews were 30–60 min in length and were later transcribed and analyzed. The analysis was carried out in several iterations during which the authors reviewed the responses for mentioning or discussing the key elements of SOI, including longer time horizons, problem definitions spanning individual and societal aspects, and multidimensionality (Buhl et al., 2019). In addition, the systems maps generated by participants were collected for analysis and assessed for the same elements.

Of the six participating teams in the business case, all teams identified a minimum of five different sectors or dimensions intrinsic to their problem space. Typically, these dimensions included economic sectors (finance and market structures), social sectors (various user groups and government policies), and environmental sectors (for example, waste management, climate footprint, water quality).

Four out of six teams identified a minimum of two feedback loops. Of the two teams that did not identify feedback, one team did not participate in the whole workshop. The second team stated that they did not have sufficient time to complete the task during the workshop, but that they had continued to work with the systems mapping exercise after the workshop both as a team and individually, and that continued work revealed interesting and potentially important dynamics.

One team drafted a comprehensive systems map during the workshop and identified about a dozen minor and major feedback loops, straddling several dimensions. Their map included both individual and societal perspectives and identified tensions between these perspectives. This team reported that identifying causal feedback in their problem space was particularly useful for moving forward with the innovation task.

4.2. *SSOI in educational settings*

At the end of the course, we conducted a brief survey of students (response rate = 52%) to gauge their experience and learning. We also collected the systems maps created by the students for analysis.

Five out of six teams developed detailed systems map during the workshop, including a minimum of four and a maximum of eight dimensions spanning environmental, economic, and societal sectors. Two teams continued to work on their systems map after the workshop, and both of these teams increased the number of variables and links in their systems maps by a factor of three. All teams who successfully created a systems map also identified key feedback loops and interactions among sectors in their system.

Fig. 4 shows the work of one of the teams in the student case. The team worked on defining a SOI problem related to an emerging industry of deep water mineral extraction on the Norwegian continental shelf. None of the team members had any prior knowledge of the subject, and information about the case was given to them on the morning of the workshop. The systems map they created is not comprehensive, but instead represents the group's status at the end of the 1.5 hour workshop.

The systems map introduces a number of dimensions into the problem space beyond the individual "user," in this case a company invested in deep sea minerals. The team started with the

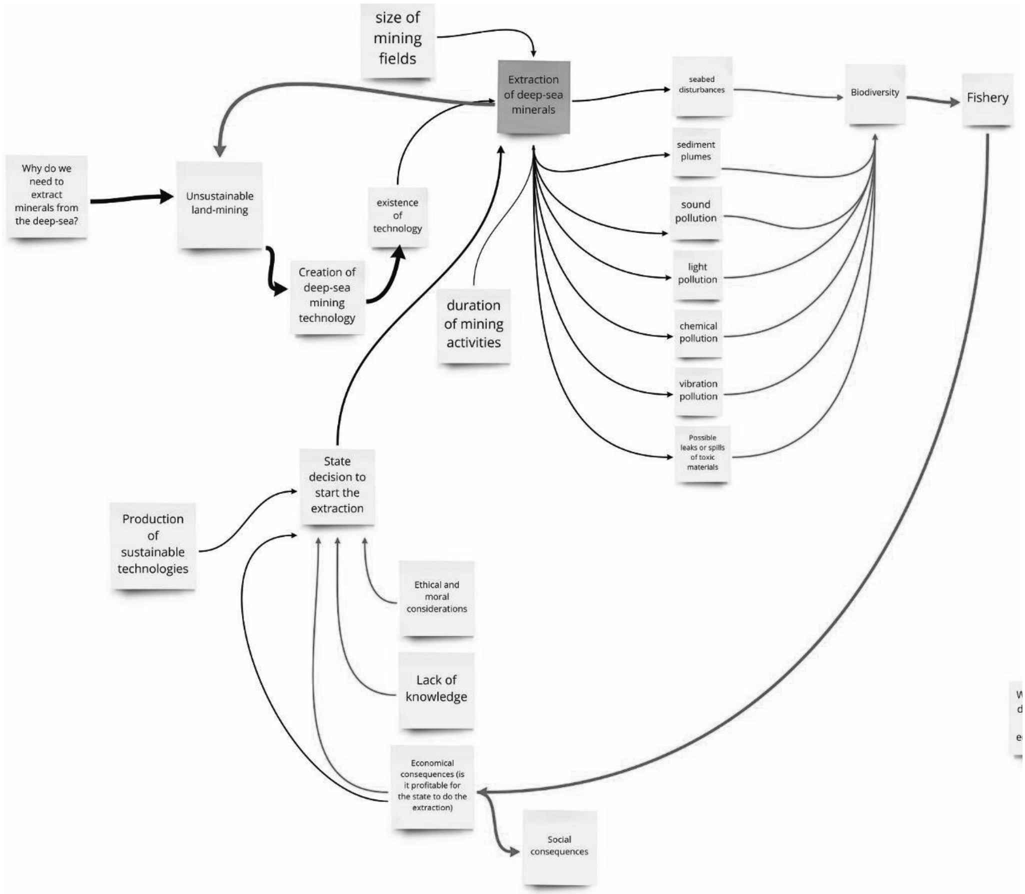

Fig. 4. Example systems map from the education case. Students identified interactions among economic, environmental, and societal sectors within their problem definition.

key variable "Extraction of minerals in the deep sea." Using a "mapping backward" technique, they identified both the presence of mining technology and state policy as primary factors affecting deep sea mining. State policy is affected by technological development and knowledge status, ethical considerations, and profitability. Profitability is affected by activities in the fisheries sector (a major industry in Norway). The fisheries sector is affected by changes in the physical and biological environment, and those environmental factors are affected, in turn by deep sea mining, the key variable. Further, students identified link polarity (shown as black and red arrows in Fig. 4). Link polarity refers to the direction in which one variable affects another over time. For example, increased seabed mining increases seabed disturbances (black arrow), which has a negative impact on biodiversity (red arrow).

In sum, we can see that the students identified economic, environmental, and societal sectors and explored how those sectors relate to and influence each other. The system map identifies important dynamics in the problem space as it evolves over time. It implicitly includes a long time horizon, as the causal loop described above will play out dynamically over many years.

Survey results indicate that most students had no previous experience in system mapping or design thinking (Fig. 5). Almost all respondents found the SSOI workshop to be useful or very useful. The strongest values they reported from the workshop include using the systems map as a discussion tool and reference object and identifying innovation ideas (intervention points) within the map. Almost 30% of respondents continued to develop the systems map on their own after the workshop.

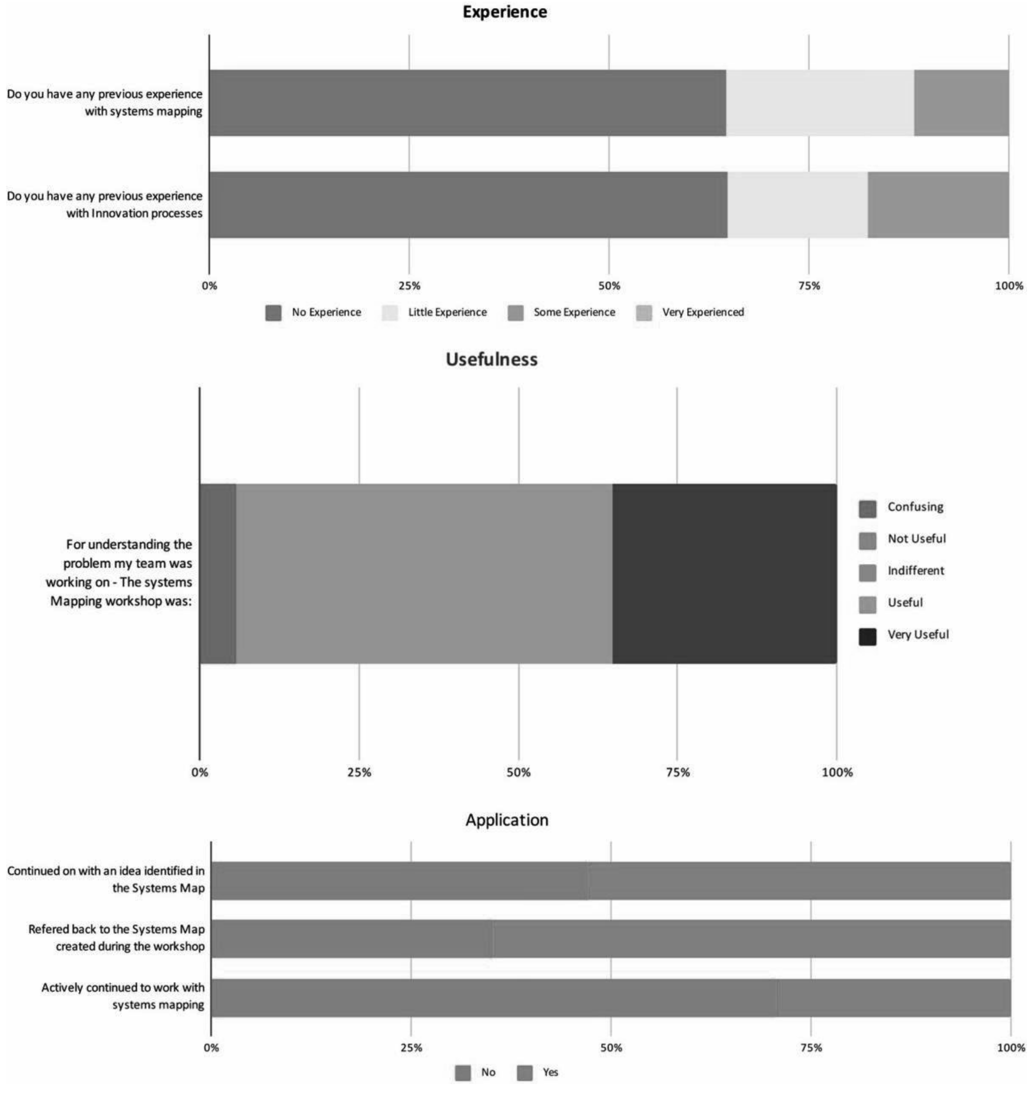

Fig. 5. Summary results from student survey after the workshop.

5. Discussion

Through employing systems mapping in the problem definition phase of design thinking, we aimed to incorporate the specific requirements of sustainability in an innovation context: a systems vantage point, individual and societal interactions, and multidimensionality. Our analysis shows that SSOI provides value as both as a capacity-building process and as a product for highlighting sustainability aspects in problem definitions.

The usefulness of design thinking for innovation processes has been well documented (Carlgren et al., 2016; Roth et al., 2020). Originally designed as methodology for product development, design thinking has been adapted and adopted to a broader range of innovation processes in recent years. While use of different design thinking tools may emphasize different qualities and criteria, the design thinking approach has remained more or less bounded within the double diamond framework. We find design thinking's simplicity and ubiquity to be advantageous, as it provides simple "scaffolding" on which to test new approaches. We recognize, however, that design thinking takes many forms, and the design thinking approach discussed in this article is not the only form of design thinking.

Our case studies illustrate the potential role of systems mapping as an intervention in design thinking innovation processes in business and educational settings. While the main goals of these two examples were different, both cases demonstrate how systems mapping can be applied to increase understanding and definition of the problem space for sustainability-oriented innovation. Further, the cases demonstrate that systems mapping methodology can be implemented by and provide useful results for participants in different phases of their education and career and with different levels of background and experience in the problem being discussed.

In both cases, systems mapping contributed to a more holistic understanding of the problem. Our analysis of the systems maps indicates that participants both expanded the boundaries of their problem and, in most cases, included environmental, economic, and social sectors. They could also see connections between elements that they hadn't focused on before, which provoked new thinking about the problem. Several groups explicitly identified tensions and interactions between individual users and broader segments of society. Though almost none of the students in the education case had previous experience in design thinking or systems mapping, 94% reported that the systems mapping workshop was useful or very useful for understanding the problem space. As one business case participant commented, "We saw complexity in the issue that we hadn't seen before, especially as we came from different perspectives… We saw that we could come to a completely different solution than what we had originally thought."

While the primary goal of SSOI has been to set the problem in a systems perspective to improve problem definition, we also found that systems mapping contributed to creating a shared understanding of a complex problem and aided communication among team members. This is a documented effect of systems mapping (Rouwette, Korzilius, Vennix, & Jacobs, 2011; Videira et al., 2017), but we argue that this effect is especially valuable in the context of SOI, where diversity in background and perspective contributes to a more holistic problem definition.

In the business case, systems mapping as a communication tool proved particularly beneficial for teams from large companies, where team members typically came from different departments, with different backgrounds and responsibilities. These teams in particular remarked on the usefulness of the systems map to create a shared understanding of a complex problem and generate discussion around how the system functions over time.

Several student teams also continued to build on and refer to their systems map throughout the innovation process. Survey results indicate that 42% of students actively used the systems map as a tool for framing discussions within their teams throughout the course. Further, more than half the students continued to refer back to the systems map they developed as the course progressed and continued to work with an idea that was identified during the brief workshop.

In the business case, both observations during the workshop and interviews confirmed that systems mapping was the most cognitively demanding step in the workshop, even with facilitator support. Connecting variables and describing relationships was new for most participants, as was the concept of feedback. In the education case, most students were able to quickly get started and work independently in teams. In both cases, facilitators periodically “checked in” with groups to ensure they understood and were making progress on the systems map. Our experiences indicate that while participants were able to successfully build a systems map in both cases, facilitators trained in systems mapping are needed to support teams through the process.

Subsequent to both of the workshops, some teams, both advanced and more inexperienced, reported that they planned on, or already had, employed the methodology in other sustainability innovation processes. This indicates that participants were able to internalize and gain confidence in the methodology despite receiving only a brief introduction. It also indicates that participants identified a clear value in the perspective and insights that systems mapping have to offer SOI. In particular, several interviewees from the business case mentioned the value of having a tool that helped them visualize connections that were often otherwise not articulated.

The SSOI approach has particular relevance to education. Systems thinking, put into practice as systems mapping, lies at the intersection of many modern higher-education priorities, including training students in collaboration, problem-based learning, and communicating across disciplines. We propose that incorporating systems mapping into innovation courses will not only improve student-generated projects, but will also strengthen students capacities to meet complex, real world challenges outside the university.

These brief (less than two hour) systems mapping interventions allowed participants to clearly see and define the sustainability aspects in their problem definition. Participants valued the actual systems map as a tool for problem definition and a boundary object for communication. They also valued the learning process and capacity building generated through creating the map. Though further development and testing is needed, our initial results indicate that systems mapping can be a valuable and efficient addition to standard design thinking approaches to SOI.

6. Conclusion

Innovating for sustainability requires a deep understanding of a system and its interactions. We present SSOI as an approach to advance the research, practice, and implementation of SOI practices. Our work demonstrates the potential of this approach to improve problem definition for sustainability innovation. Our results also show that participants valued and learned from the SSOI process, and that many planned on incorporating systems mapping into future innovation processes. Using SSOI to define the problem space supports sustainability aims by enforcing a holistic, coherent perspective that connects individuals and society.

Participants confirmed that SSOI is valued as a process for learning and internalizing a systems understanding of sustainability as it relates to innovation. As an intervention to standard design thinking practices, SSOI requires further study to evaluate how it can be used to improve SOI processes and products. Process- and results-based comparisons among various SOI approaches would be a significant contribution towards understanding how innovation processes relate and contribute to sustainability and systems perspectives. In addition, developing quality criteria for problem definition in innovation would allow for a standardized analysis of results. These are vital next steps if we expect design thinking to be a valuable tool to shape innovations for sustainability.

CRediT authorship contribution statement

Brooke Wilkerson: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Lars- Kristian Lunde Trellevik:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Declaration of Competing Interest** None.

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8. Appendix II

Mineral Economics
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ORIGINAL PAPER

Reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations in mineral industry transition

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Abstract
This study pinpoints three current factors that could be momentous in a possible transition to marine mining, namely reserve-dependent capital efficiency (accessibility and grade-dependent output per unit capital), cross-sector competition (competition between two separate mining sectors), and asymmetric mineral security considerations (e.g., the resource owner(s) and government(s) tied to a sector desires production for profit *and* security reasons). Moreover, four *conceptual* optimization problems are explored to specify the potential roles of said factors in a possible transition. The first problem considers a principal agent, who make decisions on behalf of resource owner(s), government(s) and producer(s), and invests and extracts to maximize the net present value of extraction from onshore and offshore reserves while facing reserve-independent capital efficiency. The second problem considers the same as the first, except here, the principal meets reserve-dependent capital efficiency. The third problem considers two principals, each representing resource owner(s), government(s), and producer(s) tied to a sector, who invest and extract to maximize the net present value of extraction from the respective reserves subject to the decisions of the other principal. Finally, the last problem considers a duopoly setting in which the marine principal values both financial gain and mineral security. The results illustrate that reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations can, in different ways, drive a possible transition to marine mining. Possible counter effective factors are highlighted and discussed.

Keywords Terrestrial minerals · Marine minerals · Industry transition · Monopoly · Duopoly · Geopolitics

JEL codes C61 · D24 · D25 · Q30 · Q32 · Q33 · Q34 · Q37 · Q40 · Q50

Introduction

Critical non-fuel minerals are compounds of elements that are crucial to growing economies on a path towards increased digitalization, electrification, and decarbonization (Buchholz and Brandenburg 2018; Coulomb et al. 2015; Henckens 2021; International Energy Agency (IEA) 2021; Kalantzakos 2020; Toro et al. 2020; Watari et al. 2019). Restricted access to such minerals can result in a range of short and long-term challenges, for example, challenges regarding green transitioning and sustainable economic growth (Calvo and Valero 2021; Herrington 2021).

Today, critical non-fuel minerals are exclusively mined on land (Kaluza et al. 2018; United States Geological Survey (USGS) 2020). However, increasing demand, declining onshore resources, falling ore grades, increasing extraction costs, and centralized supply raise worries about future access to critical minerals, especially for non-producing import economies.

Marine minerals may possibly alleviate concerns and contribute to the future supply of critical minerals (Hein et al. 2013; Petersen et al. 2016; Rona 2003). However, marine mineral exploration and mining involve technical, economic, environmental, and social challenges (Carver et al. 2020; Hoagland et al. 2010; Niner et al. 2018; Toro et al. 2020;

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Van Dover et al. 2017; Volkmann and Lehnen 2018). Thus, it is unclear whether, how, and when the industry will transition into commercial extraction of marine non-fuel mineral resources.

Existing literature has been highly focused on the opportunities and challenges of offshore mining (Carver et al. 2020; Hein et al. 2013; Hoagland et al. 2010; Petersen et al. 2016; Rona 2003; Toro et al. 2020; Volkmann and Lehnen 2018; Watzel et al. 2020). However, the literature is limited in conceptual, aggregate, and explorative studies on how a transition from onshore to offshore mineral extraction may unfold. This study intends to fill parts of that gap and spark research further in that direction.

Inspired by the ongoing development in the mining industry and geopolitical landscape, and considering existing research gaps, this study sets out to investigate the roles of reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations in a possible transition from onshore to offshore mining.

Reserve-dependent capital efficiency means that output per unit capital depends on the deposits in terms of their accessibility and ore grade. Cross-sector competition refers to possible competition between terrestrial and marine mining. In relation to settings without cross-sector competition, the industry, including both sectors, should here be understood as an entity consisting of resource owner(s), government(s), and producer(s), represented by a principal, with no competition from the outside—i.e., a monopoly cartel. In relation to settings dealing with cross-sector competition, each sector should here be understood as an entity consisting of resource owner(s), government(s), and producer(s), represented by a principal, and competing against the other sector—i.e., each sector represents a cartel that is part of a duopoly. While the monopoly and duopoly configurations represent abstractions from reality, in which there is more competition, these simplified perspectives allow clear focus on the effects of cross-sector competition.

Mineral security considerations mean that at least one sector desires production for profit *and* security reasons. In relation to this, one can imagine that the principal in charge of a sector makes a decision on behalf of the resource owner(s) and government(s) to provide extraction licenses and subsidies to the producer(s)—the subsidies to reflect the mineral security considerations, which could, e.g., be geopolitically motivated. In the real world, mineral security considerations may directly affect both onshore and offshore mining. However, we shall here focus on the simplified case where mineral security considerations only directly affect the marine sector. This is motivated by the fact that mineral security considerations may have an asymmetric effect—potentially benefiting the possibly emerging offshore sector more than the existing onshore sector (in a global perspective).

Specifically, we present four conceptual dynamic optimization problems to achieve the objectives. We present problems with reserve-independent and reserve-dependent capital efficiency to investigate the effects of reserve-dependent capital efficiency on a potential transformation to offshore mineral extraction. Furthermore, we present problems with monopoly and duopoly competition (terrestrial vs. marine) to investigate the effects of cross-sector competition. Finally, we present problems where both sectors value only financial gain and a problem where the marine sector values both financial gain and mineral security. This is done to investigate the effects of asymmetric mineral security considerations.

Although this study is conceptual, it offers practical value by pinpointing factors that are highly relevant to a possible transition to marine mining. Furthermore, it contributes by providing an understanding of how those factors can affect a possible transition. Hopefully, the model framework and approach can also serve as a venture point for future studies and thereby contribute to building further insight and eventually indicating whether, how, and when a transition will occur.

The three following sections provide background on the demand and supply of critical minerals, and the relevance of supply risks and mineral security considerations. The subsequent sections outline the optimization problems, solutions, and sensitivity analysis. Then, the results are discussed. Finally, conclusions are drawn.

Demand for critical minerals

Seven thousand years before the common era, humanity started working with copper—since then, it is fair to establish that access to minerals have been closely tied, even critical, to human advancement (Radetzki 2009).

Mineral contents are crucial inputs in several vital technologies, such as those required for electrifying and decarbonizing industry and transportation (Herrington 2021; Kaluza et al. 2018; Watari et al. 2019). Copper, cobalt, nickel, lithium, rare earth elements (REEs), chromium, zinc, platinum group metals (PGMs), manganese, and aluminum are all examples of elements that are critical to different green technologies (International Energy Agency (IEA) 2021; National Minerals Information Center, U. 2020).

In the 1850s, new technologies and electrification led to a surge in demand for copper (Radetzki 2009). In 2022, global demand for critical minerals is projected to increase significantly, also this time on account of new technologies and electrification, partly in response to climate change and partly in response to geopolitical development (Campbell 2020; Coulomb et al. 2015; International Energy Agency

(IEA) 2021; Kalantzakos 2020; Toro et al. 2020). As such, access to minerals is becoming increasingly important.

Supply of critical minerals

Today's commercial supply of critical non-fuel minerals is based on onshore mining and recycling (Kaluza et al. 2018). Onshore mining is mainly executed as open-pit and underground mining from mineral reserves unevenly distributed across countries, economies, and interest spheres. Open-pit mining involves the removal of overburden with excavators, bulldozers, and explosives. Upon retrieving the ore, the valuable elements are extracted through mechanical, chemical, and thermal processes (Hein et al. 2013; Westfall et al. 2016). Underground mining is often executed on higher-grade ore—and involves less removal of waste rock.

The rate of recycling is dependent on several factors, including element properties and their recycling potential, the recycling costs, and the alternative costs of recycling. Recycling rates differ significantly between elements; e.g., gold is recycled at 86%, copper at 45%, molybdenum at 20%, while boron, bismuth, and indium have a 0% recycling rate (Henckens 2021). In some cases, such as for lithium-ion batteries for electric vehicles, recycling can generate significantly higher costs, energy consumption, and emissions than the initial extraction and refinement of the elements (Golroudbary et al. 2019). In such cases, it may be preferable to extract new minerals rather than recycling.

In recent years, the mining industry has started depleting many established sites (International Energy Agency (IEA) 2021; Petersen et al. 2016). Moreover, easily accessible, high-grade ore is becoming increasingly difficult to locate. As a result, miners turn towards lesser deposits to meet demand, increasing the unit extraction costs (Haugan and Levin 2020; Hein et al. 2013; Ragnarsdóttir 2008; Toro et al. 2020). Moreover, there are insufficient mineral resources in circulation to sustain technological development and economic growth through recycling—even with significant improvements in the rates of recycling and circular resource utilization (Coulomb et al. 2015; Herrington 2021; International Energy Agency (IEA) 2021; Watzel et al. 2020). This makes it interesting to consider alternative sources of supply—perhaps by exploring marine minerals.

The HMS Challenger identified marine mineral deposits already in the 1870s. However, focused exploration and scientific research is more recent, dating back to the 1960s (Hein et al. 2013; Rona 2003). Since the 1960s, marine mineral deposits have been identified in international waters and within different countries' exclusive economic zones—also in economic zones where there is little or no onshore mining, which can indicate future cross-sector competition.

Several attempts have been made to extract marine minerals (Glasby 2000; Mccullough and Nassar 2017; Sparenberg 2019; Toro et al. 2020; Volkmann and Lehnen 2018). So far, there has been no positive return on investment (Alvarenga et al. 2022; Childs 2020; Glasby 2002; International Energy Agency (IEA) 2021). However, increasing demand for critical minerals, increasing onshore mineral scarcity, increasing onshore extraction costs, and geopolitical polarization and security considerations may point towards a future with commercially viable offshore mining.

Supply risks and mineral security

Today, certain countries dominate the global supply of several critical non-fuel minerals. This induces supply risks for importing nations, partly because current exporting countries may prioritize supply to their own industries in events of increased scarcity, or wield their dominance as a strategical tool in the geopolitical landscape; also, supply can be disrupted by stand-alone events such as natural disasters and conflicts (Childs 2020; Hao and Liu 2011).

When Russia launched a full-scale invasion of Ukraine in February 2022, western nations rallied to sanction Russia. However, western dependence on Russian oil and gas inhibited sanctions on Russia's most significant exports—at least up until the moment of writing in early May 2022. The European costs of imposing an oil and gas embargo on Russia have so far been considered too high for implementation. This safeguards significant revenue for Russia, which in turn enable Russia's continued offensive in Ukraine, which is expensive. This has rendered Russia's geopolitical advantage of controlling supply of oil and gas to Europe conspicuous. At the same time, from a European perspective, it has demonstrated the strategic perils of not controlling supply of oil and gas.

The war in Ukraine and the European Union's dependence on Russian oil and gas highlight the importance of secure access to oil, gas, and energy. In principle, they also highlight the importance of secure access to other critical raw materials such as critical minerals. And in March 2022, the European Council released a declaration emphasizing the importance of securing the supply of critical raw materials (European Council 2022).

The European Union and European Economic Area are net importers of many critical minerals (Dominish et al. 2019; European Commission 2020; Herrington 2021; International Energy Agency (IEA) 2021; Kaluza et al. 2018). At the same time, some of the countries within this area have access to marine minerals (Hoagland et al. 2010; Pedersen et al. 2021; Sharma 2017). That, together with an increasing focus on securing access to critical raw materials, makes it interesting to investigate the effects of mineral security considerations in a possible transition to marine mining.

The war in Ukraine and the European Union's dependence on Russian oil and gas are also relevant in a more intricate way. The newly strengthened European desire to reduce dependence on Russian oil and gas has led the European Union to send signals about doubling down on renewable energy transition, electrification, and digitalization. This represents an acceleration in the already increasing demand for renewable energy, electrification, and digitalization in Europe, which will undoubtedly further increase the demand for minerals in Europe. This makes secure access to critical minerals even more crucial for Europe than it otherwise would have been.

If Europe does not secure access to critical minerals, it will risk swapping dependence on Russian oil and gas for dependence on possibly non-desirable interest sphere's critical minerals—a situation it seems reasonable to conclude the European Union prefer to avoid.

Strategic considerations and increasing European demand for minerals may indicate an increase in support schemes to advance the European mining industry, including the existing onshore sector and a possible marine mining sector.

Conceptual optimization problems

This study presents four conceptual dynamic optimization problems. The problems draw upon ongoing real-world development, as well as theory and research on optimal exploitation of nonrenewable resources. The problems are inspired by Herfindahl (1967), Solow and Wan (1976), Amigues et al. (1998), Holland (2003), and Meier and Quaas (2021) who all focus on optimal order to extract different deposits. They are further inspired by Campbell (1980) and Cairns (2001) who focus on extraction under investments and capacity constraints. Finally, the problems draw upon Hotelling (1931), Salant (1976), Reinganum and Stokey (1985), Lewis and Schmalensee (1980), Loury (1986), Hartwick and Sadorsky (1990), and Salo and Tahvonen (2001) who partly discuss and partly focus on oligopoly models of nonrenewable resources.

The problems start out with some simplifying assumptions. This is done to isolate the focus on the roles of reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations in mineral industry transformation. First, it is assumed that all commercially interesting resources have been identified both onshore and offshore. Hence, the problems do not consider the process of converting resources to reserves, which includes exploration and more. Instead, the problems start out with the assumption of given reserves in each sector, which cannot be added to. Moreover, the problems disregard the full scale of competition in the mining sector, recycling, and the projected increase in demand. These simplifications represent abstractions from the real world but allow clear focus on the objectives of the study.

All problems consider one or two agents that aim to maximize the net present value of extraction from the reserves at their disposal by choosing capital investment and production rates. The agents maximize the objective function(s) subject to a set of constraints, in which two of the constraints determine the upper limits on extraction in each sector based on relevant states in the system, while other constraints deal with the dynamics of the system. The only direct interaction between the two sectors is observed through the demand function, in which onshore and offshore production influence the price that both sectors receive for their production in the end-market.

The first problem considers a principal who invests and extracts to maximize the net present value of extraction from onshore and offshore reserves while facing reserve-independent capital efficiency. This scenario is far from realistic. However, it allows isolated study of the effects of reserve-dependence by establishing a baseline for comparison. The second problem considers the same as the first, except here the principal faces reserve-dependent capital efficiency, which is more realistic.

The third problem considers two principals, each representing one cartel, that invest and extract to maximize the net present value of extraction from their respective reserves subject to the decisions of the other cartel. For intuitive purposes, the reader can think of the two sectors as separated by ownership and geographical location while competing in the same well-functioning and stable international market. The terrestrial sector starts out as dominant, while the marine sector starts out as subordinate, or basically nonexistent.

The last problem considers a duopoly setting in which the principal responsible for the marine sector values both financial gain and mineral security. For intuition, the reader can think of the two sectors as separated by ownership and geographical location while competing in the same functioning but unstable and nervous international market, where the owner of the marine sector wants to hedge against possible future market disruptions to make sure it can satisfy a certain demand without supply from the terrestrial sector. The terrestrial sector starts out as dominant, while the marine sector starts out as subordinate, or basically nonexistent, just like in the third problem.

The following sections give detailed descriptions of the problems and their numerical specifications.

Problem 1: reserve-independence

Problem 1 is written as follows: $\underset{u_{i,t}\geq 0, I_{i,t}\geq 0}{\text{Max}} \sum_{t=0}^{T}\sum_{i=1}^{I} e^{-rt}\left(\frac{P_{max}}{1+P_c\sum_{i=1}^{2}u_{i,t}}u_{i,t} - \frac{\alpha_i u_{i,t}}{A_i} - \beta_i I_{i,t}^{\gamma_i}\right)$ subject to $x_{i,\ t+1} = x_{i,\,t} - u_{i,\,t}$, $k_{i,\,t+1} = k_{i,\,t} - d_i k_{i,\,t} + I_{i,\,t}$, $u_{i,\,t} \leq A_i k_{i,\,t}$,

$x_{i,\,t} \geq 0$, $k_{i,\,t} \geq 0$, given positive values of all parameters, and given initial values of all state variables. We define time $t = (0, 1, \ldots, T)$ with T=200 years. However, the study assumes that the agents are mainly interested in what happens in the first 100 years. In other words, the agents are not interested in the end-phase, where the incentive for conservation goes to zero. Sector $i = (1, 2)$ represents the terrestrial and marine sector, respectively. $u_{i,\,t}$ and $I_{i,\,t}$ denote the production and investment decisions, respectively. Furthermore, e^{-rt} is the discount factor, while P_{max} and P_c are price parameters, and α_i, β_i, and γ_i are cost parameters. $k_{i,\,t}$ and $x_{i,\,t}$ denote the capital levels and mineral reserve levels, respectively. Finally, d_i denote the depreciation rates, while A_i is a parameter that describes the factor productivity of capital in each sector.

The component $\frac{P_{max}}{1+P_c \sum_{i=1}^{2} u_{i,t}}$ represents the demand function, where P_{max} is the willingness to pay when supply is non-existent, and P_c is a curvature parameter. The demand function is a downward sloping convex curve starting at (0, P_{max}) with $\lim_{q(\ldots)\to\infty} P(\ldots) = 0$—indicating that the willingness to pay for the resource becomes progressively higher for lower supply.

The component $\frac{\alpha_i u_{i,t}}{A_i}$ represents the operation costs, which are independent of the reserves. Although not directly visible, the operation costs are directly related to the employment of capital. The factor $\frac{u_{i,t}}{A_i}$ represents the level of capital needed to execute the production decision $u_{i,\,t}$. As such, the term $\frac{\alpha_i u_{i,t}}{A_i}$ is equal to $\alpha_i k_{i,\,t}$ when the production capacity constraint is binding, that is, when $u_{i,\,t} = A_i k_{i,\,t}$. However, since it is allowed for utilizing less capital than what is available, $u_{i,\,t} \leq A_i k_{i,\,t}$, the operation costs is represented by $\frac{\alpha_i u_{i,t}}{A_i}$, which means that the principal only pays operating costs proportionally to the capital in use, not the capital available for use. Relating to this, it is worth highlighting that the production constraint is reserve-independent in problem 1. This is the explanation as to why the operation costs are reserve-independent.

The term $\beta_i I_{i,t}^{\gamma_i}$ represents the investment costs, and $\gamma_i >$ 1 is imposed such that there are increasing marginal costs of investment in each sector. When compared to constant marginal costs of investment, this gives incentives to spread orders over wider time intervals rather than ordering a large magnitude of capital for delivery at the next time step.

Worth noting regarding the capital dynamics is the assumption of irreversible, or quasi-reversible investments; i.e., capital is highly specialized, and excess capital can therefore not be sold, and as such, investments can only be diminished through depreciation.

Although there are no direct costs relating to idle capacity, there are obvious indirect costs. Not utilizing the full capacity means there is overcapacity, i.e., that excessive investments has been made, or that the capital is initialized at a level higher than what is optimal. At the same time, it means that a trade-off is made between increasing production at relatively low cost today and postponing production, which involve discounted revenue, and may involve costs tied to maintenance and/or re-accumulation of capital.

Problem 2: reserve-dependence

Problem 2 is similar to problem 1, except here $x_{i,\,t}$ affects the production capacity and amount of capital needed to execute a production decision. That is, the principal meets reserve-dependent capital efficiency. The problem is written as: $\underset{u_{i,t}\geq 0, I_{i,t}\geq 0}{\text{Max}} \sum_{t=0}^{T} \sum_{i=1}^{I} e^{-rt} \left(\frac{P_{max}}{1+P_c \sum_{i=1}^{2} u_{i,t}} u_{i,t} - \frac{\alpha_i u_{i,t}}{A_i x_{i,t}} - \beta_i I_{i,t}^{\gamma_i} \right)$ subject to $x_{i,\,t+1} = x_{i,\,t} - u_{i,\,t}$, $k_{i,\,t+1} = k_{i,\,t} - d_i k_{i,\,t} + I_{i,\,t}$, $u_{i,\,t} \leq A_i k_{i,\,t} x_{i,\,t}$, $x_{i,\,t} \geq 0$, $k_{i,\,t} \geq 0$, given positive values of all parameters, and given initial values of all state variables. Note that the model does not consider accessibility and ore grade explicitly. Instead, it assumes that the principal extracts the deposits in each sector in order of their attractiveness such that there is correlation between the size of the reserves in each sector, and the attractiveness of the current-best deposit. This is a common assumption in theoretical non-renewable resource economics (see, e.g., Chapter 5.6 Reserve-dependent Cost in Conrad (2010)).

Problem 3: cross-sector competition

Problem 3 is more complex than problem 1 and 2. Problem 3 involve both reserve-dependent capital efficiency *and* cross-sector competition. When dealing with cross-sector competition, we are interested in dynamic Cournot Nash equilibria (OECD 2013), which are obtained through an iterative and repetitive optimization process, in which each agent makes decisions to maximize the net present value of extraction from their respective reserves, taking the other agent's decisions as given (Cournot), until neither agent can improve its decisions given the other agent's decisions (Nash). The algorithm for problem 3 is outlined as follows:

- $\underset{u_{1,t}\geq 0, I_{1,t}\geq 0}{\text{Max}} \sum_{t=0}^{T} e^{-rt} \left(\frac{P_{max}}{1+P_c \sum_{i=1}^{2} u_{i,t}} u_{1,t} - \frac{\alpha_1 u_{1,t}}{A_1 x_{1,t}} - \beta_1 I_{1,t}^{\gamma_1} \right)$ subject to $x_{1,\,t+1} = x_{1,\,t} - u_{1,\,t}$, $k_{1,\,t+1} = k_{1,\,t} - d_1 k_{1,\,t} + I_{1,\,t}$, $u_{1,\,t} \leq A_1 k_{1,\,t} x_{1,\,t}$, $x_{1,\,t} \geq 0$, $k_{1,\,t} \geq 0$, given positive values of all parameters, and given initial values of all state variables, and given values for all variables relating to sector 2.
- Store the solutions relating to sector 1 and treat them as given in the next optimization step.
- $\underset{u_{2,t}\geq 0, I_{2,t}\geq 0}{\text{Max}} \sum_{t=0}^{T} e^{-rt} \left(\frac{P_{max}}{1+P_c \sum_{i=1}^{2} u_{i,t}} u_{2,t} - \frac{\alpha_2 u_{2,t}}{A_2 x_{2,t}} - \beta_2 I_{2,t}^{\gamma_2} \right)$ subject to $x_{2,\,t+1} = x_{2,\,t} - u_{2,\,t}$, $k_{2,\,t+1} = k_{2,\,t} - d_2 k_{2,\,t} + I_{2,\,t}$,

$u_{2,t} \leq A_2 k_{2,t} x_{2,t}$, $x_{2,t} \geq 0$, $k_{2,t} \geq 0$, given positive values of all parameters, and given initial values of all state variables, and given values for all variables relating to sector 1.
- Store the solutions relating to sector 2 and treat them as given in the next optimization step.
- Calculate the difference between newly obtained decision vectors and previously given decision vectors.
- If there is no significant difference between newly obtained decision vectors and previously given decision vectors, then report the last obtained decision vectors and exit the algorithmic procedure, else repeat the steps above.

Problem 4: mineral security considerations

Problem 4 is like problem 3 but with a key difference—in problem 4, the marine principal does not only value financial gain but also mineral security. This is incorporated by the inclusion of a new term $m_2 u_{2,t}$ in the objective function of the marine principal, in which m_2 is a parameter that adds a constant value to each unit of production. For the sake of intuition, this can be interpreted as a unit subsidy on production in the marine sector. The algorithm for problem 4 is:

- $\underset{u_{1,t} \geq 0, I_{1,t} \geq 0}{\text{Max}} \sum_{t=0}^{T} e^{-rt} \left(\frac{P_{max}}{1+P_c \sum_{i=1}^{2} u_{i,t}} u_{1,t} - \frac{\alpha_1 u_{1,t}}{A_1 x_{1,t}} - \beta_1 I_{1,t}^{\gamma_1} \right)$ subject to $x_{1,t+1} = x_{1,t} - u_{1,t}$, $k_{1,t+1} = k_{1,t} - d_1 k_{1,t} + I_{1,t}$, $u_{1,t} \leq A_1 k_{1,t} x_{1,t}$, $x_{1,t} \geq 0$, $k_{1,t} \geq 0$, given positive values of all parameters, and given initial values of all state variables, and given values for all variables relating to sector 2.
- Store the solutions relating to sector 1 and treat them as given in the next optimization step.
- $\underset{u_{2,t} \geq 0, I_{2,t} \geq 0}{\text{Max}} \sum_{t=0}^{T} e^{-rt} \left(m_2 u_{2,t} + \frac{P_{max}}{1+P_c \sum_{i=1}^{2} u_{i,t}} u_{2,t} - \frac{\alpha_2 u_{2,t}}{A_2 x_{2,t}} - \beta_2 I_{2,t}^{\gamma_2} \right)$ subject to $x_{2,t+1} = x_{2,t} - u_{2,t}$, $k_{2,t+1} = k_{2,t} - d_2 k_{2,t} + I_{2,t}$, $u_{2,t} \leq A_2 k_{2,t} x_{2,t}$, $x_{2,t} \geq 0$, $k_{2,t} \geq 0$, given positive values of all parameters, and given initial values of all state variables, and given values for all variables relating to sector 1.
- Store the solutions relating to sector 2 and treat them as given in the next optimization step.
- Calculate the difference between newly obtained decision vectors and previously given decision vectors.
- If there is no significant difference between newly obtained decision vectors and previously given decision vectors, then report the last obtained decision vectors and exit the algorithmic procedure, else repeat the steps above.

Numerical specifications

So far, the problems have been described in general notation—very little has been said about the numerical specifications of the problems. The numerical specifications represent fabricated values. However, they are chosen to articulate the units and values at play in parts of the mineral industry, e.g., the manganese mineral industry. Table 1 provides an overview of the parameters, their unit of measure, and their numerical specifications. Most important to note is that $x_{i=1,t=0} < x_{i=2,t=0}$, and $k_{i=1,t=0} > k_{i=2,t=0}$, and $A_1 > A_2$ are imposed in all problems.

The study assumes that the onshore reserves are smaller than the offshore reserves based on the fact that marine mineral deposits are thought to be abundant relative to remaining accessible onshore mineral deposits (Schulz et al. 2017, pp. F13, L10, L12).

Onshore capital is initialized at a positive level to make sure the onshore mining sector starts out with a significant production capacity. Marine capital is initialized at zero to reflect that the marine sector is in its infancy.

Onshore capital efficiency is set higher than marine capital efficiency to reflect that the marine mining sector is thought to be more capital-intensive than the onshore mining industry. In other words, all else equal, the onshore mining sector will have higher output per unit capital than the marine mining sector.

Finally, the reader should note that the numerical specification of the factor productivity parameters in problem 1 differ from the numerical specification of said parameters in problems 2, 3, and 4. The factor productivity parameter values are specified such that the onshore mining sector starts out with the same production capacity in all scenarios. This makes the solutions more comparable.

Results

The optimization problems are solved by use of GAMS and the KNITRO solver (GAMS 2022a). KNITRO implements both state-of-the-art interior point and active-set methods for solving non-linear dynamic optimization problems (GAMS 2022b). This makes it well suited for solving the problems presented here. For the interested reader, we have made our code available on GITHUB (Bang and Trellevik 2022). The GITHUB repository also contains instructions on how to solve the scenarios

Table 1 Numerical specifications of the dynamic optimization problems

Parameter	Units	Problem 1	Problem 2	Problem 3	Problem 4
$x_{i=1,\,t=0}$	Thousand tons	2,000,000	2,000,000	2,000,000	2,000,000
$x_{i=2,\,t=0}$	Thousand tons	3,000,000	3,000,000	3,000,000	3,000,000
$k_{i=1,\,t=0}$	Capital units	40	40	40	40
$k_{i=2,\,t=0}$	Capital units	0	0	0	0
r	Dimensionless	0.05	0.05	0.05	0.05
P_{max}	Billion USD per thousand tons	0.006	0.006	0.006	0.006
P_c	Dimensionless	0.0001	0.0001	0.0001	0.0001
m_2	Billion USD per thousand tons	-	-	-	0.0005
α_1	Billion USD per unit employed capital	0.3	0.3	0.3	0.3
α_2	Billion USD per unit employed capital	0.3	0.3	0.3	0.3
β_1	Billion USD per unit investment raised by the power of γ_1	0.5	0.5	0.5	0.5
β_2	Billion USD per unit investment raised by the power of γ_2	0.5	0.5	0.5	0.5
γ_1	Dimensionless	1.1	1.1	1.1	1.1
γ_2	Dimensionless	1.1	1.1	1.1	1.1
A_1	Production per unit employed capital/production per unit employed capital per size of reserves	600	0.0003	600	0.0003
A_2	Production per unit employed capital/production per unit employed capital per size of reserves	300	0.0001	300	0.0001
d_1	Dimensionless	0.1	0.1	0.1	0.1
d_2	Dimensionless	0.1	0.1	0.1	0.1

presented in this study. In the following, we present the solutions to the problems.

Figure 1 provides an overview of the solution to problem 1, i.e., the monopoly case with reserve-independent capital efficiency. The principal chooses investment rates (top left panel), which leads to accumulation of capital (top right panel), which allows for positive production decisions resulting in production/extraction (second to top left panel), which further leads to decline in mineral reserves (second to top right panel). Total production determines price (bottom left panel). Based on the previous information, and information about the discount rate, the net present value is calculated (bottom right panel).

The solution to problem 1 indicates that it is optimal to extract in order of increasing unit extraction costs, aligned with Herfindahl (1967), Solow and Wan (1976), and others. However, since the terrestrial reserves do not get depleted within the first 100 years, there is no transition to marine mining. Problem 1 is solved with a doubling of the factor productivity parameters to confirm that the characteristics of the solution align with existing theory and research. The solution is shown in Appendix Fig. 9 and illustrates what a transition would look like in the monopoly-case with reserve-independent capital efficiency. The solution clearly confirms what was already indicated by the solution in Fig. 1.

On one hand, the solution to problem 1 is unsurprising, in that it resonates theory and common sense. On the other hand, it is useful to know that the core part of the model produces reasonable results before moving into more complex scenarios. Moreover, the solution to the problem helps identifying the ceteris paribus effects of reserve-dependent capital efficiency by serving as a baseline solution for comparison.

Figure 2 provides an overview of the solution to problem 2, i.e., the monopoly case with reserve-dependent capital efficiency. The optimal behavior is different to the behavior witnessed in the monopoly scenario with reserve-independent capital efficiency (Fig. 1 vs. Fig. 2).

In the monopoly scenario with reserve-independent capital efficiency, the deposits were extracted in order of increasing extracting costs. However, since the terrestrial reserves did not get depleted within the first 100 years, we witnessed no transition to marine mining within the given time horizon. In the solution to problem 2, we witness extraction in order of increasing extracting costs, just like in the solution to problem 1. However, in problem 2, the output per unit capital is increasing with positive changes in the reserves, i.e., decreasing with negative changes in the reserves. Thus, the unit extraction costs are dependent on the size of the reserves. As such, the reserve-dependent model allows for switching between what resource stock has the highest unit extraction costs.

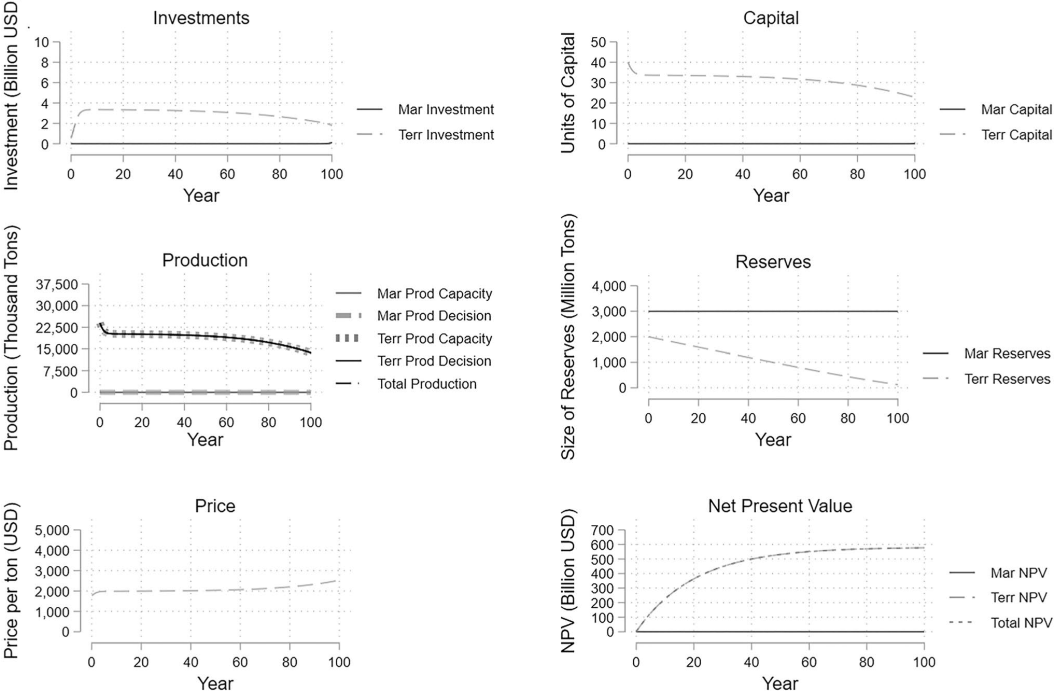

Fig. 1 Solution to problem 1: reserve-independent capital efficiency, no competition, and no mineral security considerations

The initial marine reserves are abundant relative to terrestrial reserves, while initial marine capital is low relative to terrestrial capital. The relative abundance of marine reserves has an indirect positive effect on the relative attractiveness of marine investment, while the relative abundance of terrestrial capital exists as a competitive disadvantage for the marine sector. Moreover, the marine total factor productivity is lower than the terrestrial total factor productivity. The lower marine total factor productivity has negative effects on the relative attractiveness of marine investment.

Figure 2 clearly shows that the additional abundance of marine reserves does not fully compensate for the lower marine total factor productivity and the marine disadvantage of no initial capital. Therefore, the principal begins with onshore extraction, just like in the monopoly scenario with reserve-independent capital efficiency (see Fig. 1 vs. Fig. 2). However, through terrestrial extraction and reduction in terrestrial reserves, the terrestrial unit efficiency goes down. This continues until the relative attractiveness of marine investment reaches a level where the principal reduces investment in terrestrial capital to build up marine capital through marine investment while letting the terrestrial capital depreciate. The principal then seeks to enter investment paths that ensure terrestrial and marine extraction are equally attractive.

Figure 3 provides an overview of the solution to problem 3, i.e., the duopoly case with reserve-dependent capital efficiency. The solution to this problem sketches out a different behavior than those observed in the monopoly scenarios.

In line with what to expect from an increase in competition, total production is higher in the duopoly scenario with reserve-dependent capital efficiency when compared to the monopoly scenario with reserve-dependent capital efficiency. Consequentially, the price is also lower through this period (Fig. 2 vs. Fig 3). Consistent with expectation, the overall NPV is lower in the duopoly scenario with reserve-dependent capital efficiency than in the monopoly scenario with reserve-dependent capital efficiency. And the marine NPV is much higher in the duopoly scenario with

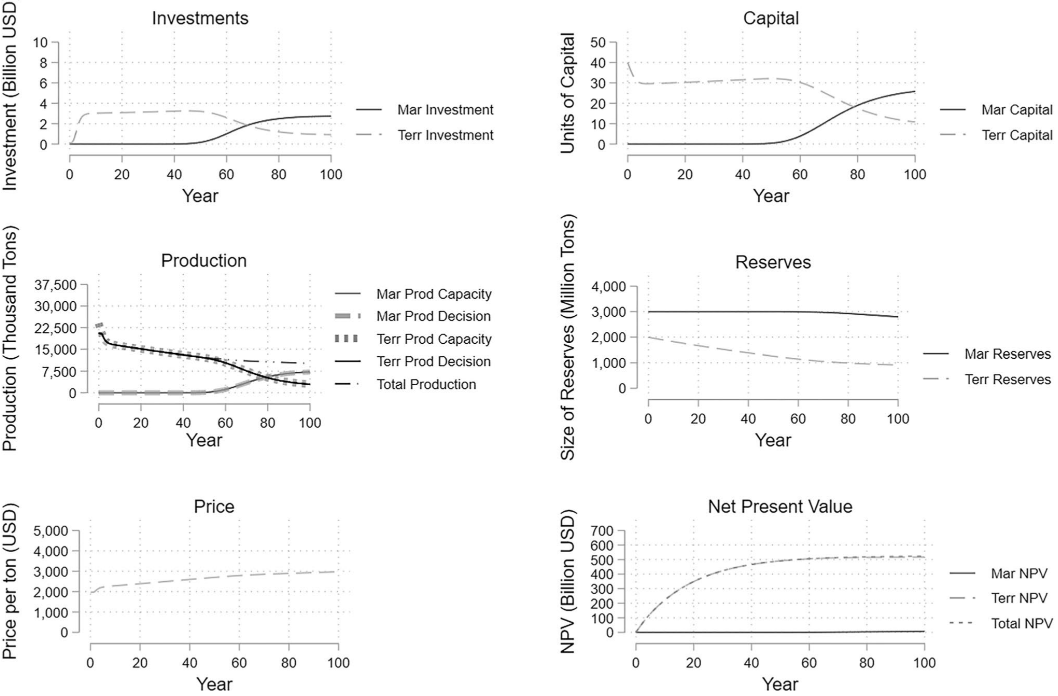

Fig. 2 Solution to problem 2: reserve-dependent capital efficiency, no competition, and no mineral security considerations

reserve-dependent capital efficiency than in the monopoly scenario with reserve-dependent capital efficiency. More surprisingly, the transition to an industry with marine production starts already at time zero.

Figure 4 provides an overview of the solution to problem 4, i.e., the duopoly case with reserve-dependent capital efficiency and marine mineral security considerations.

The solution to problem 4 is similar to the solution to problem 3. However, when compared to the solution to problem 3, the introduction of marine mineral security consideration leads to a significant increase in the marine investments and production, resulting in an overall much higher production.

Sensitivity analysis

Several changes can be considered in a sensitivity analysis here—ranging from changes in the initial values of the state variables, to changes in the discount rate, price parameters, cost parameters, productivity parameters, and the depreciation rates of capital, across all four scenarios. However, the analysis concentrates on how changes in P_{max}, γ_2, A_2, and m_2 affect the solutions to problem 3 and 4. Together, these changes offer broad insight to how changes in various types of parameters affect the optimal solutions in the cross-sector competition scenarios.

Specifically, we consider the following questions. How does the solution to problem 3 respond to a 20% increase in the price parameter P_{max}? How does the solution to problem 3 respond to a doubling of the investment cost exponent γ_2? How does the solution to problem 3 respond to a doubling of the factor productivity of marine capital A_2? And how does the solution to problem 4 respond to a doubling of the mineral security consideration parameter m_2?

Figures 5, 6, and 7 show the solutions to problem 3 with a 20% increase in P_{max}, a doubling of γ_2, and a doubling of A_2, respectively. Figure 8 shows the solution to problem 4 with a doubling of m_2.

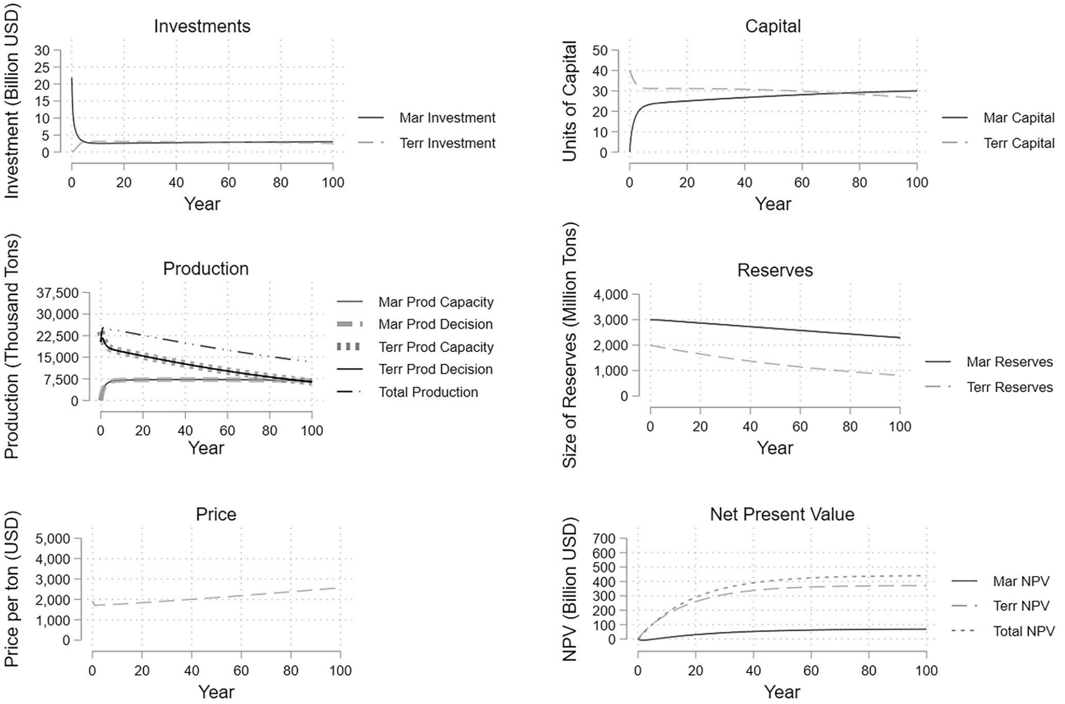

Fig. 3 Solution to problem 3: reserve-dependent capital efficiency, cross-sector competition, and no mineral security considerations

The sensitivity results show that an increase in P_{max} increases the extraction in both sectors, but relatively more in the marine sector compared to the terrestrial sector, which is interesting, as it indicates that the marine sector has more to gain from an increase in demand than the terrestrial sector (Fig. 5). The increase in γ_2 weakens the competitive ability of the marine sector, and prolongs the build-up time of marine capital, both of which lead to different behavior and overall reduced marine extraction (Fig. 6). Interestingly, the terrestrial sector does not respond to this by increasing its extraction, but rather choose to reduce it slightly. The weak negative extraction response in the terrestrial sector is explained by the fact that it gains more market power and works to push the production schedule towards the monopoly solution (Fig. 6 vs. Fig. 2). A doubling of the marine factor productivity turns the marine sector into the dominant producer, even though it starts out with no initial capital and must take on large investment costs to build up capital for production (Fig. 7). This goes on to show that the marine mining sector could leverage its advantage of abundant resources if it finds a reasonable approach to extraction. A doubling of m_2 also turns the marine sector into the dominant producer (Fig. 8).

Discussion

In the monopoly scenario with reserve-independent capital efficiency, our results indicate that a transition will take place when the terrestrial reserves near depletion, far out in time, outside the given time horizon of interest. The behavior exhibited in this solution is aligned with theory and common sense. The problem is unrealistic, and the solution is unsurprising. However, it serves a purpose by validating the model's functionality and establishing a baseline for comparison.

Reserve-independent capital efficiency suggests that mineral sites are equally accessible and that the mineral concentration and distribution in mines are uniform, onshore, and offshore, respectively. However, accessibility and ore grades are in decline, increasing the unit

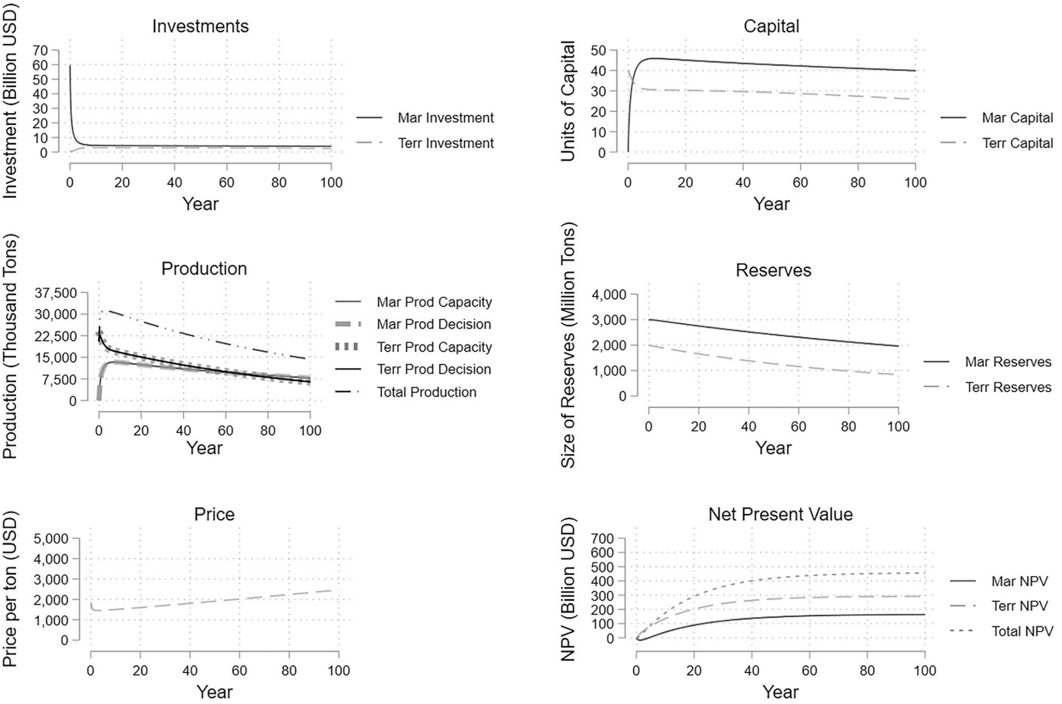

Fig. 4 Solution to problem 4: reserve-dependent capital efficiency, cross-sector competition, and asymmetric mineral security considerations

costs of extraction (International Energy Agency (IEA) 2021; Ragnarsdóttir 2008; Schulz et al. 2017; Sverdrup et al. 2019). Such development can also be expected in a possible marine industry after possible initiation and prolonged marine mining—rational miners will prefer to start with the most accessible sites with the highest ore grade before moving on to less accessible sites with lower ore grade (given full knowledge of all resources).

The second scenario, which considers a monopoly situation with reserve-dependent capital efficiency, demonstrates the effects of declining accessibility and ore grade. The conceptual results show that a transition to marine mining will occur well before the terrestrial reserves near depletion, at a much earlier point in time, within the given time horizon. Moreover, the results indicate a transition to an industry with co-existing terrestrial and marine mining. Under monopoly conditions, there is no competition driving the transition, yet the principal maximizes profits by entering marine mining early to offset the effects of declining ore grade or accessibility in terrestrial resources. As such, these results clearly indicate that reserve-dependence can drive a possible transition. This suggests that the observed real-world phenomena of declining ore grade and accessibility can play a significant role in the future development of the mining industry, for example, to include extraction of less accessible but higher-grade ore, which marine mineral deposits may represent.

The duopoly configuration of the model abstracts two phenomena—the emergence of a marine mining sector that is separate from the existing onshore mining sector in terms of ownership, and a changing geopolitical environment for minerals supply. The geographical distribution of minerals, including both onshore and offshore minerals, can indicate separate onshore and offshore owners, implying possible cross-sector competition between the existing onshore industry and an emerging marine industry. There have already been several initiatives to advance the emergence of a commercial marine mining industry. For decades, different

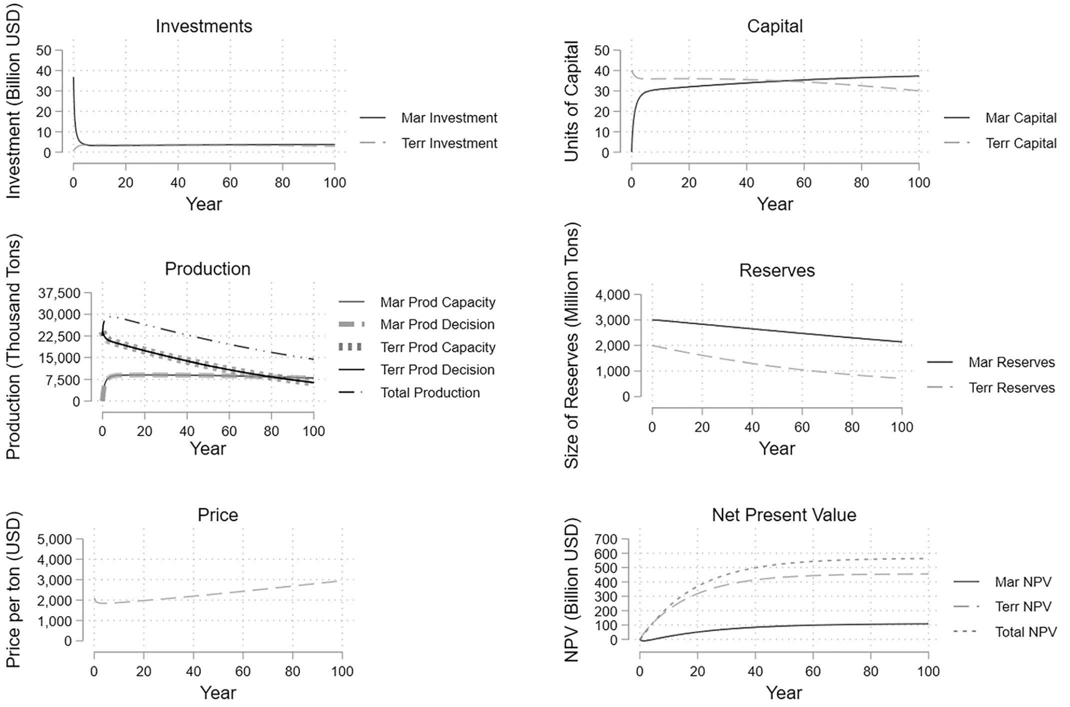

Fig. 5 Solution to problem 3 with 20% increase in P_{max}: reserve-dependent capital efficiency, cross-sector competition, and no mineral security considerations

national, international, and private organizations have worked towards establishing commercial marine mining (Boomsma and Warnaars 2015; Childs 2020; Sparenberg 2019; Volkmann and Lehnen 2018). Even though no commercial success has been achieved as of May 2022, the initiatives to develop technology, legislation, and commercial entities to extract minerals from the seabed continue to persist outside interest spheres that are currently dominating mineral supply.

In the duopoly situation with reserve-dependent capital efficiency, but without mineral security considerations, the results indicate an immediate and powerful transition to an industry with co-existing terrestrial and marine mining. Now, this scenario is interesting because it truly shows the effect of competition on transition in a resource-based, resource-scarce, and profitable industry. Considering the development in the onshore mining industry, with falling ore grades and increasing extraction costs, it is useful to demonstrate that reserve-dependence and cross-sector competition can trigger transition towards marine mining.

The geopolitical divides made evident by the full-scale Russian invasion of Ukraine in 2022 actualize the duopolistic model configuration with asymmetric mineral security considerations. In the wake of the war in Ukraine, the European Union responded almost immediately by declaring the urgency of a diversified supply of critical raw materials (European Council 2022). As such, the two competing cartels may be considered a simplified representation of, e.g., a western interest sphere on the one side and a Russo-aligned interest sphere on the other. Moreover, it is not farfetched to suggest that interests in mineral security can result in support schemes for further development of the European mining industry, including marine mining—i.e., Europe assigning additional value to independent European extraction of minerals beyond the financial gain from extraction.

The results from the duopoly scenario with reserve-dependent capital efficiency and marine mineral security considerations indicate an immediate transition to an industry with co-existing terrestrial and marine mining, just like in the duopoly scenario with reserve-dependent

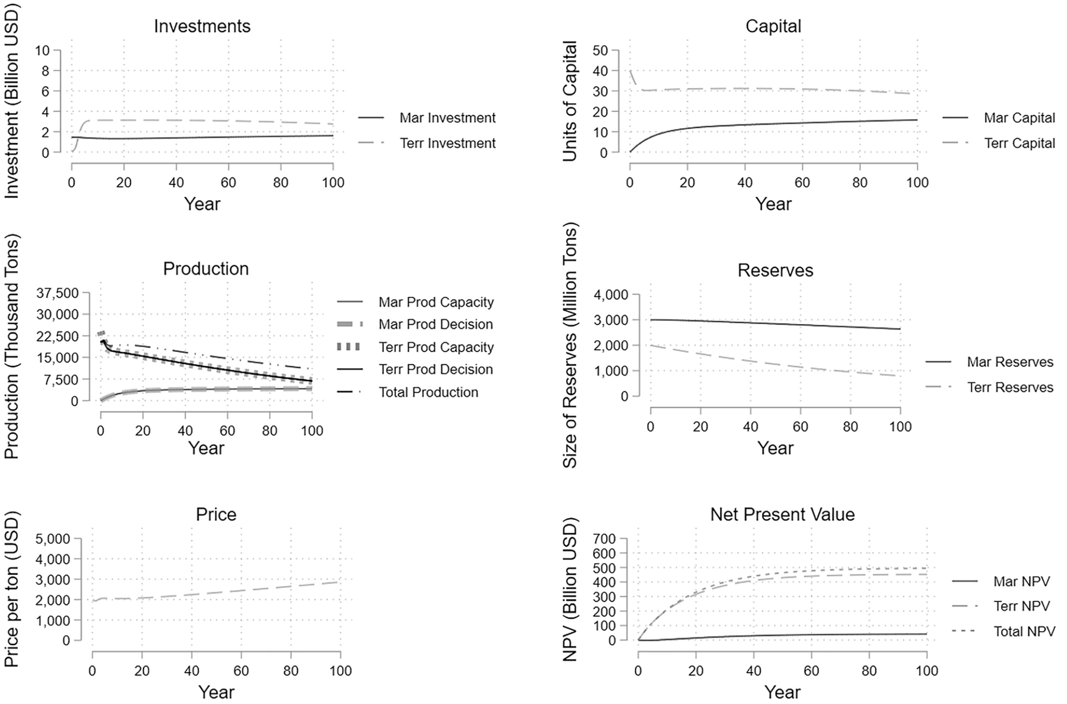

Fig. 6 Solution to problem 3 with doubling of γ_2: reserve-dependent capital efficiency, cross-sector competition, and no mineral security considerations

capital efficiency and no mineral security considerations. However, in the duopoly scenario with reserve-dependent capital efficiency and mineral security considerations, the marine mining sector increases initial investments and extraction, leading to an overall much higher production. As such, these results also show that mineral security considerations can help drive transition to marine mining.

Security considerations have received considerable attention in lieu of the 2022 invasion of Ukraine. In the Versailles declaration of March 2022, the European Council expressed intent to secure access to critical materials (European Council 2022). This makes the insight from the solution to problem 4 highly relevant and can be encouraging to those organizations already investing in the development of a marine mining industry. That said, the reader should also note that European mineral security considerations can also impact the terrestrial mining sector in the European sphere of allies—it would not only impact marine mining. As such, European mineral security considerations need not have an as strong asymmetric effect upon a transition to marine mining as sketched out by our results.

Although our results indicate that an industry with both onshore and offshore mining may be near, and that a transition may happen quickly, we must remind the reader that our model and analysis is conceptual, and that there are certain limitations. First, the model does not consider exploration, costs tied to innovation, technological development, delays, nor externalities. Second, the numerical specifications of our problems represent fabricated values—as such, they are only meant for illustrative purposes and cannot be considered realistic, although they do have some empirical grounding. A more realistic model would consider at least some of the forementioned factors. And a model that incorporate these factors may sketch out a different transitional behavior than the ones outlined in the solutions to the problems presented here. As such, our results should not, and cannot, be considered forecasts.

Regarding the missing factors, we can only speculate how they would affect a transition. For example,

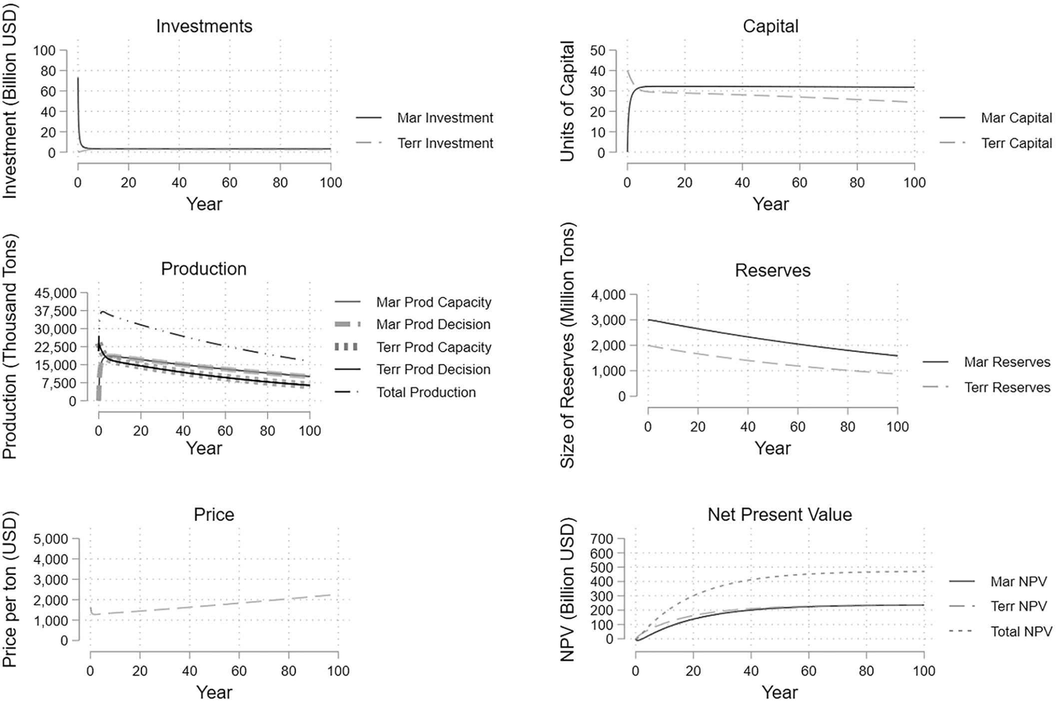

Fig. 7 Solution to problem 3 with doubling of A_2: reserve-dependent capital efficiency, cross-sector competition, and no mineral security considerations

significant effort must be put into exploration and identification of potential marine mining sites. This could be costly in terms of both money and time, and as such, push a transition further out. Moreover, in the real world, significant new mineral discoveries can be made onshore, and onshore technology could improve significantly relative to marine technology. New onshore discoveries and development in onshore mining technology could impede the emergence of marine mining. Furthermore, it is possible that inclusion of delays and costs tied to innovation would hamper a transition, and change the behavior seen during the build-up of marine capital, for example, from a concave development to a convex development, i.e., a capital-development that is initially slow, and then accelerates (until reaching some desired level, and thereafter decline). This seems reasonable because investment-delivery delays infer that expenditure occur today, while the benefits are reaped much later, and as such, discounted harder. Furthermore, it seems reasonable to argue that the costs of acquiring one unit of production capital are high when the technology is not yet invented, because time and money must be invested in research and development.

From a societal point of view, externalities are also important to consider. Many studies have investigated the potential ecological impact of marine mining, and it is apparent that the risks are significant (Niner et al. 2018; Sharma 2017, pp. 445–507; Van Dover et al. 2017; Wakefield and Myers 2018). Such considerations could also be built into models for future research on mineral industry transition. In such a case, one must also consider the question whether the potential immediate environmental costs associated with marine mining can be offset by the potential contribution of minerals as input factors to green-tech technologies. This is a complex discussion, but nevertheless, an interesting one.

Conclusion

This study pinpoints three highly relevant factors that can play important roles in a possible transition to marine mining, namely reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations. Furthermore, it investigates how these factors can

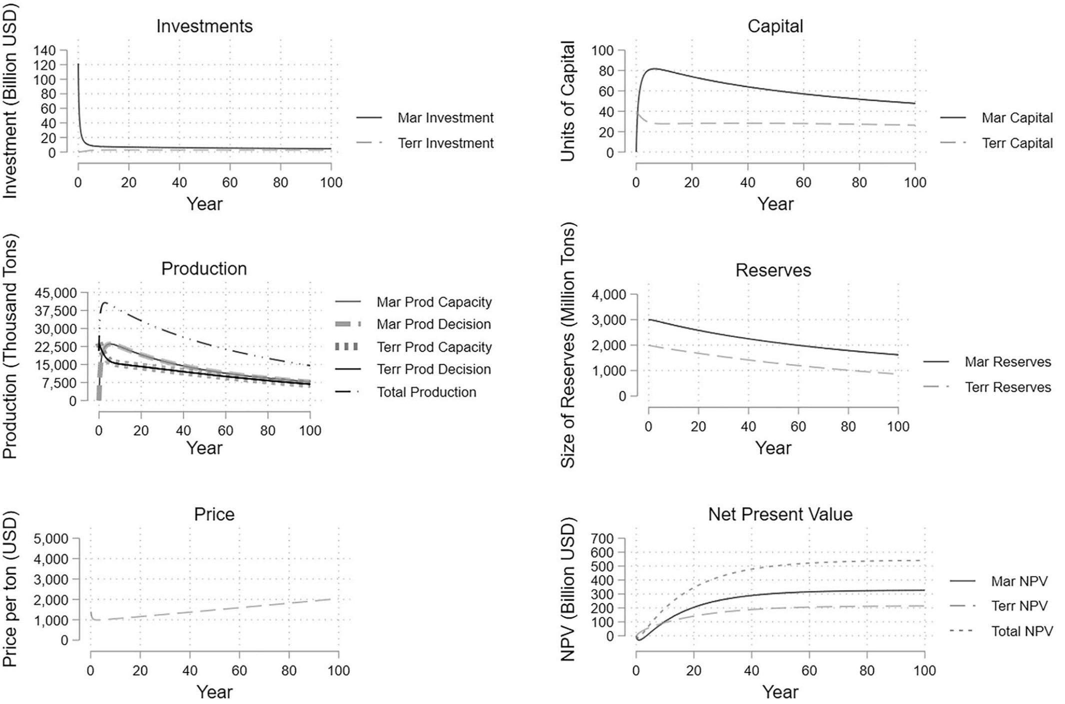

Fig. 8 Solution to problem 4 with doubling of m_2: reserve-dependent capital efficiency, cross-sector competition, and mineral security considerations

affect a transition. The optimization results and sensitivity analysis indicate that all three factors can catalyze transition to marine mineral extraction.

Today's terrestrial mining sector is turning towards lesser deposits with lower accessibility and ore grade to meet demand. As a result, onshore miners experience increasing unit extraction costs. By studying development trajectories when miner(s) face reserve-independent and reserve-dependent capital efficiency, we were able to isolate and illustrate the effect of reserve-dependency on a transition to marine mining. The relevant results suggest that the phenomenon of reserve-dependency can initialize or strengthen the emergence of a marine mining industry.

Although there is no commercial extraction of marine minerals in 2022, several technological, legislative, and commercial initiatives are ongoing. Considering decreasing ore grades and accessibility on land, the model results suggest that competition can trigger or strengthen the emergence of commercial marine mineral extraction. However, that said, we also highlight that new mineral discoveries onshore, and development in onshore mining technology, may hamper a transition to marine mining.

In the wake of the 2022 war in Ukraine, the European Union has expressed an explicit intent to secure the supply of critical materials, which may imply future European support schemes to the mineral industry in Europe, including a possible marine mining industry. When studying a situation in which the marine agent who make decisions on behalf of marine resource owner(s), government(s), and producer(s), value mineral security, while the onshore agent does not, the model results show that mineral security can accelerate the emergence of a marine minerals industry. However, in the real world, mineral security considerations may also have a positive impact on existing onshore industry. This is of course also of relevance to when a possible transition may occur.

Appendix

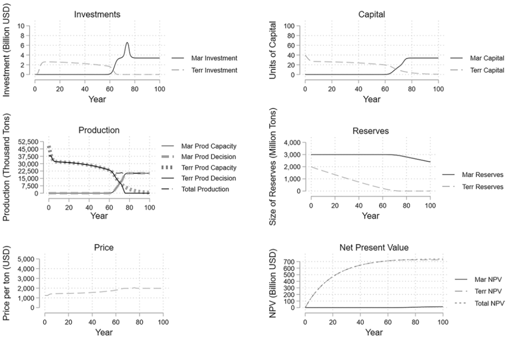

Fig. 9 Solution to problem 1 with doubling of A_1 and A_2: reserve-dependent capital efficiency, no competition, and no mineral security considerations

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Author contribution The authors have contributed to the project on equal terms.

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Declarations

The authors declare no competing interests. The author, Lars-Kristian Trellevik, who has 15 years of onshore and offshore industry experience with surveying/exploration, salvage, and autonomous operations, works as an external technical (survey and mapping) consultant for a company that aims to take part in the potential future marine mineral industry in Norway. However, the author's work here has no ties or direct relevance to his work as a consultant for that company.

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9. Appendix III

Mineral Economics
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ORIGINAL PAPER

Perspectives on exploration and extraction of seafloor massive sulfide deposits in Norwegian waters

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Abstract

We present a stochastic dynamic simulation model for exploration and extraction of seafloor massive sulfide (SMS) mineral deposits on the Norwegian Continental Shelf (NCS). The model is developed based on selected industry knowledge, expectations, and perceptions elicited through a participatory systems mapping session with 82 participants and 20 in-depth interviews with experts from industry, academia, and the public policy sector. Using the model, we simulate the expected ranges of resource- and economic potential. The simulation results indicate an expected commercial resource base of 1.8 to 3 million tons of copper, zinc, and cobalt, in which copper makes out the most significant part. Relating to the expected commercial resource base, we highlight a discrepancy between academic and industrial expectations, in which the academic expectations are more conservative than the industrial expectations. The corresponding net present values lie in the range of a net present loss of 970 million USD up to a net present gain of 2.53 billion USD, in which the academic expectations are projected to yield a negative net present value, while the industrial expectations are projected to yield a positive net present value. Closer investigation of the results reveals that one of the main challenges regarding SMS exploration and extraction is the initial exploration costs associated with coring operations. These costs are expected to be high with today's exploration technology. Moreover, they occur relatively early in time compared to revenue-generating activity, which has a significant negative impact on the net present value of the industry due to discounting. Thus, a key focus of the industry should be to find ways to reduce the costs associated with coring operations and/or the time it takes from initial exploration to extraction and generation of revenue.

Keywords Deep-sea mining · Marine minerals · Seafloor massive sulfide deposits

JEL Classification C63 · D24 · D25 · Q30 · Q32 · Q33 · Q34

Introduction

Global commercial supply of critical minerals is based on onshore mining and recycling (Kaluza et al. 2018; United States Geological Survey (USGS) 2020). However, the onshore industry is facing declining resources, falling ore grades, and increasing extraction costs (Watari et al. 2019). At the same time, population growth, economic growth, and the green shift are increasing the demand for metals (International Energy Agency (IEA) 2021; Kaluza et al. 2018; Watzel et al. 2020). According to today's projections, the future demand for metals can only partly be satisfied through extraction from onshore sites and increased recycling (International Energy Agency (IEA) 2021; Ministry of Petroleum and Energy 2021; Sparenberg 2019; Watzel et al. 2020). This may pave the way for alternative mining, such as deep-sea mining (Bang and Trellevik 2022b).

The deep sea may be earth's final frontier—it is poorly explored and the knowledge gaps are significant (Lusty and Murton 2018). Nevertheless—the deep sea is known to hold significant deposits of critical minerals (Hein et al. 2013; Petersen et al. 2016; Sharma 2017). Marine mineral deposits

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were first identified in the 1870s (Sparenberg 2019; Volkmann and Lehnen 2018). Since then, deposits have been identified both in international waters and within different countries' exclusive economic zones (EEZs). Several attempts have also been made to extract marine minerals, but none of these attempts has yet been commercially successful (Childs 2020; Hyman et al. 2022; Toro et al. 2020). Nevertheless, new attempts are in progress, and it is possible that the future holds a mining industry including an onshore mining sector and a commercially viable deep-sea mining sector.

Seabed minerals have been identified in Norwegian waters, primarily in the form of sulfides and manganese crusts (NPD 2021; Pedersen et al. 2021; Pedersen and Bjerkgård 2016). Sulfides contain mainly lead, zinc, copper, gold, and silver, while manganese crusts contain manganese and iron, and small amounts of titanium, cobalt, nickel, cerium, zirconium, and rare earths.

In 2019, the Norwegian parliament passed a marine minerals act and the parliament is scheduled to vote on the formal opening of the Norwegian EEZ for commercial mineral exploration and extraction in 2023, pending an ongoing environmental impact assessment (NPD 2021; Pedersen et al. 2021; Regjeringen.no 2021).

At least three mineral exploration and production companies have already been established in Norway. These are currently positioning themselves for the scheduled opening in 2023. The authors have also identified at least four substantial industrial corporations engaging and investing in the potential marine minerals industry, as well as initiatives by a plethora of service and technology providers, historically catering to other subsea industries. A conservative estimate by the authors indicate that some 300 million NOK have already been invested in the marine minerals initiatives on the Norwegian Continental Shelf (NCS)—with significantly larger investments in the pipeline.[1]

Although an opening is in progress and investments are being made, there is currently limited knowledge about the mineral resource potential on the NCS, and whether extraction will be profitable. The Norwegian marine minerals industry is barely in its infancy—currently without parliamentary consensus to proceed—seeking to extract resources that are poorly explored, in an environment that is poorly understood, using technology that has yet to be developed and proven. Thus, the future of the Norwegian mining industry is riddled with uncertain, unknown, and even unknowable factors.

Motivated by the lack of literature on deep-sea mining on the NCS, and the otherwise limited literature on deep-sea mining, this study maps and synthesizes the industrial complex evolving around exploration and extraction of marine minerals from seafloor massive sulfides (SMS) on the Norwegian continental shelf. Based on the mapping and synthesis, it simulates possible industry development trajectories, the expected resource potential, and the expected economic potential, per selected material including knowledge, expectations, and perceptions regarding the geological resources, available technology for exploration and extraction, operational factors, commercial factors, and regulatory factors.

To achieve the objectives, a simulation model is developed based on literature and database reviews, observation, participatory modelling, as well as qualitative interviews, with a wide array of stakeholders and experts. The broad-spectrum approach affords access to a comprehensive range of information. This in turn, enables description, modelling and simulation of current consensus and various scenarios. The environmental aspect of deep-sea mining is important and a significant uncertainty for the industry. However, this aspect is largely left out of the scope of this study.

Methods

We build an exploratory system dynamics model with stochastic features based on numerical and written databases as well as knowledge, expectations, and perceptions elicited from experts and stakeholders. By way of Monte Carlo simulation and sensitivity analysis, we explore possible development trajectories and uncertainties. We run simulations for various resource scenarios and conduct sensitivity analyses for key variables and parameters pertaining to the resource base, discounting, costs, and revenue.

System dynamics is useful for mapping and simulating complex and uncertain systems. This makes it appropriate for achieving the objectives of this study. System dynamics has a strong tradition for making use of data extracted from a number of different sources, including numerical, written, and mental databases (Forrester 1987, 2007; Forrester 1992; Luna-Reyes and Andersen 2003a; Sterman 2002). Mental databases include information such as subjective expert knowledge, experience, expectations, and perceptions. Such information can be valuable, especially when the numerical and written databases are limited and/or incomplete, which is typical for emerging industries such as the deep-sea mining industry.

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[1] This estimate is a simple summary of public and private spending on marine minerals surveying expeditions, business incubation grants, technology development, and acquisitions as disclosed by experts and stakeholders participating in the study—as well as investments made in marine mineral companies recently established in Norway. All underlying information for this estimate is publicly available. The estimate is conservative as it does not account for spending not made publicly available such as R&D spending in the private sphere.

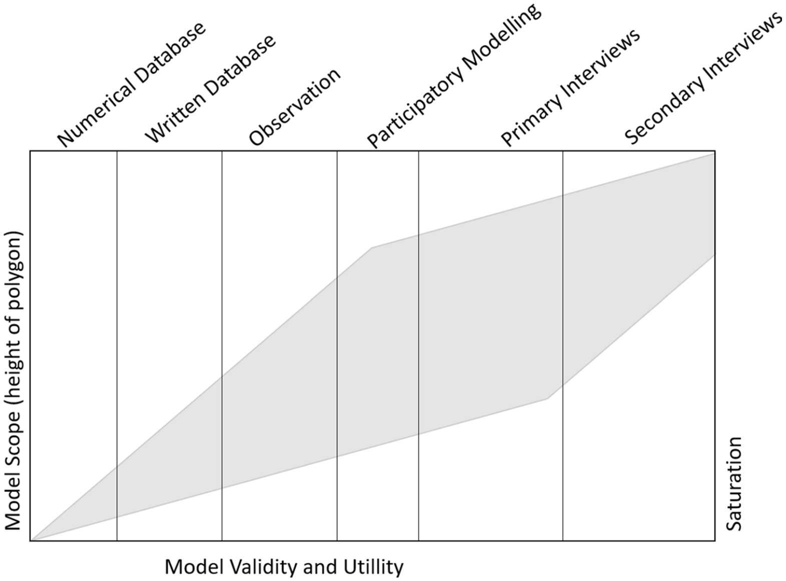

Fig. 1 Illustration of the model development process and how it relates to model scope, saturation, as well as model validity and utility

Since the numerical and written databases for mineral resources and deep-sea mining on the NCS are scarce, the work presented here employs transferable analogous concepts or technological principles familiar from related and more established domains, such as onshore mining and offshore oil and gas. Moreover, it relies on information from the mental databases of stakeholders and experts. Through organized engagement with experts and stakeholders, we map structural elements, elicit parameter values, and perceptions of uncertainty as they are described by people with first-hand insight to the possibly emerging industry, including stakeholders and experts from industry, government, and academia. This pragmatic and comprehensive approach to information gathering allows access to information that is currently unavailable in terms of numerical and written data. This in turn puts us in position to form a full perspective of the possibly emerging industry.

The structural elements and parameters applied in the model are elicited through four consecutive and iterative steps including review of numerical and written databases, observation, participatory modelling, and iterative disconfirmatory interviews. Figure 1 illustrates the model development process used to formulate the model presented in this study. The height of the polygon indicates the boundaries of the model scope., i.e., a higher height of the polygon suggests that more elements are included and vice versa. Saturation indicates the rate to which the model structure is confirmed by triangulation between participating stakeholders and experts. Model validity indicates the level to which the model structure is accepted. The utility indicates the usefulness of the model. With limited access to numerical and written data, the model starts off with a narrow scope, low validity, and low utility. Through the qualitative steps, the model boundaries increase, as new information is retrieved. Through the modelling process, the model boundaries are focused on relevant structure for research objectives, while both validity and utility increase.

Repenning (2002), and later, Kopainsky and Luna-Reyes (2008) assert that the system dynamics approach to developing models have many similarities with the concept of theory building. In this perspective, the methodology and modelling process applied here can be said to develop a theory about the emerging exploration and extraction industry tied to SMS deposits on the Norwegian continental shelf.

Numerical and written databases

The first step in the modelling process employed involve survey of available numerical and written data. The available ecological, geographic, and geological survey data of SMS deposits on the NCS is limited; the industry forming has yet to launch and document their commercial, operational, and technological concepts; and the regulation is yet not settled. As such, these databases are limited in their direct applicability. There is, however, an available body of academic, commercial, technical, and regulatory work on analogous marine mineral cases available from international contexts. There is furthermore a substantial body of work available from analogous industries such as offshore oil and gas, as well as onshore mining. Available numerical and written databases inform the work presented here and establish a venture point for model development, qualitative research, and data retrieval. Written and numerical data are also revisited through the process of model development. Important sources of numerical and written data includes but is not limited to the Norwegian Ministry of Petroleum and Energy (2021), the Norwegian Petroleum Directorate (2021), Pedersen et al. (2021), Rystad Energy (2020), Hein et al. (2013), Boomsma and Warnaars (2015), and Sharma (2017). Other sources worth mentioning include Jankowski et al. (2010) and Stanton and Yu (2010).

Observation

Observation is a valuable qualitative approach in the field of system dynamics (Luna-Reyes and Andersen 2003). Over a period of 3 years, the authors have observed and interacted with experts and stakeholders by participating in conferences and collaborative forums addressing marine minerals, and via direct dialogue with stakeholders engaging in the marine mineral domain. Access to these forums were encouraged and formalized as members of academia—and the forums, conferences, and other dialogue platforms were cross disciplinary and included stakeholders and experts from industry, government, academia, and various interest organizations.

The authors have participated in 8 different conferences and 16 forum meetings. In addition, the authors had a high number of informal conversations and discussions with other experts. This has allowed the authors an overarching grasp of involved parties and conceived technical, environmental, commercial, and regulatory concepts and challenges, in turn, enabling the further qualitative steps towards eliciting information from mental databases. The extensive observation has also proven important in terms of validating structural elements of the model.

Participatory systems mapping

Participatory modelling, Group Model Building, or Participatory Systems Mapping, are common knowledge elicitation methods within system dynamics (Hovmand et al. 2012; Vidal et al. 2019; Videira et al. 2010). Participatory modelling is a facilitated process wherein experts and stakeholders work in teams to describe important variables, as well as causal relationships, within a system. This form of collaboration can produce a negotiated consensus from a large group of stakeholders and experts in an effective manner.

The participatory modelling session conducted for this study was organized at an industry conference where 82 experts from the offshore industry participated. The group participating was a relatively diverse group within the offshore and subsea professional domain, spanning different nationalities, technical disciplines, levels of seniority, professional roles, and different opinions on marine minerals.

The participatory modelling workshop was designed to follow the systems mapping approach proposed by Wilkerson and Trellevik (2021), where systems mapping is proposed as a venture point for problem definition in innovation processes. The session was executed over a period of 2 h. First, the teams were presented with a seed-model as a point of departure for the mapping exercise. The seed-model presented was a graphical stock and flow model, which can be retrieved from the author's GITHUB repository (Bang and Trellevik 2022a). Subsequently, the participants were tasked with developing several system-maps with the aim to capture variables and causal relationships within the problem- and development-space of marine minerals exploration and extraction. The explicit challenge presented to participants was to map out how exploration and extraction of marine minerals could unfold as an operational and commercial concept. Following the mapping session, all teams debriefed their results with facilitators, and the system maps were collated, and analyzed to define structural model elements and parameters of relevance for further model development.

Iterative disconfirmatory interviews

Based on the preceding quantitative and qualitative data elicitation, a detailed system dynamics simulation model was developed. As the authors gained confidence that the model adequately abstracted and represented the data and findings, a substantive and iterative series of stakeholder- and expert interviews were ensued. A total of 20 stakeholders and experts were interviewed through this phase of the modelling process. The interview subjects were representatives from industry, public policy, and academia— all with specific expert knowledge and/or vested interests in marine minerals on the NCS.[2]

The interviews executed for this study were formatted as semi-structured and disconfirmatory. Disconfirmatory interviews have emerged in recent years as a rigorous methodology for research and knowledge acquisition and has informed the research methodology in this study (Andersen et al. 2012; Luna-Reyes and Andersen 2003). Iterative disconfirmatory interviews allow for continuous model improvement and validation.

The interviews used preliminary models as a starting point. In the beginning of each interview, the most recent preliminary model was presented to interview subjects, with the purpose of having the model challenged and critiqued

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[2] Please see Appendix 2 for anonymized stakeholder overview.

through the remaining parts of the interviews. The various experts and stakeholders thereby disqualified existing structures and parameters, and qualified new ones, which allowed for model modification, extension, curtailment, and improvement. Via iteration, saturation was reached. The interview-guide used for the interviews can be found in Appendix 3.

There was overlap between several subjects' competence and expertise while there was significant distance between the competence and expertise of others. All interview subjects were presented with the entire model structure and its underlying assumptions, logic, and formulations—and were encouraged to challenge the material presented. One-third of the subjects were re-interviewed to either evaluate model changes, or to provide supplementary information. Supplementary interviews were also executed when there was disagreement between interviewees, this to seek negotiated agreement on model structure or parameters and identify for which cases several scenarios should be run.

Model structure validation

The model abstracts and synthesizes the knowledge, expectations, and perceptions of an emerging industry. Therefore, there is no historical data of system behavior towards which the model behavior can be validated against. Validation is henceforth focused on the model structure, which has also been a dominating focus in system dynamics the last two–three decades (Barlas 1996; Barlas and Carpenter 1990; Ford and Sterman 1998).

System dynamics models are causal mathematical models and base their mathematical expressions on postulated causal relations within the system they model. In this, system dynamics models constitute theories about the system they abstract and as theories they can be validated following commonly accepted norms of scientific theory testing. This obviously raises a number of fundamental philosophical questions, pertaining to justification of a knowledge claims, constitution of scientific confirmation, and more, and renders model validation a complicated matter (Barlas and Carpenter 1990).

Through the modelling process, the model both improves—and is validated in terms of its structure as well as its parameterization. Iterative rounds of interviews with representatives from both similar and different niches of expertise, as well as association to the domain afford an opportunity to both reach saturation—and to triangulate between conceptions of the emerging model structure.

The authors have also rigorously tested the model functionality and for mathematical integrity along the way. This includes numerical integration error tests, behavioral tests, consistency tests, and extreme conditions tests. The model is producing behavior aligned with expectations when reviewing the causal relationships of the system components. With a validated model structure as well as mathematical integrity—the authors are confident that the model presented enables analysis and clarity on this emerging industry.

The modelling process has allowed mapping of several emerging system structures, the underlying dynamics, as well as discovery of a range of plausible future trajectories for SMS mineral exploration and extraction on the Norwegian continental shelf. However, the reader should note that the authors are careful not to make any actual predictions. Considering all the uncertainties involved and the nature of this study, that would be futile. Rather, in addition to mapping the exploration and extraction structures, we attempt to simulate the outcome of collective stakeholder and expert knowledge, expectations, and perceptions.

Geological resources

There are two types of marine mineral deposits identified on the Norwegian continental shelf: ferro-manganese crusts and SMS deposits. The two deposit types are considerably different from each other in the mode of deposition, depositional characteristics, mineral composition, and locale of deposition. However, the geological engine driving the mineral deposition of both potential resources is hydrothermal activity around the ultra-slow spreading oceanic ridge system around the island of Jan-Mayen (Lusty and Murton 2018; NPD 2021; Rolf B Pedersen et al. 2021). In deep waters (> 2500 MSW), the oceanic plate is relatively thin and adjacent to magmatic heat. As this is a tectonically active area, the ocean plate is fractured and largely consisting of porous volcanic rock-types. Due to the porosity and fracturing, as well as the considerable water pressure at these depths, seawater percolates into the seabed. Here, it is exposed to magmatic heat, expands, and rises back towards the surface. Migrating through the seabed, exposed to extreme temperatures, the seawater is enriched with minerals. As the seawater rises, and eventually is exhausted back into the ocean, it cools and precipitates minerals.

Ferro-manganese crusts are vast layers of hard material deposited on exposed rock-faces of sufficient inclination to not retain significant sedimentation. Ferro-manganese crusts typically form off-axis from the ridge system, and at under-water mountainsides with slope-angles of at least 30°. The crusts can straddle several kilometers, typically with a hardness of about 8 and with a thickness of an approximate maximum of 20 cm. Ferromanganese crusts have been proven to contain Co, Te, Mo, Bi, Pt, W, Zr, Nb, Y, and rare-earth elements (REEs) (Hein et al. 2013; NPD 2021; Pedersen et al. 2010).

SMS deposits form as piles of material. Hydrothermal-vents build up as chimney-like stalagmite-features. With time, the chimneys collapse, and the hydro-thermal vent finds an alternative route and starts building new stalagmites.

The lifespan of a hydrothermal vent system forming SMS deposits appears to be around 50,000 years—after which time the magmatic heat-source either migrates or the deposition field is covered by a lava-flow. There appear to be on average one active vent-site per 100 km of ridge—leaving the Norwegian continental shelf with approximately 5 active vent-sites at any given time. The water temperature inside the hydrothermal vents is approximately 400 °C—and the active vent sites are home to a remarkable biosphere of poorly understood life-forms. Because of both the high temperature and pressure in active vent-sites, as well as the abundant life—active vent-sites are not being considered for mining operations either by licensing bodies or by the industry itself—rather, extinct or dormant fields are being explored for mining purposes. The SMS deposits on the NCS have proven resources of copper, zinc, and cobalt (Pedersen et al. 2021; Pedersen and Bjerkgård 2016).

Considering the vastly different properties of SMS deposits and ferromanganese crusts, the two categories of deposits will likely require different technology both for exploration and extraction.

Exploration

There is a growing body of literature addressing industrial concepts for exploration and extraction of marine minerals exemplified by Volkmann et al. (2018), Boomsma and Warnaars (2015) and Sharma (2017). The work presented here is informed by this literature—but it is considered more a point of reference rather than structural input to the model. Exploration and extraction sectors in the model are abstracted in accordance with findings from qualitative research and as such represent exploration and extraction as envisioned by experts and stakeholders.

Deep sea exploration for marine minerals is conceived in four consecutive steps where the geographic boundaries are reduced while the data resolution and geological certainty increase. In specific cases, there may be repetition of various steps. However, that is circumstantial operational details beyond the scope of the work presented here.

The first stage of exploration is conceived as regional exploration wherein relatively small and cost-efficient vessels with hull-mounted or towed echosounders, or other acoustic sensors, survey large areas in search of bathymetry or other geomorphological features indicative of SMS deposits.

Areas of high interest are identified based on the regional survey data. These areas are then explored further with autonomous underwater (AUV), or remotely operated vehicles (ROV) mobilized from larger, advanced multi-purpose vessels with a considerable technical crew onboard. AUVs or ROVs carry several acoustic, optical, and chemical sensors and operate relatively close to the seabed. The proximity to the seabed reduces the geographic footprint of multibeam-echosounders, synthetic aperture sonars, and other sensors—but high-resolution data on possible SMS deposits is collected. The swath and survey speed are strongly affecting the high-resolution survey efficiency. The industry leans towards utilizing several AUVs in simultaneous operation, thus increasing the geographic footprint per time of operation. To obtain the data resolution required, AUVs will fly at an altitude of about 30 m above seabed. At this flying-height, typical opening angles at dual-head Multi Beam Ecco Sounders (MBES) will allow a lateral swath of about 500 m and at a survey speed of about 1.3 knots. With several AUVs operating simultaneously, the aggregated swath is obviously increased. AUVs fitted with the relevant sensors can typically operate for about 60 h at 3000 m water depth—and with a charge, service, and data-download turnover of about 12 h. The AUVs are dependent on acoustic positioning signals from the surface vessel to maintain navigational integrity throughout the dive—and as such the number of AUVs being operated from one single surface vessel is limited, practically to three AUVs. ROVs are far less efficient—as well as less navigationally stable platforms for data retrieval and will most likely not be utilized widely for this purpose and is henceforth not represented in the aggregate model.

Based on high-resolution data, the final stage of SMS exploration involves retrieving core-samples from the prospective areas. Coring units, essentially remotely operated vehicles with drill-rigs attached, are mobilized to the same type of advanced subsea-vessels as utilized for high-resolution mapping and the seabed is sampled via 50–200-m-deep drill-cores. One single core will require about 48 h to retrieve, and several coring samples are needed to confirm the existence of commercial ore at a site and generate resource estimates.

Throughout the operation, the coring-unit will require assistance from a large work-class ROV for replacement of coring tubes, visual inspection, and general support. As such, a substantial offshore crew is required for coring operations. Geologists will then evaluate the mineral presence—or absence, in the prospect areas sampled, and potentially commence the process of obtaining licenses for extraction. Obtaining such a license will require an environmental impact assessment (EIA). EIA will require a broad-spectrum survey of the prospect area, including numerous sensors collecting a plethora of baseline data. Such environmental surveys are expected to be carried out from the same category of multi-purpose vessels as is chartered for high-resolution survey and coring operations.

Extraction

Extraction of marine minerals from SMS deposits has not yet been conducted with commercial success and the technology is not yet finalized. Nautilus pursued SMS extraction from the Solwara 1 field in the Bishmarck sea, but the company ran into financial and regulatory challenges and the plans were never realized (Childs 2020; Haugan and Levin 2019).

The SMS extraction sector in the model presented here is based on the insight retrieved from Rystad (2020), the participatory systems mapping, and the in-depth interviews—and it is conceived at an aggregate level. The model structure and parameterization are grounded in the Rystad report and calibrated based on insight from industry stakeholders and an up-to-date company budget. Jankowski et al. (2010) and Stanton and Yu (2010) also present data that is relevant for the extraction sector of the model. However, the latter two have not been used in the development of this model but are mentioned such that readers may investigate these sources if interested.

SMS extraction must necessarily include subsea units, ore-transportation equipment, surface operational, and processing platform and transport ships to retrieve ore from the seabed and bring it to shore. The subsea units in question will be relatively large units, capable of excavating ore from the seabed and loading the ore further onto some device for transporting the ore to the surface. Surfacing of ore will most likely be executed via mechanical lifting in skips or containers—or via a riser system utilizing heavy-duty pumps and piping. On the surface, the ore will be received and pre-processed, de-watered as a minimum, to some extent. This will happen onboard a large mining surface vessel, that also serves as the operating platform for subsea and water-column transportation unit—as well as loading unit for transport ships. Barges or transport-ships will bring the ore to shore for further processing and refinement.

Model

The model presented here is non-spatial and aggregates all discoveries from exploration and resources for extraction. This makes the model well-suited for aggregate studies such as this one, but inappropriate for disaggregate studies. The model is parameterized to study the processes of exploration and extraction of SMS deposits on the NCS, and its perceived resource and economic potential. However, the model can also be used to explore the processes of exploration and extraction of other marine mineral deposits elsewhere, as well as their potential, with alternative parameterization, modifications, and/or extensions.

The model has been set up in the system dynamics software STELLA Architect (Isee Systems 2022). This software can be used to build and run simulation models. It also has useful features for running Monte Carlo simulations and sensitivity analysis, both of which are used extensively in this study.

Figure 2 provides a simplified high-level overview of the model structure. This figure serves as a venture point for the following high-level presentation of the model. The full model description, which is complex but useful for gaining deep insight into the model, can be found in Appendix 1. The model has also been uploaded to a GITHUB repository, which can be accessed by anyone interested in making use of the model—that be directly or indirectly through alternative parameterization, modification, and/or extension (link will be provided upon acceptance of the paper).

Overall, the model can be viewed as a collection of five sectors. The first sector, in the lower left of Fig. 2, gives a high-level overview of the exploration process. The second sector, in the upper left, outlines the exploration technology. The third sector, in the lower right, describes the mining process, while the fourth, in the middle right, outlines the mining technology. Finally, the fifth sector takes care of financial accounting.

The starting point for this model is that there exists a significant area that has yet to be explored for marine minerals (*Prospect Area for Regional Survey* in the lower left of Fig. 2). The initialization value of this stock represents a key initial value, and it is set to 80,000 km^2 based on information from the respondents in the semi-structured interviews. There is suspicion, and even expectation, that there are several commercial mineral deposits in the initial area for regional survey, but exactly where and how much is unknown.

To find out where and how much mineral resources are available for commercially intended extraction, several steps must be taken to explore the area, starting out with regional surveys covering large areas using regional survey vessels (*Committed Regional Survey Fleet* in the top left of Fig. 2), before focusing on smaller areas and executing high-resolution mapping with ships that are appropriately equipped (*Ships Committed to Hi-Res Survey* in top left of Fig. 2), and then taking coring samples using the same ships but with other equipment (*Ships committed to Coring* in the top left of Fig. 2). Finally, before any area can be opened for extraction, an environmental impact assessment must be conducted using ships equipped with the same equipment used for the high-resolution mapping (*Ships Committed to EIA* in the top left of Fig. 2).

In each step along the chain of exploration steps, some areas are discarded as areas no longer interesting for further investigation or commercial extraction, accumulating in a stock of all areas that have been discarded (*Discarded Area* in the lower left of Fig. 2). In the real world, these areas could become subject to new or further investigation in some

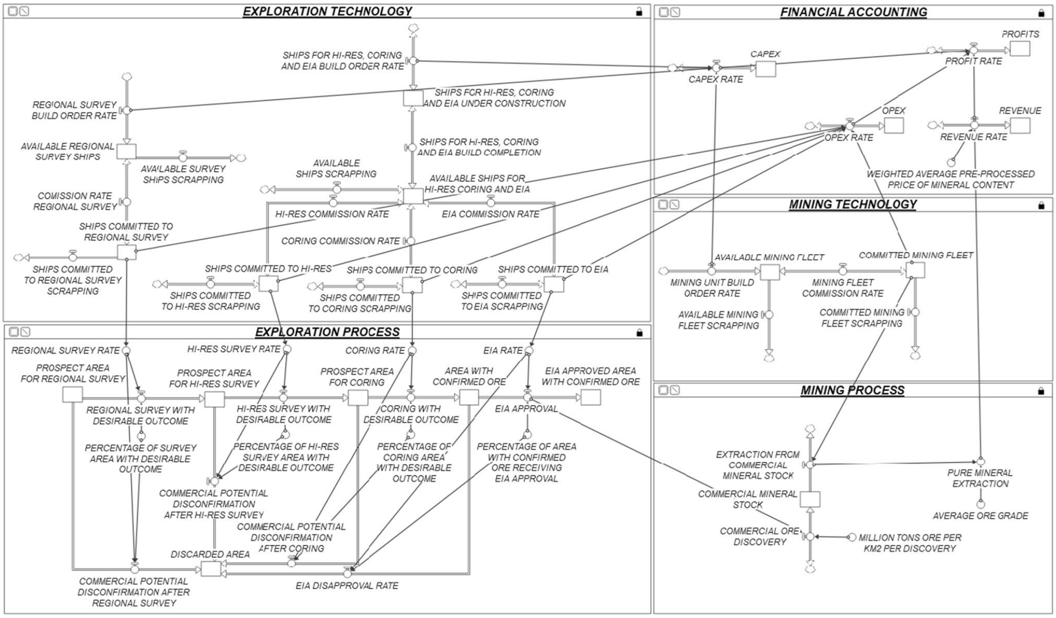

Fig. 2 Simplified high-level model overview

future. However, to reduce complexity, it is left outside the scope of this simulation model.

The proportions of area moving from one exploration step to the next, and thus not being discarded, are determined by lognormal distributed variables with given means (expectations) and standard deviations (perceptions of uncertainty), which then also implicitly determine how much is discarded. The means and standard deviations are based on information collected from the semi-structured interviews. The specifics and logic behind these important details can be found in Appendix 1. Whatever area going through the entire chain ends up being the area that is confirmed viable for commercial extraction (*EIA Approved Area with Confirmed Ore* in the lower left of Fig. 2*)*.

To execute the exploration steps, it is necessary to acquire and commit the appropriate ships and equipment through investments and commission. All ships have constant unit build costs, build time, and lifetime, technical specifications, and day rates, which have been specified in accordance with written and numerical data, and in conference with interview subjects. The ship investments are defined as part of the capital expenditure (CAPEX) in the model. In addition, there are operational costs associated with the commission of the various ships and equipment. These costs are defined as part of the operational expenditure (OPEX). The specifics regarding ship unit build costs, build times, lifetime of ships, technical specifications, and day rates can be found in Appendix 1.

When an area with confirmed ore is approved after an environmental impact assessment, which we assume applies to all areas with confirmed ore, we move into the sector describing the mining process, in the lower right of Fig. 2. Based on the impact assessment approval rate of area with confirmed ore, and assumptions regarding the tons of ore per square kilometer, ore accumulates in what we define as the *Commercial Mineral Stock*.

The tons of ore per square kilometer is an important variable in this model. According to interview subjects, it is also one that bears a lot of uncertainty. In the model, the tons of ore per square kilometer is determined by a lognormal distributed variable with mean and standard deviation set in accordance with the expectations and perceptions of the interview subjects. The details on this can be found in Appendix 1. Finally, the discovered ore can be extracted using a mining fleet (*Committed Mining Fleet* in the middle right of Fig. 2).

To execute the mining process, it is necessary to acquire and commit mining units through investments and commission. The mining unit, which includes a surface platform, riser-system, subsea vehicles, logistical elements, and more, has constant unit build cost, build time, lifetime, technical specifications, and day rates which have been specified in accordance with written and numerical data, and in conference with interview subjects. The mining unit investments are defined as part of the capital expenditure (CAPEX) in the model. In addition, there are operational costs associated with the commission of mining units. These costs are defined as part of the operational expenditure (OPEX). The specifics regarding mining unit build costs, build times, lifetime of units, technical specifications, and day rates can be found in Appendix 1.

The revenue from the extraction process is calculated based on the employed mining fleet, production capacity per mining unit, and assumptions regarding the average ore grade, which determines the amount of pure minerals extracted per ton ore extracted and the weighted average price of its contents, the latter of which we treat as constant over time.

The average ore grade, which we here define as the percentage concentration of copper, zinc, and cobalt in the identified ore, is a key parameter in the model. The interview subjects have different opinions on what numerical value this parameter should take on. Specifically, the interview subjects from the industry report a higher expectation regarding mineral concentration than the interview subjects from the academic sphere, which perhaps one would expect. The industry players report expectations of mineral percentages of at least 5%, which is also the mineral percentage used by Rystad Energy (2020), while the academic interview subjects are more pessimistic, reporting an expectation of around 3%, given the specified number of tons of ore per square kilometer. In the concentrated mix, we assume 77.8% copper, 16.7% zinc, and 5.6% cobalt, based on intelligence from interview subjects.

While the expectations regarding mineral concentration differ between the interview subjects from industry and academia, there is consensus that the actual mineral concentration is uncertain, with the interview subjects from academia being more hesitant in specifying an expectation, which highlights the lack of information and consequential level of uncertainty at play—i.e., it would not be surprising if the mineral concentration is different from expectation given the assumption of tons of ore per square kilometer. To describe the differences in expectation, while also accounting for the uncertainty to some extent, we run simulations with different assumptions regarding the average mineral concentration in identified ore.

The net value and net discounted value can be calculated based on the CAPEX, OPEX, revenue, the discount rate, and time. Worth highlighting here is the use of a discount rate of 10%, somewhat lower than convention for lifecycle analyses in mineral economics, but somewhat higher than what is commonly used in other sectors. The mathematical descriptions of the calculations are relatively straightforward and can be found in Appendix 1.

A few more important things need mention before moving on to the simulation results. To run any simulation, a set of policies must be defined. How much should be invested in regional survey ships? How much should be invested in ships that can execute high-resolution surveys, coring, and EIAs? How much should be invested in ships that can execute the mining process? In the events of too few ships available for high-resolution survey, coring, and EIA, how should the allocation of ships be made? What activities should receive priority? These are all policy-related questions for which answers must be given to enable any simulation.

To keep things simple and practical, we define target shares of area covered per year per exploration activity and target production relative to the commercial mineral stock, which in turn play parts in the determination of the target outflows for the different stocks. These policy parameters are built into the model such that the investment behavior and commission behavior become target-seeking. Investments and commission will be made in attempt to reach the target shares and outflows. However, we also define two different ways in which this target-seeking behavior unfolds, and only one of them can be active at a time.

In what we refer to as the "Wait and See" policy setting, the industry makes investments and commit ships based only on current observations, with no concern for the anticipated future desired needs. That is, e.g., if there is no prospect area for coring at the current time, and no available ships for coring, then no investments will be made, even if there is a lot of prospect area undergoing high-resolution survey, and the future total desire for ships can be expected to be higher than the current total number of ships. That said, it also takes time from any build order is placed to that build order is completed, and it also takes some time, albeit not much, to commit a ship or mining unit to their respective activities. As such, this policy has the weakness of not being able to deliver exactly when the desire for commission arises. However, it has the strength of not taking on the risk of making any unnecessary investments, i.e., order ships that will not be needed in the immediate future after all, despite the expectations.

In what we refer to as the "Anticipatory" policy setting, the industry makes investments and commit ships and mining units based on current and anticipated future needs. That is, e.g., if there is no prospect area for coring at the current time, and no ships available for coring, but there are a lot of prospect area undergoing high-resolution survey, some of which is expected to qualify for coring after a certain amount of time, then investments will be made. As such, this policy has the advantage of being better than the wait and see policy at delivering capital as the desire for capital arises, given that the actual future need is close to the anticipation. However, consequently, it also has the weakness of risking unnecessary investment costs, which will occur when the future need is lower than the anticipated future need. Although excess ships may come of use later, the industry will still have taken costs earlier than desired under the assumption of perfect knowledge. If the excess ships were not built, or their orders were placed later in time, the present CAPEX value would have been reduced, and as such been cost saving.

In the model, there is no guarantee that the desired amount of capital committed to an activity will always be met. When it comes to the regional survey and the mining process, things are quite simple. If there is not enough available capital to satisfy the desire for capital for the respective activities, one must wait for more capital to become available through investment, and once that capital eventually is ready for commission, it will be committed to the respective activity if the desire for ships is still there. However, when it comes to the high-resolution surveys, coring, and EIAs, for which the same ships are used, albeit with different equipment and at different day rates, things get messier. If there is not enough capital to satisfy the total desired committed ships, then the activities must be prioritized. In the simulation model presented here, the activities are prioritized in reversed order of their placement in the exploration chain—as such, whatever exploration area and activity that is closer to generate a discovery, will get the highest priority, etc. This is perhaps not completely realistic in a competitive industry, yet it can be argued that it is a sensible approach for the industry as a whole—because the sooner revenue is generated, the better, since any delays will mean heavier discounted revenue.

To summarize, the model presented above describes the exploration and mining processes as well as the technologies and financial accounts associated with them. It also outlines the two sets of policies that are built in for simulation purposes. Regarding the policies, the reader should note that these policies are not the optimal policies, but rather practically oriented and simplistic policies derived from reason. Thus, it is very much possible that the economic potential of the industry could be higher with alternative policies, which is obviously something that could be interesting to consider in future studies. Altogether, the model including the policies allows simulation of the perceived and possible potential of the industry.

Baseline results

This study considers six main simulation scenarios. The scenarios differ from each other in terms of the assumptions regarding ore grade and in policy.

Ore grade or mineral concentration here refers to the average percentage of copper, zinc, and cobalt found in the prospect SMS deposits. Low concentration (3%) corresponds to the expectations or hypothesis expressed by experts and stakeholders from academia. It is expected that peer-reviewed resource estimates will be published early in 2023. The high concentration (5%) corresponds to what appears to be the consensus among experts and stakeholders from the industrial domain. This concentration is also referred to in a report by Rystad Energy (2020) which appears to have been influential among the industrial stakeholders.

There are two different sets of policies: “Wait and See” and “Anticipatory.” The “Wait and See” policy assumes a risk averse agent that will not invest in extraction capital until a certain level of mineral stock is confirmed via exploration. The “Anticipatory” policy represents a more proactive agent—choosing to invest in extraction capital at an earlier stage of exploration—and as such betting on sufficient minerals for commercially viable extraction being identified.

The results presented are the average values across 1000 Monte Carlo runs where four stochastic seed variables are assigned varying values. The seed variables relate to the percentages of area moving through the exploration chain and the tons of ore per square kilometer per discovery (see Appendix 1 for further details). The baseline results are shown in Table 1.

The simulation results reveal an interesting range for expected total extraction. With a low estimate of 1.8 million tons of copper, zinc, and cobalt, up to a high estimate of 3 million tons—there is an implicit range of net present value straddling a negative value of 970 million USD up to a positive value of 2.53 billion USD.

As mentioned above, interviewed experts from academia expect a mineral concentration of approximately 3%—this is based on informed assumptions regarding tons of ore per square kilometer. Given a discount rate of 10%, the simulation results indicate that the industry will not be profitable if these assumptions are correct. Industry experts and stakeholders, on the other hand, expect an ore grade of 5%. This condition allows for a profitable industry yielding net present values between 1.33 and 2.53 billion USD. Should the actual ore grade lies between the low and the high scenario—a profitable industry is to be expected, with a net present value ranging between 170 million USD and 780 million USD.

The non-discounted net value is positive for all scenarios, yet the net present value is not. This is an important observation as it points to a key challenge for the SMS exploration and extraction industry on the NCS, namely high exploration cost, and a significant delay between exploration and mined minerals entering the commodity market. Non-discounted revenue is high relative to non-discounted cost—yet the discounted revenue contracts considerably more than discounted cost on account of the long time passing between the early exploration phase and extracted minerals generating revenue.

Table 1 Overview of baseline simulation results. Average values across 1000 Monte Carlo runs

Resource scenario	Policy	Expl. CAPEX (bill. $)	Expl. OPEX (bill. $)	Mining CAPEX (bill. $)	Mining OPEX (bill. $)	Total extraction (mill. tons)	Total revenue (bill. $)	Net Non-disc. value (bill. $)	Net present value (bill. $)
Low average ore grade (3% mix of copper, zinc, cobalt)	Wait and See	3.21	6.96	7.93	6.32	1.82	35.28	10.85	−0.98
	Anticipatory	3.56	6.96	5.36	6.28	1.81	35.10	12.92	−0.97
Medium average ore grade (4% mix of copper, zinc, cobalt)	Wait and See	3.21	6.96	7.93	6.32	2.42	47.04	22.60	0.17
	Anticipatory	3.56	6.96	5.36	6.28	2.41	46.80	24.61	0.78
High average ore grade (5% mix of copper, zinc, cobalt)	Wait and See	3.21	6.96	7.93	6.32	3.03	58.80	34.35	1.33
	Anticipatory	3.56	6.96	5.36	6.28	3.01	58.50	36.30	2.53

In the low ore-grade scenario, the “Wait and See” and “Anticipatory” policies perform similarly in terms of net present value. However, the “Anticipatory” policy performs significantly better than the “Wait and See” policy in both medium and high ore-grade scenarios. This is a result of several factors. First, the “Anticipatory” policy commences acquisition of exploration and extraction capital sooner—and is henceforth able to bring minerals to market sooner. Revenue is thus not discounted as hard as in the alternative “Wait and See” policy. Second, the “Wait and See” policy will in its risk averse design accumulates a larger discovered mineral stock before commencing investment in extraction capital. The initially passive approach will then be aggressively compensated once mineral discoveries pass through the exploration phases and start accumulating. The latter as the delayed reaction of the “Wait and See” policy generates a much higher accumulated mineral stock, which in turn requires more production capability to meet target production relative to the mineral stock. Although this cannot be ascertained from the table above, this observation is important as it indicates that the “Wait and See” policy designed for the purpose of this study, in fact will generate an overcapacity problem once mineral stocks starts to deplete.

Figure 3 shows an overview of a random selection of Monte Carlo runs in the medium ore-grade scenario with the “Wait and See” and “Anticipatory” policies. These results indicate that even though positive discounted profits for these scenarios are expected, as shown in Table 1, it is possible that a negative net present value will be the case, on account of random chance. Considering the vast uncertainty inherent to this domain—this is an important observation.

Figure 4 shows the anticipated fleet sizes of multi-purpose offshore vessels required for exploration and for deep-sea mining vessels in the medium ore-grade and “Anticipatory” scenarios. The figure shows the trajectories in a random selection of Monte Carlo runs. The variance between these scenarios is significant—where the largest simulated fleet sizes are more than twice as large as the lowest scenarios. In terms of invested capital such difference is obviously significant—and will have considerable effects for the Norwegian shipping industry as well as associated industries.

Sensitivity analysis

Simulation of SMS exploration and extraction on the NCS is subject to a vast number of uncertainties. This is acknowledged by stakeholders and experts across academia, industry, and public policy. The uncertainties apply to nearly all aspects of the emerging industry, which makes sensitivity analysis crucial.

There are several elements in the model that can be tested for sensitivity to enhance the understanding of these underlying uncertainties and henceforth possible development trajectories of this evolving industry. This includes, for example, changes in the discount rate; the geological resource base—because it is poorly explored; the cost of extraction—because the technology is not yet fully mature; and the future price of minerals—because the growth, electrification, and geopolitical turmoil are projected to increase demand for minerals (Boomsma and Warnaars 2015; Haugan and Levin 2019; International Energy Agency (IEA) 2021; Kaluza et al. 2018; NPD 2021; Petersen et al. 2016; Ragnarsdóttir 2008).

Although the study presented here includes sensitivity analysis of several different variables and parameters ranging between technology, resource base, commercial dimensions, and policy dimensions, it is limited to four tests, namely changes in the discount rate, expected tons of ore per square km, extraction cost, and weighted average price of pre-processed mineral content. The model in its entirety is made available in a GITHUB repository, and the interested

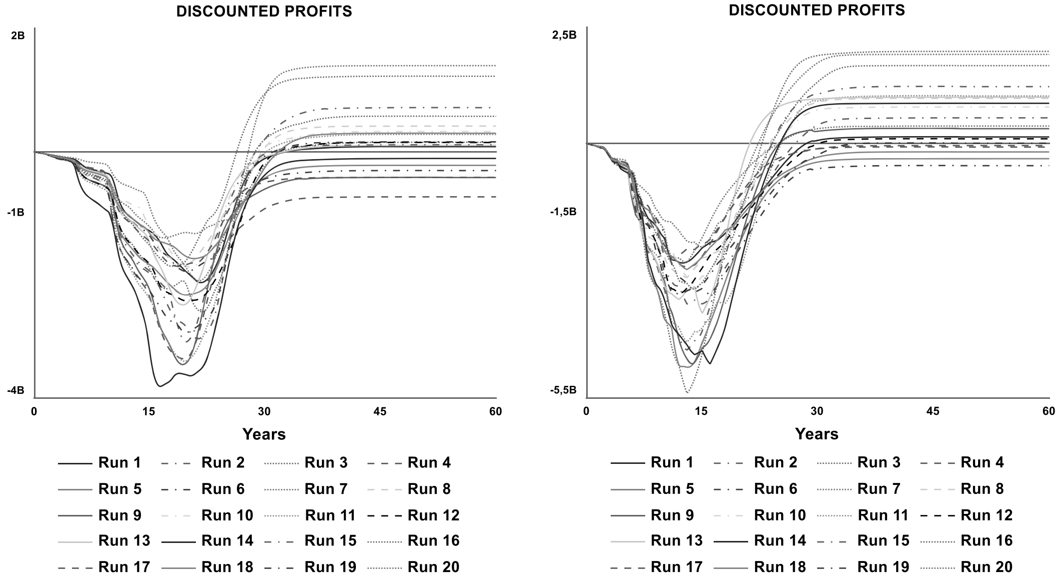

Fig. 3 Discounted profit trajectories over a random selection of Monte Carlo runs in the medium average ore-grade scenario with the "Wait and See" policy (left) and the "Anticipatory" policy (right)

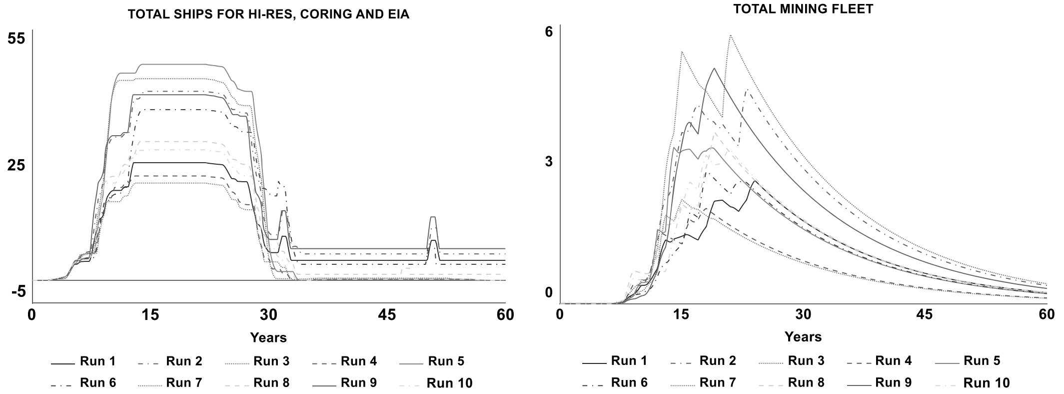

Fig. 4 Total ships and mining units trajectories over a random selection of Monte Carlo runs in the medium average ore-grade scenario with the "Anticipatory" policy

reader is encouraged to further explore sensitivity and the model in general (Bang and Trellevik 2022a).

Tables 2, 3, 4, and 5 show the results of the four sensitivity tests included in this study. The differences from the base line results are presented in square brackets.

Rystad Energy (2020) and interviewed stakeholders and experts unanimously provide a 10% discount rate as basis for their assessment and analysis. Thus, the baseline scenario in this study applies a discount rate of 10%. However, during the qualitative research phase of this study, analogies from the offshore oil and gas sector were frequently brought up as highly relevant for the marine mineral sector. In the offshore oil and gas industry, a discount rate of 15% is commonly applied for deep water projects (Wood Mackenzie 2018). It

Table 2 Overview of simulation results with 15% discount rate. Average values across 1000 Monte Carlo runs with baseline results in brackets

Resource scenario	Policy	Expl. CAPEX (bill. $)	Expl. OPEX (bill. $)	Mining CAPEX (bill. $)	Mining OPEX (bill. $)	Total extraction (mill. tons)	Total revenue (bill. $)	Net non-disc. value (bill. $)	Net present value (bill. $)
Low average ore grade (3% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.95 [6.96]	7.89 [7.93]	6.3 [6.32]	1.81 [1.82]	35.21 [35.28]	10.85 [10.85]	−1.02 [−0.98]
	Anticipatory	3.57 [3.56]	6.96 [6.96]	5.36 [5.36]	6.28 [6.28]	1.81 [1.81]	35.08 [35.10]	12.89 [12.92]	−1.50 [−0.97]
Medium average ore grade (4% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.95 [6.96]	7.89 [7.93]	6.3 [6.32]	2.42 [2.42]	46.95 [47.04]	22.57 [22.60]	−0.60 [0.17]
	Anticipatory	3.57 [3.56]	6.96 [6.96]	5.36 [5.36]	6.28 [6.28]	2.41 [2.41]	46.77 [46.80]	24.57 [24.61]	−0.72 [0.78]
High average ore grade (5% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.95 [6.96]	7.89 [7.93]	6.3 [6.32]	3.02 [3.03]	58.68 [58.80]	34.30 [34.35]	−0.18 [1.33]
	Anticipatory	3.57 [3.56]	6.96 [6.96]	5.36 [5.36]	6.28 [6.28]	3.01 [3.01]	58.46 [58.50]	36.25 [36.30]	0.05 [2.53]

Table 3 Overview of simulation results with 25% reduction in expected million tons of ore per square kilometer. Average values across 1000 Monte Carlo runs with baseline results in brackets

Resource scenario	Policy	Expl. CAPEX (bill. $)	Expl. OPEX (bill. $)	Mining CAPEX (bill. $)	Mining OPEX (bill. $)	Total extraction (mill. tons)	Total revenue (bill. $)	Net non-disc. value (bill. $)	Net present value (bill. $)
Low average ore grade (3% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.95 [6.96]	6.11 [7.93]	4.73 [6.32]	1.36 [1.82]	26.43 [35.28]	5.42 [10.85]	−1.37 [−0.98]
	Anticipatory	3.57 [3.56]	6.96 [6.96]	4.07 [5.36]	4.71 [6.28]	1.36 [1.81]	26.30 [35.10]	6.97 [12.92]	−1.66 [−0.97]
Medium average ore grade (4% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.95 [6.96]	6.11 [7.93]	4.73 [6.32]	1.82 [2.42]	35.23 [47.04]	14.22 [22.60]	−0.50 [0.17]
	Anticipatory	3.57 [3.56]	6.96 [6.96]	4.07 [5.36]	4.71 [6.28]	1.81 [2.41]	35.07 [46.80]	15.73 [24.61]	−0.35 [0.78]
High average ore grade (5% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.95 [6.96]	6.11 [7.93]	4.73 [6.32]	2.27 [3.03]	44.04 [58.80]	23.02 [34.35]	0.36 [1.33]
	Anticipatory	3.57 [3.56]	6.96 [6.96]	4.07 [5.36]	4.71 [6.28]	2.26 [3.01]	43.84 [58.50]	24.49 [36.30]	0.95 [2.53]

Table 4 Overview of simulation results with 10% increase in all costs associated with extraction. Average values across 1000 Monte Carlo runs with baseline results in brackets

Resource scenario	Policy	Expl. CAPEX (bill. $)	Expl. OPEX (bill. $)	Mining CAPEX (bill. $)	Mining OPEX (bill. $)	Total extraction (mill. tons)	Total revenue (bill. $)	Net non-disc. value (bill. $)	Net present value (bill. $)
Low average ore grade (3% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.95 [6.96]	8.68 [7.93]	6.93 [6.32]	1.81 [1.82]	35.21 [35.28]	9.43 [10.85]	−1.18 [−0.98]
	Anticipatory	3.57 [3.56]	6.96 [6.96]	5.90 [5.36]	6.91 [6.28]	1.81 [1.81]	35.08 [35.10]	11.72 [12.92]	−1.23 [−0.97]
Medium average ore grade (4% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.95 [6.96]	8.68 [7.93]	6.93 [6.32]	2.42 [2.42]	46.95 [47.04]	21.16 [22.60]	−0.03 [0.17]
	Anticipatory	3.57 [3.56]	6.96 [6.96]	5.90 [5.36]	6.91 [6.28]	2.41 [2.41]	46.77 [46.80]	23.40 [24.61]	0.52 [0.78]
High average ore grade (5% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.95 [6.96]	8.68 [7.93]	6.93 [6.32]	3.02 [3.03]	58.68 [58.80]	32.88 [34.35]	1.13 [1.33]
	Anticipatory	3.57 [3.56]	6.96 [6.96]	5.90 [5.36]	6.91 [6.28]	3.01 [3.01]	58.46 [58.50]	35.09 [36.30]	2.27 [2.53]

Table 5 Overview of simulation results with 10% increase in the weighted average price of mineral content. Average values across 1000 Monte Carlo runs with baseline results in brackets

Resource scenario	Policy	Expl. CAPEX (bill. $)	Expl. OPEX (bill. $)	Mining CAPEX (bill. $)	Mining OPEX (bill. $)	Total extraction (mill. tons)	Total revenue (bill. $)	Net non-disc. value (bill. $)	Net present value (bill. $)
Low average ore grade (3% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.95 [6.96]	7.89 [7.93]	6.30 [6.32]	1.81 [1.82]	38.73 [35.28]	14.37 [10.85]	−0.63 [−0.98]
	Anticipatory	3.57 [3.56]	6.96 [6.96]	5.36 [5.36]	6.28 [6.28]	1.81 [1.81]	38.59 [35.10]	16.39 [12.92]	−0.44 [−0.97]
Medium average ore grade (4% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.95 [6.96]	7.89 [7.93]	6.30 [6.32]	2.42 [2.42]	51.64 [47.04]	27.26 [22.60]	0.64 [0.17]
	Anticipatory	3.57 [3.56]	6.96 [6.96]	5.36 [5.36]	6.28 [6.28]	2.41 [2.41]	51.45 [46.80]	29.24 [24.61]	1.48 [0.78]
High average ore grade (5% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.95 [6.96]	7.89 [7.93]	6.30 [6.32]	3.02 [3.03]	64.55 [58.80]	40.16 [34.35]	1.91 [1.33]
	Anticipatory	3.57 [3.56]	6.96 [6.96]	5.36 [5.36]	6.28 [6.28]	3.01 [3.01]	64.31 [58.50]	42.09 [36.30]	3.40 [2.53]

is henceforth interesting to simulate the economic potential in terms of net present value with a higher discount rate—and perhaps particularly with a discount rate of 15%. The results in Table 2 indicate that the discount rate is important, indeed—with a discount rate of 15% and all else equal, the high ore-grade and "Anticipatory" policy scenarios are the only scenarios generating a positive net present value. In the baseline scenario, with a discount rate of 10%, all scenarios for medium and high ore grades yield positive results. This is explained by revenue being generated at a late stage while costs start accruing during the initial exploration phases—thus, net present value is heavily reduced by discounting.

The mineral resource base of SMS deposits on the NCS is highly uncertain as it is yet poorly explored. To reflect the uncertainty tied to tons of ore per square kilometers, this was included in the model as a random stochastic variable. However, considering the extent to which this uncertainty is pronounced by the interviewed stakeholder and experts—sensitivity towards the mean expectation of this stochastic variable was also tested. As clearly indicated in Table 3, a 25% reduction of this mean value significantly reduces both total extraction and net present value. Only the high ore-grade scenarios yield positive net present value under this condition.

As the actual SMS mineral extraction technology has yet to be built and tested, extraction cost is clearly uncertain. Interview subjects broadly refer to similar technologies developed within offshore oil and gas, and studies and estimates for extraction costs have been carried by stakeholders within the emerging industry. Nevertheless, sensitivity towards extraction cost is interesting all the time; there is no empirical evidence of actual extraction cost. Therefore, we test the sensitivity of the baseline results to a 10% increase of extraction costs. However, the reader should note that higher costs could also occur.

Unsurprisingly, a 10% increase of extraction cost is reflected, in the total mining CAPEX across all scenarios. The "Wait and See" policy generates relatively higher mining CAPEX than the "Anticipatory" policy. This can be accredited to the policy design in which the "Wait and See" policy is initially passive while the mineral stock accumulates—and then aggressively invests mining capital. Positive net present value is still evident for both high ore grade and the "Anticipatory" policy in the medium ore-grade scenarios.

Naturally, an increase of 10% of the weighted average price of mineral content increases the net present value across all scenarios. The weighted average price of mineral content is a variable where the price of copper, zinc, and cobalt is weighted in the bulk price according to their proportion of the ore. Interestingly, the increased price does not tip the low ore-grade scenarios into a positive net present value, yet the losses are reduced. In the low ore-grade scenarios, as in the mid and high ore-grade scenarios, the total revenue is increased—but clearly not sufficiently to yield a profit after discounting.

Discussion

This is inherently a future study and as such, there is no empirical data towards which the simulation model—or the results and analysis it affords can be tested. Rather, the model can conceptually be conceived as a theory, grounded in the perspectives, knowledge, expectations, and perceptions iteratively elicited from stakeholders and experts involved in all domains and areas of the emerging SMS exploration and extraction industry on the Norwegian continental shelf (Kopainsky and Luna-Reyes 2008; Repenning 2002).

As a theory, the model is tested and validated in terms of structure, parameterization, and in terms of mathematical integrity—and as such it enables simulation and analysis of possible future development trajectories (Barlas 1996; Barlas and Carpenter 1990). As the availability of empirical data for many parameters and structural elements is non-existent and the uncertainty is significant, also among participating experts and stakeholders—the model does not claim to produce accurate predictions. Rather, it explores possible outcomes, based on existing knowledge, expectations, perceptions, and perspectives of stakeholders engaged in the domain and in this study. Although probably inaccurate, this is valuable as it reveals something about the range of expectations and perceptions, which forms the basis of commercial decision- and public policy-making today. Henceforth, although elements of the model may have misrepresentations only evident once the future materializes, the model is still useful.

Zeckhauser (2010) argues that "..clear thinking about UU [uncertain and unknowable] situations, which includes prior diagnosis of their elements, and relevant practice with simulated situations, may vastly improve investment decisions where UU events are involved. If they do improve, such clear thinking will yield substantial benefits." Based on the perspective that "structure generates behavior," the authors argue that the synthesis of the elicited expert and stakeholder knowledge, expectations, and perceptions afford clear thinking on how and when the SMS exploration and extraction industry on the NCS can unfold (Forrester 1987; Lane and Oliva 1998). It does so, as current knowledge, expectations, and perceptions form the scaffolding on which this industry is mobilized.

There are two sets of policies governing behavior in the model. The "Wait and See" policy is a risk-averse policy wherein the agent postpones investment in exploration and extraction capital until the demand for such capital occurs—at which point the agent invests to meet a fixed targets for exploration and extraction. This has the effect that investment occurs later in time—and when they do occur—they will be aggressive. In several scenarios, this policy will therefore invest into over-capacity. The "Anticipatory" set of policies commences investment at an earlier stage—and is henceforth less risk averse. This infers a bet being made —as investment decisions are made with limited confidence in the actual resource base. Generally, the "Anticipatory" policy setting performs well across simulations.

The study clearly indicates that a major challenge for the emerging industry is the extensive time between initial investments and generation of revenue. Until minerals are offloaded onshore, the entire endeavor has only accrued cost. The inhospitable and nearly inaccessible working environment of ultra-deep water at arctic latitudes, as well as the required data resolution and ground truthing of a largely unexplored and geographically significant area, makes exploration a considerable cost. Moreover, the time required to acquire extraction licenses, and to develop and mobilize extraction technology means that a significant amount of time will pass from initial investment until revenue is generated. As such, the revenue from mineral extraction will be heavily discounted when compared to many of the investments. Sensitivity analysis shows that an increase from 10 to 15% discounting renders all but the high ore-grade "Anticipatory" scenario a futile investment with negative net present value. As discussed above, the high ore-grade scenario represents the most optimistic view on the geological resources available. From this, it may be argued that it is of importance to reduce the time lag between exploration and extraction if this industry at all is to materialize.

Coring operations constitute a substantial driver for the high exploration cost. Geophysical methods, tailored to identify and quantify mineralization in prospect deposits may reduce aggregated exploration cost significantly by reducing the amount of coring needed as well as the time required for coring. It may well also expediate the rate of exploration by expanding operational seasons and increasing the number of units in operation simultaneously. Both remotely operated surveys and geophysical qualification of deposits would be favorable for the extraction industry exposed to considerable discounting due to high exploration cost and long lead time between exploration and extraction.

The model is relatively explicit and detailed in the abstraction of the exploration phase and the involved exploration technology. The model does however not account for technological shifts within exploration technology or operational modus operandi. An element in this respect is the potential of remotely operated, and autonomous survey capability. This is an area reported by experts to be attracting much attention now—and it has the potential to reduce the need for large multipurpose vessels, and thereby the aggregated exploration cost. When examining the utilization of multipurpose vessels for high-resolution survey in the model, this is a miniscule portion of the aggregated exploration cost. Efforts towards reducing cost of high-resolution survey by way of autonomous or remotely operated survey platforms may henceforth not be pivotal for marine minerals exploration. It may however expediate the rate of initial exploration by expanding operational seasons and increasing the number of units in operation simultaneously and thereby offer the industry more data, sooner, which could be important for profitability. Operationally, this could provide a level of de-risking of further exploration decisions for the individual company and as such merit continued attention by the industry.

There is uncertainty regarding the tons of minerals per square kilometers. Where participating experts from academia argues ore-grades around 3%, the more optimistic industrial stakeholders suggest ore grades around 5%. In the baseline scenarios, the low ore-grade settings yield negative net present value irrespective of investment policy, while both the medium and high ore grades return positive results for both sets of policies. The results are sensitive to a 25% reduction across ore grades, and under these conditions, the "Wait and See" policy in the medium ore-grade scenario transforms from a positive to a negative net present value while the profits are reduced across all scenarios. It is self-evident that the viability of this industry is highly dependent on the actual mineral content of the SMS deposits, yet it is an important insight that the industry projections are highly sensitive to this fraction. Considering the meager knowledge available on mineral concentration in SMS deposits on the NCS, this presents a challenge—as exploration is required to provide sufficient data for sensible decisions, yet the effect of discounting strongly discourages extensive exploration before committing to extraction. A bet with uncertain or even unknown odds may be required.

The model is also sensitive towards the cost of extraction, which is another element of uncertainty as the technology has yet to be built. A 10% increase in extraction cost reduces net present value across scenarios with approximately 20% in the "Anticipatory" and 26% in the "Wait and See" policy condition. As such, these conditions will tip the medium ore-grade, "Wait and See" scenario negative in terms of net present value. Again, discounting reduces the revenue of the stock while the extraction cost occurs closer to revenue generation and is exposed to less discounting, and an increase here will henceforth have a larger effect. The higher impact on "Wait and See policies is explained by the design of this set of policies, where investment in extraction technology is postponed. This may suggest that speeding up exploration may have its merits—as does commencing with investment in extraction capital at an earlier stage.

The price of minerals will obviously influence the viability of the marine mineral industry in general. As expected, a 10% increase of the weighted average price of minerals increases the net present value across all scenarios. Notably though, this price increase does not generate positive net present values for the low ore-grade scenarios in the simulation model—and although the results are better relative to the baseline scenarios—it suggests that even higher mineral prices would be required for this industry to be profitable, all else equal. That on the other hand, may not be unfeasible considering general economic growth, electrification, and geopolitical supply side stability potentially increasing demand, (Kalantzakos 2020; Kaluza et al. 2018; NPD 2021; Ragnarsdóttir 2008).

At a less aggregated level, the model offers encouraging insights to the existing offshore service and subsea industries in Norway. Should indeed the exploration and extraction of SMS deposits on the Norwegian continental shelf commence—it will, according to all participating experts and stakeholders, require vessels, engineering, yardwork, subsea services, and more. In terms of multipurpose offshore vessels alone, a considerable proportion of vessels currently utilized within oil and gas potentially could find future charter in marine minerals exploration. Multipurpose vessels expected to be relevant for the AUV, coring, and environmental assessment operations embedded in the model, are relatively large ships, around 100 m, with large cranes, several subsea robots and other equipment, and a crew of 50–100 people onboard. The requirement for these vessels ranges between approximately 20 and 55 vessels over a 15-year time period. These vessels would have to be supported onshore by management, engineering, and logistical teams, and they would most likely have to be retrofitted with ice-class and deep-water equipment. Altogether, this constitutes significant activity in the Norwegian offshore fleet. The larger, and probably less versatile mining vessels will have a limited period in which they are in large demand. However, also the extraction phase will require considerable onshore support and constitute a significant element of the aggregated Norwegian offshore activity. These vessels are considerable investments, likely to outlive the high-demand period depreciation wise, long-term investors would probably consider opportunities beyond the Norwegian continental shelf once the peak-demand wanes. The latter is obviously a possibility for ships—able to relocate to other markets as they become available and attractive.

Conclusion

This study provides three contributions. First, it presents a structural synthesis of an emerging marine SMS exploration and extraction industry in Norway. Second, it provides a range for the expected resource potential. Third, it provides a range for the expected economic potential. The structural synthesis, as well as expected resource- and economic potential is drawn from the knowledge, expectations, and perceptions of experts and stakeholders embedded in this evolving system.

We present a system dynamics model based on a comprehensive quantitative and qualitative approach which taps into numerical, written, and mental databases. The model abstracts and synthesizes the expertise—the tacit and formally qualified knowledge, expectations, and perceptions of experts and stakeholders involved in different fields of the emerging marine minerals industry in Norway. The experts and stakeholders are representatives from academia, regulatory bodies, and different levels of private enterprise.

The model is simulated across six main scenarios wherein low, medium, and high ore grades are extracted as dictated by either a "Wait and See" or an "Anticipatory" set of policies. The study also tests the sensitivity of the results to changes in various factors.

The simulation results reveal a range of possible outcomes—in which the exploration and extraction of marine minerals from SMS deposits on the Norwegian continental shelf may present negative net present value—or a positive net present value.

The model results prove sensitive to the settings regarding mineral concentration. Where academic participants indicate ore grades around 3%, industry participants suggest concentrations around 5%. All else equal, if the academic participants are correctly assessing the mineral resource, the emerging industry is not expected to be profitable with today's technology—while for ore grades between academia's estimate and those of the industry, the industry is expected to be profitable with today's technology.

The considerable cost of exploration and long period indicated between early exploration and extracted minerals brought to market, suggest that the costs associated with exploration is a central concern for the emerging industry. Technology, regulation, and incentives may alleviate this challenge—and prove pivotal if indeed the ore grade of Norwegian SMS is around 3%. Cost of extraction is also a challenge—coupled with a passive investment policy, an underestimated cost of extraction may render otherwise profitable scenarios at a loss. The weighted average price of minerals is important—it would require price increases well above 10% to render low ore-grade scenarios with a profit. This may however be a likely scenario in lieu of macroeconomic development and geopolitical environment.

We consider the fact that the expected NPV values span negative and positive values an interesting and important finding because it highlights a discrepancy between academic and industrial expectations among the participants in the study. Moreover, it highlights that it is not given that this will be a profitable adventure with today's technology. There are at least two good reasons for highlighting and communicating these findings:

First, there is currently tendencies of a DSM frenzy in Norway. For reference: there is a 1000 billion NOK revenue estimate which has been put forward in Norwegian media without much talk about the costs of this endeavor (Sævik 2022). Although this revenue estimate is not far from that expected by the industry (considering we exclude value added from processing), our study highlights that high value in terms of revenue does not necessarily mean high net present value—this is an important reminder. Moreover, there are talks in media and the industry about DSM potentially being the "new oil" for Norway (Energi24.no 2021). At the same time, there is currently little that points towards this emerging SMS industry coming near to that—even when doing simulations based on industry knowledge, expectations, and perceptions. To put this in perspective, our best-case baseline scenario indicates a total revenue of about 570 billion NOK (excluding value added from processing) over the simulated time horizon. That is less than that of a year worth of Norwegian oil and gas exports, which totaled at 832 billion NOK in 2021, and expected significantly higher in 2022 due to increased prices for oil and gas (Norsk Petroleum 2022).

Second, we believe that our results can be constructive for the industry in the sense that they suggest where it can be worthwhile to put in innovation efforts—for example, we show that one of the main challenges for the DSM industry on the NCS is high costs associated with coring. As such, it could be clever to put in innovation efforts to reduce the amount of coring needed. For example, one could imagine that innovative geophysical methods, AUV, and sensor technology could contribute to reduce the amount of coring needed to identify resources and thereby reduce costs. We think such insight can be particularly interesting and valuable for the technology companies aiming to take part in the emerging industry.

If the industry indeed manifests, it will generate significant activity in the offshore service and subsea industry traditionally engaged in the offshore oil and gas sector. Considering the challenges, the limited knowledge about the resources, the harsh operational environment, the high cost of exploration, and considerable lag between initial exploration and minerals being landed onshore, there is an open space for innovation and technological improvement—geophysical methods, remotely operated, and autonomous technology may as such be a key to unlocking a profitable SMS mining industry on the NCS.

Appendix 1

Detailed model description

Detailed stock-and-flow diagrams for the exploration process and exploration technology

Figure 5

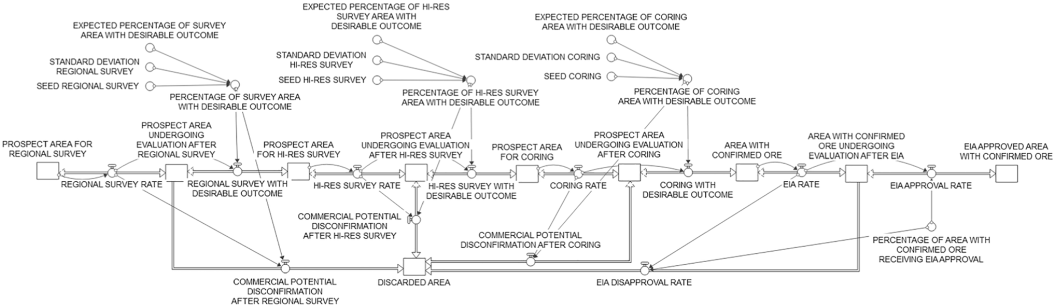

Fig. 5 Stock-and-flow diagram of the exploration process

Figure 6

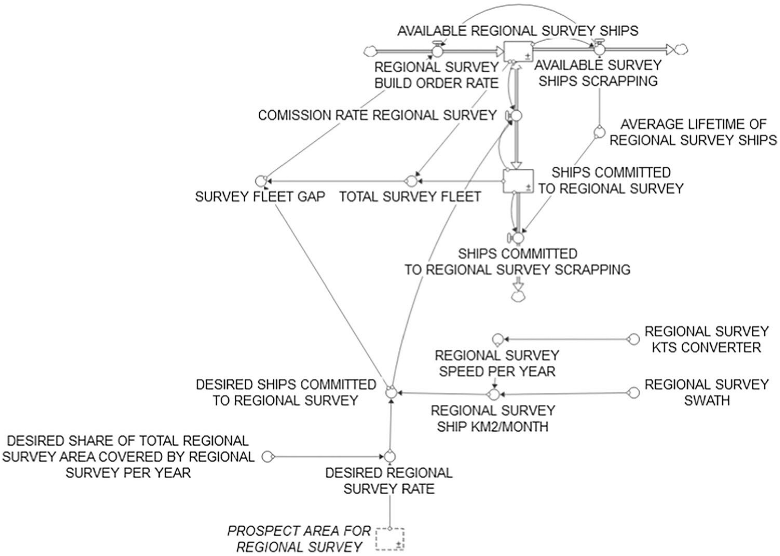

Fig. 6 Stock-and-flow diagram for regional survey capital structure

Figure 7

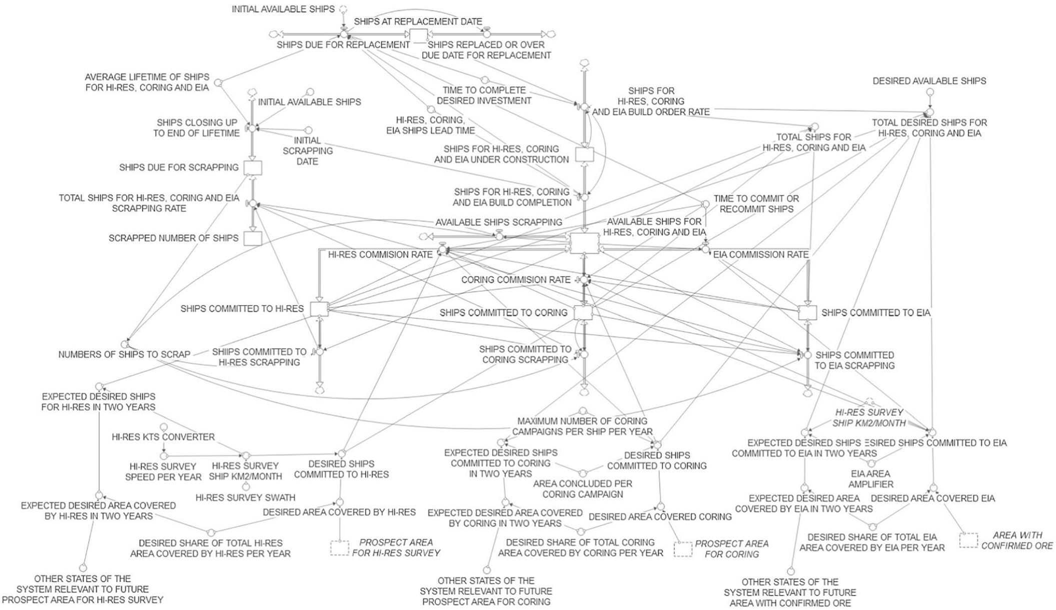

Fig. 7 Stock-and-flow diagram for Hi-Res, coring, and EIA capital structure

Detailed SFD for the mining process and mining technology

Figure 8

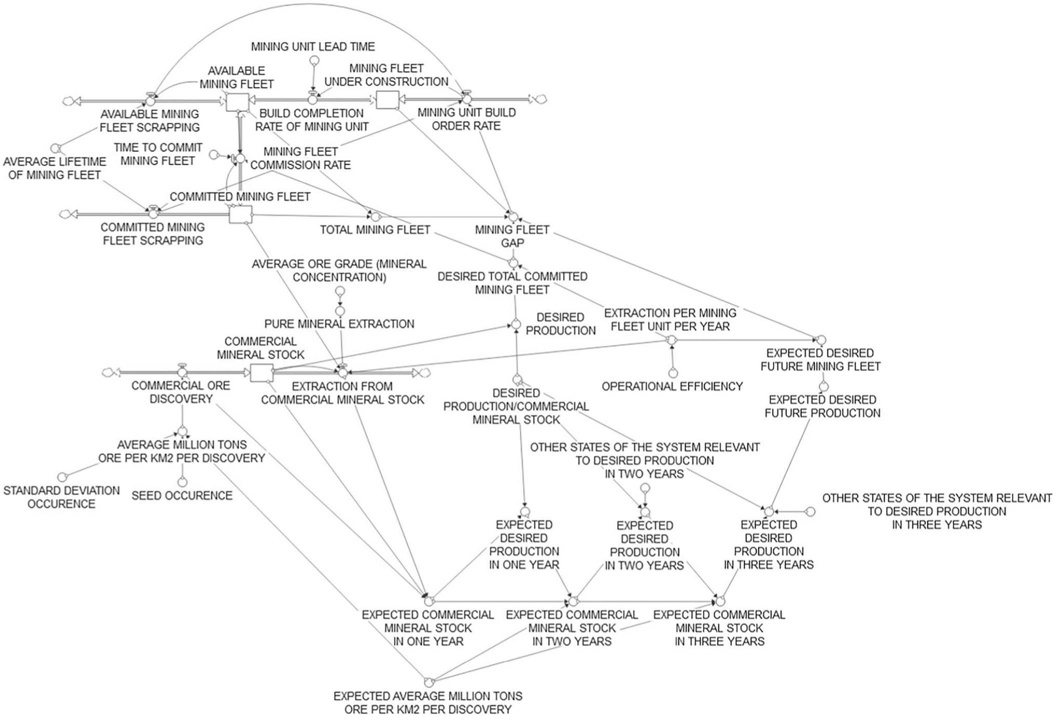

Fig. 8 Stock-and-flow diagram for the mining process and technology

Mathematical model description

NOTE REGARDING THE UNITS OF THE VARIABLES AND PARAMETERS IN THE MODEL
All variables and parameters directly relating to area are measured in square kilometers. All variables and parameters directly relating to weight is measured in million tons. All variables and parameters directly relating to monetary value is measured in US dollars. All variables and parameters directly related to time are measured in years

Regional survey

Variables and parameters	Equations	Properties	Comments
PROSPECT_AREA_FOR_REGIONAL_SURVEY(t)	PROSPECT_AREA_FOR_REGIONAL_SURVEY(t—dt) + (—REGIONAL_SURVEY_RATE) * dt	INIT PROSPECT_AREA_FOR_REGIONAL_SURVEY = 80,000	The prospect area for regional survey is determined by the size of the stock in the previous time step subtracted whatever area is moved to regional survey through the previous time step
			The initial prospect area for regional survey is set to 80,000 square kilometers, which is an approximate estimate on the area that could be interesting for exploration. This value was agreed upon by several of the experts that have been interviewed for this study
REGIONAL_SURVEY_RATE	MIN(SHIPS_COMMITTED_TO_REGIONAL_SURVEY* "REGIONAL_SURVEY_SHIP_KM2/YEAR"; PROSPECT_AREA_FOR_REGIONAL_SURVEY)		The regional survey rate is determined by the product of the number of ships committed to regional survey and the area covered by such a ship per year. If the capacity exceeds the available area, then only the available area will be surveyed
"REGIONAL_SURVEY_SHIP_KM2/MONTH"	REGIONAL_SURVEY_SPEED_PER_YEAR*REGIONAL_SURVEY_SWATH		The area covered by a regional survey ship per year is calculated based on the regional survey ship speed and the regional survey ship swath
REGIONAL_SURVEY_KTS_CONVERTER	1,852		
REGIONAL_SURVEY_SPEED_PER_YEAR	2*REGIONAL_SURVEY_KTS_CONVERTER*18*28*6		The average survey speed per year calculated as 2 knots during regional survey where operations are carried out for 18 h per 28 days per month per a 6 months ice-free season. Speed, operational hours, days and months is informed by multiple experts during modelling process and is referred to as industry standard
REGIONAL_SURVEY_SWATH	1,2		Survey Swath refers to lateral acoustic coverage of bathymetry and determined by opening angle of dual head hull-mounted multibeam echo sounder (DH-MBES) and water depth. Modern DH-MBES allows for online adjustment of opening angle in order to maintain constant swath. Swath is informed by multiple experts during modelling process and is referred to as industry standard

NOTE REGARDING THE UNITS OF THE VARIABLES AND PARAMETERS IN THE MODEL

All variables and parameters directly relating to area are measured in square kilometers. All variables and parameters directly relating to weight is measured in million tons. All variables and parameters directly relating to monetary value is measured in US dollars. All variables and parameters directly related to time are measured in years

Regional survey

Variables and parameters	Equations	Properties	Comments
DESIRED_REGIONAL_SURVEY_RATE	DESIRED_SHARE_OF_TOTAL_REGIONAL_SURVEY_AREA_COVERED_BY_REGIONAL_SURVEY_PER_YEAR*PROSPECT_AREA_FOR_REGIONAL_SURVEY		The desired regional survey rate is determined by the product of the desired share of total available area covered by regional survey per year and the prospect area for regional survey
DESIRED_SHARE_OF_TOTAL_REGIONAL_SURVEY_AREA_COVERED_BY_REGIONAL_SURVEY_PER_YEAR	1/3		The desired share of total available area covered by regional survey per year is set to 1/3
DESIRED_SHIPS_COMMITTED_TO_REGIONAL_SURVEY	DESIRED_REGIONAL_SURVEY_RATE/ "REGIONAL_SURVEY_SHIP_KM2/YEAR"		The desired ships committed to regional survey is determined by the desired are covered by regional survey per year and the capacity of one ship committed to regional survey per year
TOTAL_SURVEY_FLEET	SHIPS_COMMITTED_TO_REGIONAL_SURVEY + AVAILABLE_REGIONAL_SURVEY_SHIPS		The total survey fleet is the sum of ships committed to regional survey and available regional survey ships
REGIONAL_SURVEY_BUILD_ORDER_RATE	IF SURVEY_FLEET_GAP > 0 THEN SURVEY_FLEET_GAP + AVAILABLE_SURVEY_SHIPS_SCRAPPING + COMMITTED_SURVEY_SHIPS_SCRAPPING ELSE IF SURVEY_FLEET_GAP = 0 THEN AVAILABLE_SURVEY_SHIPS_SCRAPPING + COMMITTED_SURVEY_SHIPS_SCRAPPING ELSE 0		The regional survey build order rate is determined by the survey fleet gap, which is the total desired number of committed regional survey ships subtracted the total number of existing regional survey ships, plus whatever ships that need replacement to meet/maintain the desired committed mining fleet
SURVEY_FLEET_GAP	DESIRED_SHIPS_COMMITTED_TO_REGIONAL_SURVEY-TOTAL_SURVEY_FLEET		The regional survey fleet gap is the difference between the desired ships committed to regional survey and the total size of the regional survey fleet
AVAILABLE_REGIONAL_SURVEY_SHIPS(t)	AVAILABLE_REGIONAL_SURVEY_SHIPS(t—dt) + (REGIONAL_SURVEY_BUILD_ORDER_RATE—AVAILABLE_SURVEY_SHIPS_SCRAPPING—COMISSION_RATE_REGIONAL_SURVEY) * dt	INIT AVAILABLE_REGIONAL_SURVEY_SHIPS = 2	Available regional survey ships at time t equals the available regional survey ships at time t-dt plus earlier build orders that are completed through time t-dt subtracted what is scrapped through time t-dt and subtracted what is commissioned to the regional survey activity through time t-dt The initial number of regional survey ships is set to 2
AVAILABLE_SURVEY_SHIPS_SCRAPPING	AVAILABLE_REGIONAL_SURVEY_SHIPS/AVERAGE_LIFETIME_OF_REGIONAL_SURVEY_SHIPS		The available regional survey fleet scrapping is an outflow from the available regional survey fleet. The regional survey fleet depreciates based on a defined average lifetime. This process is approximately continuous
AVERAGE_LIFETIME_OF_REGIONAL_SURVEY_SHIPS	20		The average lifetime of reginal survey vessels is informed by multiple experts during modelling process and is referred to as industry standard. The lifetime of these vessels is dependent on initial quality of product, utilization, maintenance, and migrating client demands to quality, emissions, etc

NOTE REGARDING THE UNITS OF THE VARIABLES AND PARAMETERS IN THE MODEL

All variables and parameters directly relating to area are measured in square kilometers. All variables and parameters directly relating to weight is measured in million tons. All variables and parameters directly relating to monetary value is measured in US dollars. All variables and parameters directly related to time are measured in years

Regional survey

Variables and parameters	Equations	Properties	Comments
COMISSION_RATE_REGIONAL_SURVEY	IF DESIRED_SHIPS_COMMITTED_TO_REGIONAL_SURVEY-SHIPS_COMMITTED_TO_REGIONAL_SURVEY < 0 AND SHIPS_COMMITTED_TO_REGIONAL_SURVEY > DESIRED_SHIPS_COMMITTED_TO_REGIONAL_SURVEY-SHIPS_COMMITTED_TO_REGIONAL_SURVEY THEN (DESIRED_SHIPS_COMMITTED_TO_REGIONAL_SURVEY-SHIPS_COMMITTED_TO_REGIONAL_SURVEY)/DT ELSE IF DESIRED_SHIPS_COMMITTED_TO_REGIONAL_SURVEY-SHIPS_COMMITTED_TO_REGIONAL_SURVEY < 0 AND SHIPS_COMMITTED_TO_REGIONAL_SURVEY < DESIRED_SHIPS_COMMITTED_TO_REGIONAL_SURVEY-SHIPS_COMMITTED_TO_REGIONAL_SURVEY THEN SHIPS_COMMITTED_TO_REGIONAL_SURVEY/DT ELSE IF DESIRED_SHIPS_COMMITTED_TO_REGIONAL_SURVEY-SHIPS_COMMITTED_TO_REGIONAL_SURVEY > 0 AND DESIRED_SHIPS_COMMITTED_TO_REGIONAL_SURVEY-SHIPS_COMMITTED_TO_REGIONAL_SURVEY < AVAILABLE_REGIONAL_SURVEY_SHIPS THEN (DESIRED_SHIPS_COMMITTED_TO_REGIONAL_SURVEY-SHIPS_COMMITTED_TO_REGIONAL_SURVEY)/DT ELSE IF DESIRED_SHIPS_COMMITTED_TO_REGIONAL_SURVEY-SHIPS_COMMITTED_TO_REGIONAL_SURVEY > 0 AND DESIRED_SHIPS_COMMITTED_TO_REGIONAL_SURVEY-SHIPS_COMMITTED_TO_REGIONAL_SURVEY > AVAILABLE_REGIONAL_SURVEY_SHIPS THEN AVAILABLE_REGIONAL_SURVEY_SHIPS/DT ELSE 0		The commission rate for regional survey ships is a target seeking algorithm that commits and decommits ships based on the total available ships, the desired number of committed ships, and the committed number of ships
SHIPS_COMMITTED_TO_REGIONAL_SURVEY(t)	SHIPS_COMMITTED_TO_REGIONAL_SURVEY(t—dt) + (COMISSION_RATE_REGIONAL_SURVEY—SHIPS_COMMITTED_TO_REGIONAL_SURVEY_SCRAPPING) * dt	INIT SHIPS_COMMITTED_TO_REGIONAL_SURVEY = 0	The ships committed to regional survey is determined by the number of ships committed to regional survey in the previous time step plus the commission of ships through the previous time step subtracted the number of ships committed to regional survey that are scrapped

NOTE REGARDING THE UNITS OF THE VARIABLES AND PARAMETERS IN THE MODEL

All variables and parameters directly relating to area are measured in square kilometers. All variables and parameters directly relating to weight is measured in million tons. All variables and parameters directly relating to monetary value is measured in US dollars. All variables and parameters directly related to time are measured in years

Regional survey

Variables and parameters	Equations	Properties	Comments
			The initial number of ships committed to regional survey is set to 0
SHIPS_COMMITTED_TO_REGIONAL_SURVEY_SCRAPPING	SHIPS_COMMITTED_TO_REGIONAL_SURVEY/AVERAGE_LIFETIME_OF_REGIONAL_SURVEY_SHIPS		The ships committed to regional survey depreciates based on the average lifetime of such ships. This process is approximately continuous in nature
PROSPECT_AREA_UNDERGOING_EVALUATION_AFTER_REGIONAL_SURVEY(t)	PROSPECT_AREA_UNDERGOING_EVALUATION_AFTER_REGIONAL_SURVEY(t—dt) + (REGIONAL_SURVEY_RATE—REGIONAL_SURVEY_WITH_DESIRABLE_OUTCOME—COMMERCIAL_POTENTIAL_DISCONFIRMATION_AFTER_REGIONAL_SURVEY) * dt	INIT PROSPECT_AREA_UNDERGOING_EVALUATION_AFTER_REGIONAL_SURVEY = 0	The prospect area undergoing evaluation after regional survey is determined by the size of the stock in the previous time step plus whatever is added from regional surveys conducted through the previous time step subtracted whatever area is confirmed or disconfirmed
			The initial prospect area undergoing evaluation after regional survey is set to 0
REGIONAL_SURVEY_WITH_DESIRABLE_OUTCOME	DELAY(REGIONAL_SURVEY_RATE*PERCENTAGE_OF_SURVEY_AREA_WITH_DESIRABLE_OUTCOME; 1)		The regional survey with desirable outcome is determined by the product of the percentage of survey area with desirable outcome and the regional survey rate one year ago. The reason for the delay is that it takes time to analyze the results from regional surveys and seasonal restrictions on when the next activity can take place
PERCENTAGE_OF_SURVEY_AREA_WITH_DESIRABLE_OUTCOME	LOGNORMAL(EXPECTED_PERCENTAGE_OF_SURVEY_AREA_WITH_DESIRABLE_OUTCOME; STANDARD_DEVIATION_REGIONAL_SURVEY; SEED_REGIONAL_SURVEY; 0; 1; 1)		
EXPECTED_PERCENTAGE_OF_SURVEY_AREA_WITH_DESIRABLE_OUTCOME	0,15		Set in accordance with information and statements from the interview subjects
STANDARD_DEVIATION_REGIONAL_SURVEY	0,075*STD_SCALING_FACTOR*STOCHASTIC_SWITCH		Standard deviation parameter of stochasticity parameter as informed by geology experts
COMMERCIAL_POTENTIAL_DISCONFIRMATION_AFTER_REGIONAL_SURVEY	DELAY(REGIONAL_SURVEY_RATE*(1-PERCENTAGE_OF_SURVEY_AREA_WITH_DESIRABLE_OUTCOME); 1)		Commercial potential disconfirmation after regional survey at time t is modeled as the product of the percentage of regional survey area with desirable outcome and the regional survey rate one year ago. The reason for the delay is that it takes time to analyze the data from coring surveys and seasonal restrictions on when the next activity can take place

High resolution survey, coring, and environmental impact assessment

Variables and parameters	Equations	**Properties**	**Comments**
“PROSPECT_AREA_FOR_HI-RES_SURVEY”(t)	“PROSPECT_AREA_FOR_HI-RES_SURVEY”(t—dt) + (REGIONAL_SURVEY_WITH_DESIRABLE_OUTCOME – “HI-RES_SURVEY_RATE”) * dt	INIT “PROSPECT_AREA_FOR_HI-RES_SURVEY” = 0	The prospect area for high-resolution survey is determined by the size of the stock in the previous time step plus whatever is added from desirable outcomes from regional surveys through the previous time step subtracted whatever area is moved on to high-resolution survey through the previous time step The initial prospect area for high-resolution survey is set to 0
“HI-RES_SURVEY_RATE”	MIN(“SHIPS_COMMITTED_TO_HI-RES “*”HI-RES_SURVEY_SHIP_KM2/YEAR”; “PROSPECT_AREA_FOR_HI-RES_SURVEY”)		The high-resolution survey rate is determined by the number of ships committed to said activity and the area covered by ships committed to this activity per year. If the capacity exceeds the available area, only the remaining area will be surveyed
“HI-RES_KTS_CONVERTER”	1,852		
“HI-RES_SURVEY_SHIP_KM2/YEAR”	“HI-RES_SURVEY_SPEED_PER_YEAR”* “HI-RES_SURVEY_SWATH”		The area covered by a high-resolution survey ship is calculated based on the high-resolution survey ship speed and the high-resolution survey ship swath
“HI-RES_SURVEY_SPEED_PER_YEAR”	1*"HI-RES_KTS_CONVERTER“*18*28*6		
“HI-RES_SURVEY_SWATH”	0,5		Survey Swath refers to lateral acoustic coverage of bathymetry and determined by opening angle of dual head hull-mounted multibeam echo sounder (DH-MBES) and flying-height above seabed. Modern DH-MBES allows for online adjustment of opening angle in order to maintain constant swath. Swath is informed by multiple experts during modelling process and is referred to as industry standard
“DESIRED_AREA_COVERED_BY_HI-RES”	“DESIRED_SHARE_OF_TOTAL_HI-RES_AREA_COVERED_BY_HI-RES_PER_YEAR “*”PROSPECT_AREA_FOR_HI-RES_SURVEY”		The desired area covered by high-resolution survey is determined by the product of the desired share of total available area covered by high-resolution survey per year for and the prospect area for high-resolution survey
“DESIRED_SHARE_OF_TOTAL_HI-RES_AREA_COVERED_BY_HI-RES_PER_YEAR”	1/3		The desired share of total available area covered by high-resolution survey per year is set to 1/3
“TOTAL_SHIPS_FOR_HI-RES,_CORING_AND_EIA”	“SHIPS_COMMITTED_TO_HI-RES" + SHIPS_COMMITTED_TO_CORING + SHIPS_COMMITTED_TO_EIA + “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA”		The total high-resolution survey, coring, environmental impact assessment ships equal the sum of all committed ships and the available ships of such type
“DESIRED_SHIPS_COMMITTED_TO_HI-RES”	“DESIRED_AREA_COVERED_BY_HI-RES”/ “HI-RES_SURVEY_SHIP_KM2/YEAR”		The desired ships committed to high-resolution survey is determined by the desired area covered by high-resolution survey per year and the capacity of one ship committed to high-resolution survey per year

High resolution survey, coring, and environmental impact assessment

Variables and parameters	Equations	**Properties**	**Comments**
"HI-RES_COMMISION_RATE"	IF "AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA"-(DESIRED_SHIPS_COMMITTED_TO_CORING-SHIPS_COMMITTED_TO_CORING)-(DESIRED_SHIPS_COMMITTED_TO_EIA-SHIPS_COMMITTED_TO_EIA) > 0 THEN MIN("DESIRED_SHIPS_COMMITTED_TO_HI-RES"- "SHIPS_COMMITTED_TO_HI-RES"; "AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA")/TIME_TO_COMMIT_OR_RECOMMIT_SHIPS ELSE IF "AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA"-(DESIRED_SHIPS_COMMITTED_TO_CORING-SHIPS_COMMITTED_TO_CORING)-(DESIRED_SHIPS_COMMITTED_TO_EIA-SHIPS_COMMITTED_TO_EIA) < 0 THEN—"SHIPS_COMMITTED_TO_HI-RES"/TIME_TO_COMMIT_OR_RECOMMIT_SHIPS ELSE 0		The commission rates for high-resolution surveys, coring, and environmental impact assessments are determined by algorithms that consider the available number of ships, the number of desired ships committed to each activity, the number of ships committed to the various activities. If there are enough available ships to satisfy the desired number of ships committed for all activities, then the algorithm will ensure this happens. If there are not enough available ships to satisfy the desired number of ships committed for all activities, then commission will be prioritized to the activity that is closer to generate an ore discovery
TIME_TO_COMMIT_OR_RECOMMIT_SHIPS	1/12		The average time required to secure a multipurpose vessel-charter via procurement in spot-market. Time includes announcement in market, negotiations, and contractual commitment. Parameter informed by industry and academic experts/stakeholders experienced in chartering vessels

High resolution survey, coring, and environmental impact assessment

Variables and parameters	Equations	**Properties**	**Comments**
“TOTAL_DESIRED_SHIPS_FOR_HI-RES,_CORING_AND_EIA”	(“DESIRED_SHIPS_COMMITTED_TO_HI-RES” + DESIRED_SHIPS_COMMITTED_TO_CORING + DESIRED_SHIPS_COMMITTED_TO_EIA + DESIRED_AVAILABLE_SHIPS)*(1-AGRESSIVE_POLICY_SWITCH) + AGRESSIVE_POLICY_SWITCH* MAX((“DESIRED_SHIPS_COMMITTED_TO_HI-RES” + DESIRED_SHIPS_COMMITTED_TO_CORING + DESIRED_SHIPS_COMMITTED_TO_EIA + DESIRED_AVAILABLE_SHIPS); (DESIRED_AVAILABLE_SHIPS + "EXPECTED_DESIRED_SHIPS_FOR_HI-RES_IN_TWO_YEARS" + EXPECTED_DESIRED_SHIPS_COMMITTED_TO_CORING_IN_TWO_YEARS + EXPECTED_DESIRED_SHIPS_COMMITTED_TO_EIA_IN_TWO_YEARS))		The total desired ships for high-resolution surveys, coring, and EIAs depend on the policy setting
DESIRED_AVAILABLE_SHIPS	0		The desired number of available ships is a parameter that defines how many ships are always wanted available. This parameter is set to 0

High resolution survey, coring, and environmental impact assessment

Variables and parameters	Equations	**Properties**	**Comments**
"SHIPS_FOR_HI-RES,_CORING_AND_EIA_BUILD_ORDER_RATE"	IF "TOTAL_DESIRED_SHIPS_FOR_HI-RES,_CORING_AND_EIA"- "TOTAL_SHIPS_FOR_HI-RES,_CORING_AND_EIA"- "SHIPS_FOR_HI-RES,_CORING_AND_EIA_UNDER_CONSTRUCTION" > = 0 THEN ("TOTAL_DESIRED_SHIPS_FOR_HI-RES,_CORING_AND_EIA"- "TOTAL_SHIPS_FOR_HI-RES,_CORING_AND_EIA"- "SHIPS_FOR_HI-RES,_CORING_AND_EIA_UNDER_CONSTRUCTION")/TIME_TO_COMPLETE_DESIRED_INVESTMENT + SHIPS_AT_REPLACEMENT_DATE/TIME_TO_COMPLETE_DESIRED_INVESTMENT ELSE IF "TOTAL_DESIRED_SHIPS_FOR_HI-RES,_CORING_AND_EIA" > = "TOTAL_SHIPS_FOR_HI-RES,_CORING_AND_EIA"-SHIPS_AT_REPLACEMENT_DATE THEN SHIPS_AT_REPLACEMENT_DATE/TIME_TO_COMPLETE_DESIRED_INVESTMENT ELSE 0		The build order rate for high-resolution, coring, and environmental impact assessment ships is target seeking and based on the total number of desired committed ships, the ships under construction, and the ships due for replacement if capacity is to be maintained
SHIPS_AT_REPLACEMENT_DATE(t)	SHIPS_AT_REPLACEMENT_DATE(t—dt) + (SHIPS_DUE_FOR_REPLACEMENT—SHIPS_REPLACED_OR_OVER_DUE_DATE_FOR_REPLACEMENT) * dt	INIT SHIPS_AT_REPLACEMENT_DATE = 0	The ships at replacement date keeps track of ships that are due for scrapping in near future and needs to be replaced if there is desire to avoid reduction in the exploration capacity
TIME_TO_COMPLETE_DESIRED_INVESTMENT	1		The initial number of ships at replacement date is set to 0
"SHIPS_FOR_HI-RES,_CORING_AND_EIA_BUILD_COMPLETION"	DELAY("SHIPS_FOR_HI-RES,_CORING_AND_EIA_BUILD_ORDER_RATE"; SURVEY_SHIPS_LEAD_TIME)		The completion rate for high-resolution, coring, and environmental impact assessment ships is determined by a discrete delay of previous build order rates. The length of the delay is determined by the lead time for such a ship
SURVEY_SHIPS_LEAD_TIME	2		Time required to commission, build and mobilize a regional survey vessel. Variable informed by multiple experts during modelling process and is referred to as industry standard

High resolution survey, coring, and environmental impact assessment

Variables and parameters	Equations	**Properties**	**Comments**
“AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA” (t)	“AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA” (t—dt) + (“SHIPS_FOR_HI-RES,_CORING_AND_EIA_BUILD_COMPLETION”—CORING_COMMISION_RATE—"HI-RES_COMMISION_RATE”—AVAILABLE_SHIPS_SCRAPPING—EIA_COMMISSION_RATE) * dt	INIT "AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA" = INITIAL_AVAILABLE_SHIPS	Available ships for high-resolution survey, coring, and environmental impact assessment at time t is determined by the size of the stock at time t-dt plus earlier build orders that are completed through time t-dt subtracted ships that are scrapped through time t-dt and subtracted what is commissioned to exploration activities through time t-dt The initial number of available ships is defined by a separately specified variable (which is found further down in the model documentation). However, this variable is set to 0, so the initial number of available ships for coring is 0
AVAILABLE_SHIPS_SCRAPPING	IF NUMBERS_OF_SHIPS_TO_SCRAP > 0 AND “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA” > NUMBERS_OF_SHIPS_TO_SCRAP THEN NUMBERS_OF_SHIPS_TO_SCRAP/DT ELSE IF NUMBERS_OF_SHIPS_TO_SCRAP > 0 AND “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA” < = NUMBERS_OF_SHIPS_TO_SCRAP THEN “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA”/DT ELSE 0		If there are ships for high-resolution surveys, coring, and environmental impact assessments that are due for scrapping, then scrapping will occur based on a priority-list. If there are any ships in the available ships stock, then these will be scrapped according to the equation on the left. If there are no available ships in this stock, or more ships need to be scrapped than what is available in this stock, then the model will look to the next stock on the priority list, which is the ships committed to high-resolution survey. The same procedure is then repeated before moving on to ships committed to coring, and eventually the ships committed to environmental impact assessment. This process is discrete in nature
“SHIPS_FOR_HI-RES,_CORING_AND_EIA_UNDER_CONSTRUCTION” (t)	“SHIPS_FOR_HI-RES,_CORING_AND_EIA_UNDER_CONSTRUCTION”(t—dt) + (“SHIPS_FOR_HI-RES,_CORING_AND_EIA_BUILD_ORDER_RATE”—“SHIPS_FOR_HI-RES,_CORING_AND_EIA_BUILD_COMPLETION”) * dt	INIT “SHIPS_FOR_HI-RES,_CORING_AND_EIA_UNDER_CONSTRUCTION” = 0	The ships for high-resolution surveys, coring, and environmental impact assessments under construction at time t is determined by the size of the stock in the previous time step plus the new orders in the previous time step subtracted the ships that are completed through the previous time step The initial number of ships for high-resolution surveys, coring, and environmental impact assessments are set to 0
SHIPS_DUE_FOR_SCRAPPING(t)	SHIPS_DUE_FOR_SCRAPPING(t—dt) + (“SHIPS_CLOSING_UP_TO_END_OF_LIFETIME—TOTAL_SHIPS_FOR_HI-RES,_CORING_AND_EIA_SCRAPPING_RATE”) * dt	INIT SHIPS_DUE_FOR_SCRAPPING = 0	Ships due for scrapping is a stock that keeps track of the new number of high-resolution survey, coring, and environmental impact assessment ships that are due for scrapping. The size of this stock is determined by the size of the stock in the previous time step plus the number of ships closing to the end of their lifetime in the previous time step subtracted the ships that are scrapped through the previous time step The initial ships due for scrapping is set to 0
NUMBERS_OF_SHIPS_TO_SCRAP	SHIPS_DUE_FOR_SCRAPPING		The number of high-resolution, coring, EIA ships to scrap is determined by the ships due for scrapping
SHIPS_CLOSING_UP_TO_END_OF_LIFETIME	DELAY(“SHIPS_FOR_HI-RES,_CORING_AND_EIA_BUILD_COMPLETION”;“AVERAGE_LIFETIME_OF_SHIPS_FOR_HI-RES,_CORING_AND_EIA”; 0)		The number of regional survey, coring, and environmental impact assessment ships closing to their end of their lifetime is calculated based on a discrete delay of the build order rate

High resolution survey, coring, and environmental impact assessment

Variables and parameters	Equations	**Properties**	**Comments**
“AVERAGE_LIFETIME_OF_SHIPS_FOR_HI-RES,_CORING_AND_EIA"	20		The average lifetime of multipurpose vessels is informed by multiple experts during modelling process and is referred to as industry standard. The lifetime of these vessels is dependent on initial quality of product, utilization, maintenance, and migrating client demands to comfort, capability, quality, emissions, etc
SHIPS_DUE_FOR_REPLACEMENT	DELAY(“SHIPS_FOR_HI-RES,_CORING_AND_EIA_BUILD_COMPLETION”; “AVERAGE_LIFETIME_OF_SHIPS_FOR_HI-RES,_CORING_AND_EIA”-SURVEY_SHIPS_LEAD_TIME-TIME_TO_COMMIT_OR_RECOMMIT_SHIPS-TIME_TO_COMPLETE_DESIRED_INVESTMENT)/DT		The ships due for replacement keeps track of the regional survey, coring, and environmental impact assessment ships that must be put in order and replaced to maintain current capacity
SHIPS_REPLACED_OR_OVER_DUE_DATE_FOR_REPLACEMENT	DELAY(SHIPS_DUE_FOR_REPLACEMENT; DT)		This is an outflow from the stock that keeps track of the ships that are due for replacement. Ships that are past their replacement date are removed from the stock in question
“SHIPS_COMMITTED_TO_HI-RES” (t)	“SHIPS_COMMITTED_TO_HI-RES” (t—dt) + (“HI-RES_COMMISION_RATE”—“SHIPS_COMMITTED_TO_HI-RES_SCRAPPING”) * dt	INIT "SHIPS_COMMITTED_TO_HI-RES" = 0	The ships committed to high-resolution survey is determined by the number of ships committed to high-resolution survey in the previous time step plus the commission of ships through the previous time step subtracted the number of ships committed to high-resolution survey that are scrapped The initial number of ships committed to high-resolution survey is set to 0
"SHIPS_COMMITTED_TO_HI-RES_SCRAPPING”	IF NUMBERS_OF_SHIPS_TO_SCRAP > “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA” AND “SHIPS_COMMITTED_TO_HI-RES” > NUMBERS_OF_SHIPS_TO_SCRAP- “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA” THEN (NUMBERS_OF_SHIPS_TO_SCRAP- “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA”)/DT ELSE IF NUMBERS_OF_SHIPS_TO_SCRAP- “SHIPS_COMMITTED_TO_HI-RES” > 0 AND “SHIPS_COMMITTED_TO_HI-RES" < = NUMBERS_OF_SHIPS_TO_SCRAP- “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA” THEN “SHIPS_COMMITTED_TO_HI-RES”/DT ELSE 0		If there are ships for high-resolution surveys, coring, and environmental impact assessments that are due for scrapping, then scrapping will occur based on a priority-list. If there are any ships in the available ships stock, then these will be scrapped according to the equation on the left. If there are no available ships in this stock, or more ships need to be scrapped than what is available in this stock, then the model will look to the next stock on the priority list, which is the ships committed to high-resolution survey. The same procedure is then repeated before moving on to ships committed to coring, and eventually the ships committed to environmental impact assessment. This process is discrete in nature

High resolution survey, coring, and environmental impact assessment

Variables and parameters	Equations	**Properties**	**Comments**
"PROSPECT_AREA_UNDERGOING_EVALUATION_AFTER_HI-RES_SURVEY"(t)	"PROSPECT_AREA_UNDERGOING_EVALUATION_AFTER_HI-RES_SURVEY"(t—dt) + ("HI-RES_SURVEY_RATE"—"HI-RES_SURVEY_WITH_DESIRABLE_OUTCOME"—"COMMERCIAL_POTENTIAL_DISCONFIRMATION_AFTER_HI-RES_SURVEY") * dt	INIT "PROSPECT_AREA_UNDERGOING_EVALUATION_AFTER_HI-RES_SURVEY" = 0	The prospect area undergoing evaluation after high-resolution survey is determined by the size of the stock in the previous time step plus whatever is added from high-resolution surveys conducted through the previous time step subtracted whatever area is confirmed or disconfirmed The initial prospect area undergoing evaluation after high-resolution survey is set to 0
"HI-RES_SURVEY_WITH_DESIRABLE_OUTCOME"	DELAY("HI-RES_SURVEY_RATE"* "PERCENTAGE_OF_HI-RES_SURVEY_AREA_WITH_DESIRABLE_OUTCOME"; 1)		The high-resolution survey with desirable outcome is determined by the product of the percentage of high-resolution survey area with desirable outcome and the high-resolution survey rate one year ago. The reason for the delay is that it takes time to analyze the results from high-resolution surveys and seasonal restrictions on when the next activity can take place
"PERCENTAGE_OF_HI-RES_SURVEY_AREA_WITH_DESIRABLE_OUTCOME"	LOGNORMAL("EXPECTED_PERCENTAGE_OF_HI-RES_SURVEY_AREA_WITH_DESIRABLE_OUTCOME"; "STANDARD_DEVIATION_HI-RES_SURVEY"; "SEED_HI-RES_SURVEY"; 0; 1; 1)		
"EXPECTED_PERCENTAGE_OF_HI-RES_SURVEY_AREA_WITH_DESIRABLE_OUTCOME"	0,01		Set in accordance with information and statements from the interview subjects
"STANDARD_DEVIATION_HI-RES_SURVEY"	0,005*STD_SCALING_FACTOR*STOCHASTIC_SWITCH		Standard deviation parameter of stochasticity parameter as informed by geology experts
"COMMERCIAL_POTENTIAL_DISCONFIRMATION_AFTER_HI-RES_SURVEY"	DELAY((1- "PERCENTAGE_OF_HI-RES_SURVEY_AREA_WITH_DESIRABLE_OUTCOME")* "HI-RES_SURVEY_RATE"; 1)		Commercial potential disconfirmation after high-resolution survey at time t is modeled as the product of the percentage of high-resolution survey area with desirable outcome and the high-resolution survey rate one year ago. The reason for the delay is that it takes time to analyze the data from coring surveys and seasonal restrictions on when the next activity can take place
PROSPECT_AREA_FOR_CORING(t)	PROSPECT_AREA_FOR_CORING(t—dt) + ("HI-RES_SURVEY_WITH_DESIRABLE_OUTCOME"—CORING_RATE) * dt	INIT PROSPECT_AREA_FOR_CORING = 0	The prospect area for coring is determined by the size of the stock in the previous time step plus whatever is added from desirable outcomes from high-resolution surveys through the previous time step subtracted whatever area is moved on to coring The initial prospect area for coring is set to 0
CORING_RATE	MIN(SHIPS_COMMITTED_TO_CORING*AREA_CONCLUDED_PER_CORING_CAMPAIGN*MAXIMUM_NUMBER_OF_CORING_CAMPAIGNS_PER_SHIP_PER_YEAR; PROSPECT_AREA_FOR_CORING)		The coring rate is determined by the number of ships committed to coring, the area concluded per coring campaign, the maximum number of coring campaigns per ship per year. If this capacity exceeds the area available for coring, then only the remaining area will be subject to coring

High resolution survey, coring, and environmental impact assessment

Variables and parameters	Equations	**Properties**	**Comments**
MAXIMUM_NUMBER_OF_CORING_CAMPAIGNS_PER_SHIP_PER_YEAR	2		The plausible maximum number of campaigns executable during exploration season. Considering long distance from shore, bunkering and supply requirements, crew-change requirements, weather, and operational capability there is a practical maximum for the number of campaigns a vessel can execute during the ice-free/operable season
AREA_CONCLUDED_PER_CORING_CAMPAIGN	0,2125		The spatial distribution of cores throughout an area defines the level of certainty geologist may assume when analyzing the core data. Given time to core, required cores per/area for geologic assessment and campaign duration the area concluded per campaign is defined, The parameter is informed by participating expert geologists
DESIRED_AREA_COVERED_CORING	DESIRED_SHARE_OF_TOTAL_CORING_AREA_COVERED_BY_CORING_PER_YEAR*PROSPECT_AREA_FOR_CORING		The desired area covered by coring is determined by the product of the desired share of total available area covered by coring per year and the prospect area for coring
DESIRED_SHARE_OF_TOTAL_CORING_AREA_COVERED_BY_CORING_PER_YEAR	1/3		The desired share of total available area covered by coring per year is set to 1/3
DESIRED_SHIPS_COMMITTED_TO_CORING	DESIRED_AREA_COVERED_CORING/ (AREA_CONCLUDED_PER_CORING_CAMPAIGN*MAXIMUM_NUMBER_OF_CORING_CAMPAIGNS_PER_SHIP_PER_YEAR)		The desired ships committed to coring is calculated based on the desired area covered by coring per year and the capacity of one ship committed to coring per year

High resolution survey, coring, and environmental impact assessment

Variables and parameters	Equations	**Properties**	**Comments**
CORING_COMMISION_RATE	IF "AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA"-(DESIRED_SHIPS_COMMITTED_TO_EIA-SHIPS_COMMITTED_TO_EIA) > 0 THEN MIN(DESIRED_SHIPS_COMMITTED_TO_CORING-SHIPS_COMMITTED_TO_CORING; "AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA")/TIME_TO_COMMIT_OR_RECOMMIT_SHIPS ELSE IF "AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA" (DESIRED_SHIPS_COMMITTED_TO_EIA-SHIPS_COMMITTED_TO_EIA) < 0 AND "SHIPS_COMMITTED_TO_HI-RES" > (DESIRED_SHIPS_COMMITTED_TO_EIA-SHIPS_COMMITTED_TO_EIA) THEN 0 ELSE IF "AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA"-(DESIRED_SHIPS_COMMITTED_TO_EIA-SHIPS_COMMITTED_TO_EIA) < 0 THEN MAX(-SHIPS_COMMITTED_TO_CORING; (- "AVAILABLE_SHIPS_FR_HI-RES,_CORING_AND_EIA"-(DESIRED_SHIPS_COMMITTED_TO_EIA-SHIPS_COMMITTED_TO_EIA)))/TIME_TO_COMMIT_OR_RECOMMIT_SHIPS ELSE 0		The commission rates for high-resolution surveys, coring, and environmental impact assessments are determined by algorithms that consider the available number of ships, the number of desired ships committed to each activity, the number of ships committed to the various activities. If there are enough available ships to satisfy the desired number of ships committed for all activities, then the algorithm will ensure this happens. If there are not enough available ships to satisfy the desired number of ships committed for all activities, then commission will be prioritized to the activity that is closer to generate an ore discovery
SHIPS_COMMITTED_TO_CORING(t)	SHIPS_COMMITTED_TO_CORING(t—dt) + (CORING_COMMISION_RATE—SHIPS_COMMITTED_TO_CORING_SCRAPPING) * dt	INIT SHIPS_COMMITTED_TO_CORING = 0	The ships committed to coring is determined by the number of ships committed to coring in the previous time step plus the commission of ships through the previous time step subtracted the number of ships committed to coring that are scrapped The initial number of ships committed to coring is set to 0

High resolution survey, coring, and environmental impact assessment

Variables and parameters	Equations	**Properties**	**Comments**
SHIPS_COMMITTED_TO_CORING_SCRAPPING	IF NUMBERS_OF_SHIPS_TO_SCRAP > “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA” + “SHIPS_COMMITTED_TO_HI-RES" AND SHIPS_COMMITTED_TO_CORING > NUMBERS_OF_SHIPS_TO_SCRAP- “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA”- “SHIPS_COMMITTED_TO_HI-RES” THEN (NUMBERS_OF_SHIPS_TO_SCRAP- “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA”- “SHIPS_COMMITTED_TO_HI-RES”)/DT ELSE IF NUMBERS_OF_SHIPS_TO_SCRAP- SHIPS_COMMITTED_TO_CORING > 0 AND SHIPS_COMMITTED_TO_CORING < = NUMBERS_OF_SHIPS_TO_SCRAP- “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA”- “SHIPS_COMMITTED_TO_HI-RES” THEN (SHIPS_COMMITTED_TO_CORING)/DT ELSE 0		If there are ships for high-resolution surveys, coring, and environmental impact assessments that are due for scrapping, then scrapping will occur based on a priority-list. If there are any ships in the available ships stock, then these will be scrapped according to the equation on the left. If there are no available ships in this stock, or more ships need to be scrapped than what is available in this stock, then the model will look to the next stock on the priority list, which is the ships committed to high-resolution survey. The same procedure is then repeated before moving on to ships committed to coring, and eventually the ships committed to environmental impact assessment. This process is discrete in nature
PROSPECT_AREA_UNDERGOING_EVALUATION_AFTER_CORING(t)	PROSPECT_AREA_UNDERGOING_EVALUATION_AFTER_CORING(t—dt) + (CORING_RATE—CORING_WITH_DESIRABLE_OUTCOME—COMMERCIAL_POTENTIAL_DISCONFIRMATION_AFTER_CORING) * dt	INIT PROSPECT_AREA_UNDERGOING_EVALUATION_AFTER_CORING = 0	The prospect area undergoing evaluation after coring is determined by the size of the stock in the previous time step plus whatever is added on from coring through the previous time step subtracted whatever area is confirmed or disconfirmed as commercially interesting through the previous time step The initial prospect area undergoing evaluation after coring is set to 0
CORING_WITH_DESIRABLE_OUTCOME	DELAY(PERCENTAGE_OF_CORING_AREA_WITH_DESIRABLE_OUTCOME*CORING_RATE; 1)		The coring with desirable outcome is determined by the product of the percentage of coring area with desirable outcome and the coring rate one year ago. The reason for the delay is that it takes time to analyze the data from coring activity and seasonal restrictions on when the next activity can take place
PERCENTAGE_OF_CORING_AREA_WITH_DESIRABLE_OUTCOME	LOGNORMAL(EXPECTED_PERCENTAGE_OF_CORING_AREA_WITH_DESIRABLE_OUTCOME; STANDARD_DEVIATION_CORING; SEED_CORING; 0; 1; 1)		
EXPECTED_PERCENTAGE_OF_CORING_AREA_WITH_DESIRABLE_OUTCOME	0,25		Set in accordance with information and statements from the interview subjects
STANDARD_DEVIATION_CORING	0,125*STD_SCALING_FACTOR*STOCHASTIC_SWITCH		Standard deviation parameter of stochasticity parameter as informed by geology experts interviewed

High resolution survey, coring, and environmental impact assessment

Variables and parameters	Equations	**Properties**	**Comments**
COMMERCIAL_POTENTIAL_DISCONFIRMATION_AFTER_CORING	DELAY((1-PERCENTAGE_OF_CORING_AREA_WITH_DESIRABLE_OUTCOME)*CORING_RATE; 1)		Commercial potential disconfirmation after coring at time *t* is modeled as the product of the percentage of coring area with desirable outcome and the coring rate one year ago. The reason for the delay is that it takes time to analyze the data from coring activity and seasonal restrictions on when the next activity can take place
AREA_WITH_CONFIRMED_ORE(t)	AREA_WITH_CONFIRMED_ORE(t—dt) + (CORING_WITH_DESIRABLE_OUTCOME—EIA_RATE) * dt	INIT AREA_WITH_CONFIRMED_ORE = 0	Area with confirmed ore at time *t* equals the area with confirmed ore at time t-dt plus the inflow from successful coring through time t-dt subtracted the area that moves to environmental impact assessment through time *t*-dt The initial area with confirmed ore is set to 0
EIA_RATE	MIN(SHIPS_COMMITTED_TO_EIA* "HI-RES_SURVEY_SHIP_KM2/YEAR"/EIA_AREA_AMPLIFIER; AREA_WITH_CONFIRMED_ORE)		The environmental impact assessment rate is determined by the product of the number of ships committed to the activity and the area covered per such ship for said activity divided by an environmental impact assessment area amplified (since environmental impact assessments must cover a larger area than that one is interested in extracting from). If the capacity for environmental impact assessment exceeds the available area for such activity, then only the remaining area will be covered
EIA_AREA_AMPLIFIER	314		The environmental impact assessment area amplifier is set to 314
DESIRED_AREA_COVERED_EIA	DESIRED_SHARE_OF_TOTAL_EIA_AREA_COVERED_BY_EIA_PER_YEAR*AREA_WITH_CONFIRMED_ORE		The desired area covered by EIA is determined by the product of the desired share of total available area covered by EIA per year and the prospect area for EIA
DESIRED_SHARE_OF_TOTAL_EIA_AREA_COVERED_BY_EIA_PER_YEAR	1		The desired share of total available area covered by EIA per year is set to 1
DESIRED_SHIPS_COMMITTED_TO_EIA	DESIRED_AREA_COVERED_EIA/ "HI-RES_SURVEY_SHIP_KM2/YEAR"*EIA_AREA_AMPLIFIER		The desired ships committed to EIA is calculated based on the desired area covered by EIA per year and the capacity of one ship committed to EIA per year
EIA_COMMISSION_RATE	MIN(DESIRED_SHIPS_COMMITTED_TO_EIA-SHIPS_COMMITTED_TO_EIA;"AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA")/TIME_TO_COMMIT_OR_RECOMMIT_SHIPS		The commission rates for high-resolution surveys, coring, and environmental impact assessments are determined by algorithms that consider the available number of ships, the number of desired ships committed to each activity, the number of ships committed to the various activities. If there are enough available ships to satisfy the desired number of ships committed for all activities, then the algorithm will ensure this happens. If there are not enough available ships to satisfy the desired number of ships committed for all activities, then commission will be prioritized to the activity that is closer to generate an ore discovery
SHIPS_COMMITTED_TO_EIA(t)	SHIPS_COMMITTED_TO_EIA(t—dt) + (EIA_COMMISSION_RATE—SHIPS_COMMITTED_TO_EIA_SCRAPPING) * dt	INIT SHIPS_COMMITTED_TO_EIA = 0	The ships committed to EIA is determined by the number of ships committed to EIA in the previous time step plus the commission of ships through the previous time step subtracted the number of ships committed to EIA that are scrapped The initial number of ships committed to EIA is set to 0

High resolution survey, coring, and environmental impact assessment

Variables and parameters	Equations	**Properties**	**Comments**
SHIPS_COMMITTED_TO_EIA_SCRAPPING	IF NUMBERS_OF_SHIPS_TO_SCRAP > “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA” + “SHIPS_COMMITTED_TO_HI-RES” + SHIPS_COMMITTED_TO_CORING AND SHIPS_COMMITTED_TO_EIA > NUMBERS_OF_SHIPS_TO_SCRAP- “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA”- “SHIPS_COMMITTED_TO_HI-RES”-SHIPS_COMMITTED_TO_CORING THEN (NUMBERS_OF_SHIPS_TO_SCRAP- “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA”- “SHIPS_COMMITTED_TO_HI-RES"-SHIPS_COMMITTED_TO_CORING)/DT ELSE IF NUMBERS_OF_SHIPS_TO_SCRAP-SHIPS_COMMITTED_TO_EIA > 0 AND SHIPS_COMMITTED_TO_EIA < = NUMBERS_OF_SHIPS_TO_SCRAP- “AVAILABLE_SHIPS_FOR_HI-RES,_CORING_AND_EIA”- “SHIPS_COMMITTED_TO_HI-RES”-SHIPS_COMMITTED_TO_CORING THEN SHIPS_COMMITTED_TO_EIA/DT ELSE 0		If there are ships for high-resolution surveys, coring, and environmental impact assessments that are due for scrapping, then scrapping will occur based on a priority-list. If there are any ships in the available ships stock, then these will be scrapped according to the equation on the left. If there are no available ships in this stock, or more ships need to be scrapped than what is available in this stock, then the model will look to the next stock on the priority list, which is the ships committed to high-resolution survey. The same procedure is then repeated before moving on to ships committed to coring, and eventually the ships committed to environmental impact assessment. This process is discrete in nature
AREA_WITH_CONFIRMED_ORE_UNDERGOING_EVALUATION_AFTER_EIA(t)	AREA_WITH_CONFIRMED_ORE_UNDERGOING_EVALUATION_AFTER_EIA(*t*—dt) + (EIA_RATE—EIA_APPROVAL_RATE—EIA_DISAPPROVAL_RATE) * dt	INIT AREA_WITH_CONFIRMED_ORE_UNDERGOING_EVALUATION_AFTER_EIA = 0	Area with confirmed ore undergoing evaluation after environmental impact assessment at time *t* equals the area with confirmed ore undergoing evaluation after environmental impact assessment at time t-dt plus the inflow from environmental impact assessment through time t-dt subtracted the environmental impact assessment approval and disapproval rates through time t-dt The initial area with confirmed ore undergoing evaluation after environmental impact assessment is set to 0
EIA_APPROVED_AREA_WITH_CONFIRMED_ORE(t)	EIA_APPROVED_AREA_WITH_CONFIRMED_ORE(t—dt) + (EIA_APPROVAL_RATE) * dt	INIT EIA_APPROVED_AREA_WITH_CONFIRMED_ORE = 0	Environmental assessment approved area with confirmed ore at time t is determined by the size of the stock in the previous time step plus whatever is approved through the previous timestep The initial environmental assessment approved area with confirmed ore is set to 0
EIA_APPROVAL_RATE	DELAY(PERCENTAGE_OF_AREA_WITH_CONFIRMED_ORE_RECEIVING_EIA_APPROVAL*EIA_RATE; 1)		The environmental impact assessment approval rate is determined by the product of the percentage of area with confirmed ore receiving such approval and the environmental impact assessment rate one year ago. The reason for the delay is that it takes time to analyze the results from an environmental impact assessment survey and decide regarding approval

High resolution survey, coring, and environmental impact assessment

Variables and parameters	Equations	**Properties**	**Comments**
PERCENTAGE_OF_AREA_WITH_CONFIRMED_ORE_RECEIVING_EIA_APPROVAL	1		We assume all area of interest gets an environmental impact assessment approval. This need not be the case for the actual industry
EIA_DISAPPROVAL_RATE	DELAY((1-PERCENTAGE_OF_AREA_WITH_CONFIRMED_ORE_RECEIVING_EIA_APPROVAL)*EIA_RATE; 12)		The environmental impact assessment disapproval rate is determined by the product of the percentage of area with confirmed ore receiving such approval and the environmental impact assessment rate one year ago. The reason for the delay is that it takes time to analyze the results from an environmental impact assessment survey and decide regarding approval
DISCARDED_AREA(t)	DISCARDED_AREA(t—dt) + (“COMMERCIAL_POTENTIAL_DISCONFIRMATION_AFTER_HI-RES_SURVEY” + COMMERCIAL_POTENTIAL_DISCONFIRMATION_AFTER_CORING + COMMERCIAL_POTENTIAL_DISCONFIRMATION_AFTER_REGIONAL_SURVEY + EIA_DISAPPROVAL_RATE) * dt	INIT DISCARDED_AREA = 0	Discarded area at time t is determined by the size of the stock in the previous time step plus whatever area is disconfirmed after the various exploration activities through the previous time step The initial discarded area is set to 0
“TOTAL_SHIPS_FOR_HI-RES,_CORING_AND_EIA_SCRAPPING_RATE”	AVAILABLE_SHIPS_SCRAPPING + “SHIPS_COMMITTED_TO_HI-RES_SCRAPPING” + SHIPS_COMMITTED_TO_CORING_SCRAPPING + SHIPS_COMMITTED_TO_EIA_SCRAPPING		The total ships for scrapping keeps track of the high-resolution survey, coring, and environmental impact assessment ships that have been scrapped, and removes these ships from the stock tracking the ships that are due for scrapping
SCRAPPED_NUMBER_OF_SHIPS(t)	SCRAPPED_NUMBER_OF_SHIPS(t—dt) + (“TOTAL_SHIPS_FOR_HI-RES,_CORING_AND_EIA_SCRAPPING_RATE”) * dt	INIT SCRAPPED_NUMBER_OF_SHIPS = 0	The scrapped number of ships is a stock that keeps track of how many ships have been scrapped at any point in time. It serves no other purpose in the model

Commercial ore discovery and extraction

Variables and parameters	Equations	Properties	Comments
COMMERCIAL_ORE_DISCOVERY	EIA_APPROVAL_RATE*AVERAGE_MILLION_TONS_ORE_PER_KM2_PER_DISCOVERY		The commercial ore discovery rate is determined by the environmental impact assessment approval rate multiplied by the average million tons ore per square kilometer
AVERAGE_MILLION_TONS_ORE_PER_KM2_PER_DISCOVERY	LOGNORMAL(EXPECTED_AVERAGE_MILLION_TONS_ORE_PER_KM2_PER_DISCOVERY; STANDARD_DEVIATION_OCCURENCE; SEED_OCCURENCE; 0; 100; 1)		The average million tons of ore per km^2 per discovery as assessed by interviewed geologists indicates the tonnage of material carrying commercial minerals expected to be retrieved per area within a deposit discovery. The parameter is based on the knowledge, expectations, and perceptions by participating geologists and is informed by geologic analogues from similar deposits
EXPECTED_AVERAGE_MILLION_TONS_ORE_PER_KM2_PER_DISCOVERY	2		The expected average million tons of ore per square kilometer is set to 2. This is done in accordance with input from several interview subjects
STANDARD_DEVIATION_OCCURENCE	1*STD_SCALING_FACTOR*STOCHASTIC_SWITCH		Standard deviation parameter of stochasticity parameter as informed by geology experts

Commercial ore discovery and extraction

Variables and parameters	Equations	Properties	Comments
COMMERCIAL_MINERAL_STOCK(t)	COMMERCIAL_MINERAL_STOCK(*t*—dt) + (COMMERCIAL_ORE_DISCOVERY—EXTRACTION_FROM_COMMERCIAL_MINERAL_STOCK) * dt	INIT COMMERCIAL_MINERAL_STOCK = 0	Commercial mineral stock at time *t* is determined by the stock size at time t-dt plus whatever is discovered through time t-dt subtracted whatever is extracted through time t-dt The initial commercial mineral stock is set to 0
EXTRACTION_FROM_COMMERCIAL_MINERAL_STOCK	IF COMMERCIAL_MINERAL_STOCK > COMMITTED_MINING_FLEET*EXTRACTION_PER_MINING_FLEET_UNIT_PER_YEAR THEN COMMITTED_MINING_FLEET*EXTRACTION_PER_MINING_FLEET_UNIT_PER_YEAR ELSE IF COMMERCIAL_MINERAL_STOCK < COMMITTED_MINING_FLEET*EXTRACTION_PER_MINING_FLEET_UNIT_PER_YEAR THEN COMMERCIAL_MINERAL_STOCK ELSE 0		The extraction of ore from the commercial mineral stock is determined by the number of committed mining units and the extraction per mining unit per year. If the capacity exceeds the remaining reserves, then only the remaining reserves will be extracted
EXTRACTION_PER_MINING_FLEET_UNIT_PER_YEAR	2*OPERATIONAL_EFFICIENCY		The obtainable tonnage of ore per mining unit as this is expected and perceived by participating stakeholders. The parameter corresponds to assessments suggested by Rystad Energy (Rystad 2020)
OPERATIONAL_EFFICIENCY	0,72		The expected operational up-time of mining units at sea as this is expected and perceived by participating stakeholders. The parameter corresponds to assessments suggested by Rystad Energy (Rystad 2020)
"COPPER,_ZINC,_COBALT_MIX_EXTRACTION"	"ORE_GRADE_(MINERAL_CONCENTRATION)"*EXTRACTION_FROM_COMMERCIAL_MINERAL_STOCK		The extraction of copper, zinc, and cobalt is determined by the product of the ore-grade and extraction of ore from the commercial mineral stock
EXTRACTION_RATE	"COPPER,_ZINC,_COBALT_MIX_EXTRACTION"		The extraction rate here is not to be confused with the extraction rate of ore. Extraction rate here means the extraction of valuable mineral content. This model considers copper, zinc and cobalt, which makes out defined percentages of the ore extracted
TOTAL_EXTRACTION(t)	TOTAL_EXTRACTION(t—dt) + (EXTRACTION_RATE) * dt	INIT TOTAL_EXTRACTION = 0	The total extraction is determined by the size of the stock in the previous time step plus whatever is extracted through the previous time step The initial total extraction is set to 0
"ORE_GRADE_(MINERAL_CONCENTRATION)"	0,04 | 0,05 | 0,06		
DESIRED_PRODUCTION	COMMERCIAL_MINERAL_STOCK* "DESIRED_PRODUCTION/COMMERCIAL_MINERAL_STOCK"		The desired production is determined by the product of the commercial mineral stock and the desired production relative to the size of the commercial mineral stock
"DESIRED_PRODUCTION/COMMERCIAL_MINERAL_STOCK"	0,5		The desired production relative to the size of the commercial mineral stock is set to 0.5
DESIRED_TOTAL_COMMITTED_MINING_FLEET	DESIRED_PRODUCTION/EXTRACTION_PER_MINING_FLEET_UNIT_PER_YEAR		The desired fleet committed to mining is determined by the desired production per year and the capacity of one mining unit committed to mining per year

Commercial ore discovery and extraction

Variables and parameters	Equations	Properties	Comments
TOTAL_MINING_FLEET	AVAILABLE_MINING_FLEET + COMMITTED_MINING_FLEET		The total mining fleet is the sum of mining units committed to mining and available mining units
MINING_FLEET_UNDER_CONSTRUCTION(t)	MINING_FLEET_UNDER_CONSTRUCTION(t—dt) + (MINING_UNIT_BUILD_ORDER_RATE—BUILD_COMPLETION_RATE_OF_MINING_UNIT) * dt	INIT MINING_FLEET_UNDER_CONSTRUCTION = 0	The mining fleet under construction is determined by the size of the stock in the previous time step plus new build orders occurring through the previous time step subtracted the ships that are completed through the previous time step
MINING_FLEET_COMMISSION_RATE	IF DESIRED_TOTAL_COMMITTED_MINING_FLEET-COMMITTED_MINING_FLEET < 0 THEN (DESIRED_TOTAL_COMMITTED_MINING_FLEET-COMMITTED_MINING_FLEET)/TIME_TO_COMMIT_MINING_FLEET ELSE IF DESIRED_TOTAL_COMMITTED_MINING_FLEET-COMMITTED_MINING_FLEET > 0 AND DESIRED_TOTAL_COMMITTED_MINING_FLEET-COMMITTED_MINING_FLEET < AVAILABLE_MINING_FLEET THEN (DESIRED_TOTAL_COMMITTED_MINING_FLEET-COMMITTED_MINING_FLEET)/TIME_TO_COMMIT_MINING_FLEET ELSE IF DESIRED_TOTAL_COMMITTED_MINING_FLEET-COMMITTED_MINING_FLEET > 0 AND DESIRED_TOTAL_COMMITTED_MINING_FLEET-COMMITTED_MINING_FLEET > AVAILABLE_MINING_FLEET THEN AVAILABLE_MINING_FLEET/TIME_TO_COMMIT_MINING_FLEET ELSE 0		The initial mining fleet under construction is set to 0
TIME_TO_COMMIT_MINING_FLEET	1		The required time to source, negotiate, contractually commit, and mobilize a mining unit for long-term extraction contract. The parameter as this is expected and perceived by participating stakeholders. Participating stakeholders reference commitment of analogues from offshore oil and gas i.e., commitment of FPSOs and drill rigs
AVAILABLE_MINING_FLEET(t)	AVAILABLE_MINING_FLEET(t—dt) + (BUILD_COMPLETION_RATE_OF_MINING_UNIT—AVAILABLE_MINING_FLEET_SCRAPPING—MINING_FLEET_COMMISSION_RATE) * dt	INIT AVAILABLE_MINING_FLEET = 0	Available mining fleet at time t is determined by the available mining fleet at time t-dt plus earlier build orders that are completed through time t-dt subtracted what is scrapped through time t-dt and subtracted what is commissioned to extraction activities through time t-dt The initial available mining fleet is set to 0

Commercial ore discovery and extraction

Variables and parameters	Equations	Properties	Comments
MINING_FLEET_GAP	(DESIRED_TOTAL_COMMITTED_MINING_FLEET-TOTAL_MINING_FLEET-MINING_FLEET_UNDER_CONSTRUCTION)*(1-AGRESSIVE_POLICY_SWITCH) + (EXPECTED_DESIRED_FUTURE_MINING_FLEET-TOTAL_MINING_FLEET-MINING_FLEET_UNDER_CONSTRUCTION)*AGRESSIVE_POLICY_SWITCH		
MINING_UNIT_BUILD_ORDER_RATE	MAX(MINING_FLEET_GAP + AVAILABLE_MINING_FLEET_SCRAPPING + COMMITTED_MINING_FLEET_SCRAPPING; 0)		The mining fleet unit build order rate is determined by the mining fleet gap, which is the total desired number of committed mining units subtracted the total number of existing mining units, plus whatever units that need replacement to meet/maintain the desired committed mining fleet
BUILD_COMPLETION_RATE_OF_MINING_UNIT	DELAY(MINING_UNIT_BUILD_ORDER_RATE; MINING_UNIT_LEAD_TIME)		The build completion rate of mining units is determined by previous order rates and the mining unit lead time, i.e., the time it takes to build a mining unit
MINING_UNIT_LEAD_TIME	2		The time required to commission, build and deliver a mining unit as this is expected and perceived by participating stakeholders
AVAILABLE_MINING_FLEET_SCRAPPING	AVAILABLE_MINING_FLEET/AVERAGE_LIFETIME_OF_MINING_FLEET		The available mining fleet scrapping is an outflow from the available mining fleet. The mining fleet depreciates based on a defined average lifetime. This process is approximately continuous
COMMITTED_MINING_FLEET(t)	COMMITTED_MINING_FLEET(*t*—dt) + (MINING_FLEET_COMMISSION_RATE—COMMITTED_MINING_FLEET_SCRAPPING) * dt	INIT COMMITTED_MINING_FLEET = 0	Committed mining fleet at time t is determined by the size of the stock at time t-dt plus whatever is commissioned through time t-dt subtracted whatever is scrapped through time *t*-dt The initial committed mining fleet is 0
COMMITTED_MINING_FLEET_SCRAPPING	COMMITTED_MINING_FLEET/AVERAGE_LIFETIME_OF_MINING_FLEET		The committed mining fleet scrapping is an outflow from the committed mining fleet. The mining fleet depreciates based on a defined average lifetime. This process is approximately continuous
AVERAGE_LIFETIME_OF_MINING_FLEET	15		The expected average lifespan of deep-sea mining units. Dependent on utilization, maintenance, initial quality, operating environment and more. The parameter is informed by Rystad Energy (2020) and corroborated by participating experts/stakeholders

Economics

Variablesand parameters	Equations	Properties	Comments
DISCOUNTED_PROFITS(t)	DISCOUNTED_PROFITS(t—dt) + (DISCOUNTED_PROFIT_RATE) * dt	INIT DISCOUNTED_PROFITS = 0	Total discounted profits at time t are determined by the discounted profits at the previous time step plus the discounted profit rate occurring through the previous time step The initial total discounted profits are set to 0

Economics			
DISCOUNTED_PROFIT_RATE	DISCOUNT_FACTOR*(REVENUE_RATE-MINING_CAPEX_RATE-MINING_OPEX_RATE-EXPLORATION_CAPEX_RATE-EXPLORATION_OPEX_RATE-REGIONAL_SURVEY_CAPEX_RATE-REGIONAL_SURVEY_OPEX_RATE)		The discounted profit rate is determined by a product of the discount rate and the net profits, which is calculated based on the revenue and cost rates, including both operational and capital expenditure
DISCOUNT_FACTOR	1/(1 + DISCOUNT_RATE)^TIME		The discount factor is calculated according to the equation on the left
DISCOUNT_RATE	0,1		The discount rate is set to 10%
REVENUE_RATE	“PRE-PROCESSED_PRICE”*EXTRACTION_FROM_COMMERCIAL_MINERAL_STOCK		The revenue rate is determined by the product of the pre-processed price of ore and the extraction of ore from the mineral stock
“PRE-PROCESSED_PRICE”	“PRICE_OF_PROCESSED_MINERALS_IN_END-MARKET”* “PRE-PROCESSED_FACTOR_FOR_PRICE_CALCULATION”		The pre-processed price of minerals is calculated as the product of the price of processed minerals in the end market and an adjusting factor
“PRICE_OF_PROCESSED_MINERALS_IN_END-MARKET” (t)	“PRICE_OF_PROCESSED_MINERALS_IN_END-MARKET” (t—dt) + (NET_CHANGE_IN_PRICE) * dt	INIT”PRICE_OF_PROCESSED_MINERALS_IN_END-MARKET" = PRICE_BASIS*1,000,000	The price of processed minerals in the end market is used as part of the calculation of the price that miners get for their product in the model. In other words, this is not the final price that miners receive for their production in the model. The price of processed minerals in the end market is determined by the size of the stock in the previous period plus the net change in price occurring through the previous time step. This structure allows for changes in price, for example growth in price over time. However, the net change in price in the model is zero in all simulations presented here
PRICE_BASIS	38,808		The price basis is derived by calculation of the weighted deflated average monthly future price of copper, zinc, and cobalt in the period April 2010 to March 2022. The copper, zinc, and cobalt weights used are 0.778, 0.167, and 0.056, respectively. The future prices are retrieved from https://www.investing.com/commodities/copper-historical-data, https://www.investing.com/commodities/zinc-futures-historical-data, and https://www.investing.com/commodities/cobalt. Monthly inflation data from https://fred.stlouisfed.org/series/CPIAUCSL have been used to deflate the future prices
“PRE-PROCESSED_FACTOR_FOR_PRICE_CALCULATION”	(1- “PROCESSING'S_PERCENTAGE_OF_END-MARKET_PRICE”)* “ORE_GRADE_(MINERAL_CONCENTRATION)”		The pre-processed factor for price calculation is an adjusting factor used in the price calculation. This is calculated as 1 subtracted the processing sector’s percentage of the end-market price. The resulting share of the end-market price is then multiplied by the mineral percentage
“PROCESSING’S_PERCENTAGE_OF_END-MARKET_PRICE”	0,5		The fraction of end-market value of mineral bulk retained by offshore exploration/extraction sector of industry. The parameter is suggested by participating experts/stakeholders

Economics		
MINING_CAPEX_RATE	BUILD_COST_PER_PRODUCTION_SUPPORT_VESSEL*MINING_UNIT_BUILD_ORDER_RATE	The mining capital expenditure rate is determined by the product of the build cost per production support vessels and the order rate of such vessels
BUILD_COST_PER_PRODUCTION_SUPPORT_VESSEL	1,000,000,000	The cost of procuring and commissioning deep-sea mining unit. The parameter is suggested by Rystad Energy (2020) and calibrated upwards based on input from participating experts/stakeholders
MINING_OPEX_RATE	YEARLY_RATE_FOR_PRODUCTION_SUPPORT_VESSELS*COMMITTED_MINING_FLEET	The operational expenditure tied to mining is determined by the product of the number of committed mining units and the yearly rate for production units
YEARLY_RATE_FOR_PRODUCTION_SUPPORT_VESSELS	150,000,000	The annual cost of deep-sea mining units. The parameter is suggested by Rystad Energy (2020) and corroborated by participating experts/stakeholders
EXPLORATION_CAPEX_RATE	IF "SHIPS_FOR_HI-RES,_CORING_AND_EIA_BUILD_ORDER_RATE" > 0 THEN "AVERAGE_COST_OF_NEW_HI-RES,_CORING,_EIA_SHIP"* "SHIPS_FOR_HI-RES,_CORING_AND_EIA_BUILD_ORDER_RATE" ELSE 0	The capital expenditure for high-resolution survey, coring, and environmental impact assessment ships are calculated based on the corresponding build order rate and the average cost of a new build
"AVERAGE_COST_OF_NEW_HI-RES,_CORING,_EIA_SHIP"	100,000,000	The cost of procuring and commissioning multi-purpose vessel new builds. The parameter is based on input from participating experts/stakeholders
EXPLORATION_OPEX_RATE	"HI-RES_OPEX_RATE" + CORING_OPEX_RATE + EIA_OPEX_RATE	The operational expenditures tied to high-resolution surveys, coring, and environmental impact assessment rates are calculated as the sum of the operational expenditure tied to each activity
"HI-RES_OPEX_RATE"	"YEARLY_RATE_FOR_HI-RES_SHIP"* "SHIPS_COMMITTED_TO_HI-RES"	The operational expenditure tied to high-resolution surveys is determined by the number of committed ships to this activity and the yearly rate for ships committed to the activity
"YEARLY_RATE_FOR_HI-RES_SHIP"	140,000*28*6	The average annual cost of operating multi-purpose vessels. The parameter is based on input from participating experts/stakeholders
CORING_OPEX_RATE	YEARLY_RATE_FOR_CORING_SHIP*SHIPS_COMMITTED_TO_CORING	The operational expenditures tied to coring is determined by the yearly rate for a coring ship multiplied by the number of ships committed to coring
YEARLY_RATE_FOR_CORING_SHIP	140,000*28*6	The average annual cost of operating multi-purpose vessels. The parameter is based on input from participating experts/stakeholders
EIA_OPEX_RATE	YEARLY_RATE_FOR_EIA_SHIP*SHIPS_COMMITTED_TO_EIA	The operational expenditures tied to environmental impact assessment surveys are determined by the yearly rate for such a ship committed to such an activity multiplied by the number of ships committed to the activity
YEARLY_RATE_FOR_EIA_SHIP	140,000*28*6	The average annual cost of operating multi-purpose vessels. The parameter is based on input from participating experts/stakeholders
REGIONAL_SURVEY_CAPEX_RATE	AVERAGE_COST_OF_REGIONAL_SURVEY_SHIP*REGIONAL_SURVEY_BUILD_ORDER_RATE	The capital expenditure tied to the regional survey activity is determined by the product of the average cost of a regional survey ship and the regional survey ship build order rate

Economics			
AVERAGE_COST_OF_REGIONAL_SURVEY_SHIP	35,000,000		The cost of procuring and commissioning survey-vessel new-builds. The parameter is based on input from participating experts/stakeholders
REGIONAL_SURVEY_OPEX_RATE	YEARLY_RATE_OF_REGIONAL_SURVEY_SHIP*SHIPS_COMMITTED_TO_REGIONAL_SURVEY		The operational expenditure tied to the regional survey activity is determined by the product of the yearly rate of ships committed to such activity and the number of ships committed to the activity
YEARLY_RATE_OF_REGIONAL_SURVEY_SHIP	82,500*365*0,5		The average annual cost of operating regional survey vessels. The parameter is based on input from participating experts/stakeholders

Policy-assisting variables

Variables and parameters	EquationS	Properties	Comments
STOCHASTIC_SWITCH	0 | 1		This is a switch to turn on/off stochastic features in the model. It can take the value of 0 or 1. 0 activates the "Wait and See" policy setting, while 1 activates the "Anticipatory" policy setting
EXPECTED_COMMERCIAL_MINERAL_STOCK_IN_THREE_YEARS	EXPECTED_COMMERCIAL_MINERAL_STOCK_IN_TWO_YEARS + CORING_WITH_DESIRABLE_OUTCOME*EXPECTED_AVERAGE_MILLION_TONS_ORE_PER_KM2_PER_DISCOVERY-EXPECTED_DESIRED_PRODUCTION_IN_TWO_YEARS		Input variable for the "Anticipatory" policy setting
EXPECTED_COMMERCIAL_MINERAL_STOCK_IN_TWO_YEARS	EXPECTED_COMMERCIAL_MINERAL_STOCK_IN_ONE_YEAR + EIA_RATE*EXPECTED_AVERAGE_MILLION_TONS_ORE_PER_KM2_PER_DISCOVERY-EXPECTED_DESIRED_PRODUCTION_IN_ONE_YEAR		Input variable for the "Anticipatory" policy setting
EXPECTED_DESIRED_AREA_COVERED_BY_CORING_IN_TWO_YEARS	((PROSPECT_AREA_FOR_CORING + "HI-RES_SURVEY_WITH_DESIRABLE_OUTCOME"-CORING_RATE)-(PROSPECT_AREA_FOR_CORING + "HI-RES_SURVEY_WITH_DESIRABLE_OUTCOME"-CORING_RATE)*DESIRED_SHARE_OF_TOTAL_CORING_AREA_COVERED_BY_CORING_PER_YEAR + "HI-RES_SURVEY_RATE"* "EXPECTED_PERCENTAGE_OF_HI-RES_SURVEY_AREA_WITH_DESIRABLE_OUTCOME ")*DESIRED_SHARE_OF_TOTAL_CORING_AREA_COVERED_BY_CORING_PER_YEAR		Input variable for the "Anticipatory" policy setting

Policy-assisting variables

Variables and parameters	EquationS	Properties	Comments
EXPECTED_DESIRED_AREA_COVERED_BY_EIA_IN_TWO_YEARS	((AREA_WITH_CONFIRMED_ORE + CORING_WITH_DESIRABLE_OUTCOME-EIA_RATE)-(AREA_WITH_CONFIRMED_ORE + CORING_WITH_DESIRABLE_OUTCOME-EIA_RATE)*DESIRED_SHARE_OF_TOTAL_EIA_AREA_COVERED_BY_EIA_PER_YEAR + CORING_RATE*EXPECTED_PERCENTAGE_OF_CORING_AREA_WITH_DESIRABLE_OUTCOME)*DESIRED_SHARE_OF_TOTAL_EIA_AREA_COVERED_BY_EIA_PER_YEAR		Input variable for the “Anticipatory” policy setting
“EXPECTED_DESIRED_AREA_COVERED_BY_HI-RES_IN_TWO_YEARS”	(((“PROSPECT_AREA_FOR_HI-RES_SURVEY” + REGIONAL_SURVEY_WITH_DESIRABLE_OUTCOME- “HI-RES_SURVEY_RATE”) -(“PROSPECT_AREA_FOR_HI-RES_SURVEY” + REGIONAL_SURVEY_WITH_DESIRABLE_OUTCOME- “HI-RES_SURVEY_RATE")* “DESIRED_SHARE_OF_TOTAL_HI-RES_AREA_COVERED_BY_HI-RES_PER_YEAR” + REGIONAL_SURVEY_RATE*EXPECTED_PERCENTAGE_OF_SURVEY_AREA_WITH_DESIRABLE_OUTCOME)* “DESIRED_SHARE_OF_TOTAL_HI-RES_AREA_COVERED_BY_HI-RES_PER_YEAR”)		Input variable for the “Anticipatory” policy setting
EXPECTED_DESIRED_FUTURE_MINING_FLEET	EXPECTED_DESIRED_FUTURE_PRODUCTION/EXTRACTION_PER_MINING_FLEET_UNIT_PER_YEAR		Input variable for the “Anticipatory” policy setting
EXPECTED_DESIRED_FUTURE_PRODUCTION	EXPECTED_DESIRED_PRODUCTION_IN_THREE_YEARS		Input variable for the “Anticipatory” policy setting
EXPECTED_DESIRED_PRODUCTION_IN_ONE_YEAR	“DESIRED_PRODUCTION/COMMERCIAL_MINERAL_STOCK”*EXPECTED_COMMERCIAL_MINERAL_STOCK_IN_ONE_YEAR		Input variable for the “Anticipatory” policy setting
EXPECTED_DESIRED_PRODUCTION_IN_THREE_YEARS	“DESIRED_PRODUCTION/COMMERCIAL_MINERAL_STOCK”*EXPECTED_COMMERCIAL_MINERAL_STOCK_IN_THREE_YEARS		Input variable for the “Anticipatory” policy setting
EXPECTED_DESIRED_PRODUCTION_IN_TWO_YEARS	“DESIRED_PRODUCTION/COMMERCIAL_MINERAL_STOCK”*EXPECTED_COMMERCIAL_MINERAL_STOCK_IN_TWO_YEARS		Input variable for the “Anticipatory” policy setting
EXPECTED_DESIRED_SHIPS_COMMITTED_TO_CORING_IN_TWO_YEARS	EXPECTED_DESIRED_AREA_COVERED_BY_CORING_IN_TWO_YEARS/(MAXIMUM_NUMBER_OF_CORING_CAMPAIGNS_PER_SHIP_PER_YEAR*AREA_CONCLUDED_PER_CORING_CAMPAIGN)		Input variable for the “Anticipatory” policy setting

Policy-assisting variables

Variables and parameters	EquationS	Properties	Comments
EXPECTED_DESIRED_SHIPS_COMMITTED_TO_EIA_IN_TWO_YEARS	EXPECTED_DESIRED_AREA_COVERED_BY_EIA_IN_TWO_YEARS/ "HI-RES_SURVEY_SHIP_KM2/MONTH"*EIA_AREA_AMPLIFIER		Input variable for the "Anticipatory" policy setting
"EXPECTED_DESIRED_SHIPS_FOR_HI-RES_IN_TWO_YEARS"	"EXPECTED_DESIRED_AREA_COVERED_BY_HI-RES_IN_TWO_YEARS"/ "HI-RES_SURVEY_SHIP_KM2/MONTH"		Input variable for the "Anticipatory" policy setting

Seed variables used in Monte Carlo runs

Variables and parameters	Equations	Properties	Comments
SEED_CORING	RANDOM GENERATED VALUE		Seed variable
"SEED_HI-RES_SURVEY"	RANDOM GENERATED VALUE		Seed variable
SEED_OCCURENCE	RANDOM GENERATED VALUE		Seed variable
SEED_REGIONAL_SURVEY	RANDOM GENERATED VALUE		Seed variable

Simulation run specs

Total	Count	Including array elements
Variables	191	191
Stocks	37	37
Flows	49	49
Converters	105	105
Constants	50	50
Equations	104	104
Graphicals	0	0

Run specs	
Start time	0
Stop time	60
DT	1/1000
Fractional DT	True
Save interval	0,001
Sim duration	0
Time Units	Years
Pause interval	0
Integration method	Euler
Keep all variable results	True
Run by	Run
Calculate loop dominance information	False

Appendix 2

EXPERT INTERVIEWS
(name and affiliation anonymized)

	Name	Category	Expert Field	Affiliation
1	N/A	Industry	Geoscience + technology	N/A
2	N/A	Science	Geoscience	N/A
3	N/A	Industry	Incubator	N/A
4	N/A	Science	Geoscience + incubator	N/A
5	N/A	Industry	Technology	N/A
6	N/A	Industry	Technology + geoscience + policy	N/A
7	N/A	Industry	Risk management	N/A
8	N/A	Industry	Geoscience + technology	N/A
9	N/A	Government	Policy	N/A
10	N/A	Government	Policy	N/A
11	N/A	Science	Geoscience	N/A
13	N/A	Science	Geoscience	N/A
14	N/A	Industrial-media	Geoscience	N/A
15	N/A	Industry	Technology	N/A
16	N/A	Industry	Business development	N/A
17	N/A	Industry	Technology	N/A
18	N/A	Industry	Business development	N/A
19	N/A	Industry	Geoscience	N/A
20	N/A	Industry	Geoscience	N/A

Appendix 3

INTERVIEW GUIDE
Participant: < INSERT >
Time/Place: < INSERT >

#	Interview step	Respondent	Comment/observation
1	Introduce authors		
2	Declaration of intent - This is a research project. Respondents will be anonymous. Potentially identified in general terms: i.e., "Representative from an E&P company," "Academic Researcher," "Cluster representative" etc		
3	Purpose of the research project - Map and understand the emerging structure regarding exploration and extraction in deep-sea mining - Stakeholder expectation to resource potential and economic potential - Explore policy space		
4	Purpose of interview - Elicit information from stakeholders - Identify model structure shortcomings or errors - Identify missing structures/relationships - Identify unnecessary structure and detail - Elicit parameter values - Elicit information about uncertainty/distributions		
5	Describe work up until this point -Observation of industry -GMB sessions: with students, with NOSP -Seed model development -First round of interviews completed		
6	Short Intro to SD/SFD - Build simple model to introduce the building blocks in system dynamics modeling (simple example from population dynamics)		
7	Introduce model by sectors -Exploration main motor -Exploration fleet -Extraction fleet -Show model run		
8	Introduce exploration sector - Is the structure sound? - Any missing elements? - Any missing feedback - Is something superfluous? - Parameter values? - Uncertainty?		
9	Introduce exploration fleet sector - Is the structure sound? - Any missing elements? - Any missing feedback - Is something superfluous? - Parameter values? - Uncertainty?		
10	Introduce extraction fleet sector - Aggregated representation - Is the structure sound? - Any missing elements? - Any missing feedback - Is something superfluous? - Parameter values? - Uncertainty?		
11	Ask about… - Thoughts on permitting policies		
12	Any other comments?		

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Declarations

Conflict of interest The authors have contributed to the project on equal terms as 50/50 co-authors. The authors have no financial or non-financial interests that are directly related to the work submitted for publication. The author, Lars-Kristian Trellevik, who has 15 years of onshore and offshore industry experience with deep water subsea operations, works as an external technical consultant for a company that aims to take part in the potential future marine mineral industry in Norway.

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10. Appendix IV

Mineral Economics
https://doi.org/10.1007/s13563-023-00379-x

ORIGINAL PAPER

Exploring exploration—how to look for deep-sea minerals

Lars-Kristian Lunde Trellevik[1]

Received: 15 February 2023 / Accepted: 1 May 2023

Abstract

In the spring of 2023, the subsea industry in Norway is gearing up for an opening of the Norwegian continental shelf (NCS) for deep-sea mineral exploration and extraction. Existing research indicates that the profitability of deep-sea mining with today's technology heavily depends on high ore grades. This study explores the potential for emerging techno-operational concepts for exploration to affect the profitability of seafloor massive sulfide (SMS) industry on the NCS. By way of computer simulation, the study analyzes technologies currently or soon poised to enter the subsea market concerning their advantage or disadvantage for the SMS industry on the NCS. The study indicates a significant advantage in developing geophysical sampling technology for assessing mineral resources and some advantage in developing unmanned surface vessels for regional surveys. It further indicates that developing fleet-operated autonomous underwater vehicle concepts for high-resolution surveys is not only moot but possibly counterproductive. The study thereby contributes techno-operational insight for a budding industry currently looking for technology to improve commercial prospects.

Keywords Deep-sea mining · Marine minerals · Seafloor massive sulfide deposits · Exploration technology

JEL classification C63 · D24 · D25 · O25 · O32 · O33 · Q30 · Q32 · Q33

Deep-sea mining on the NCS: context and emerging technologies

In October 2022, the Norwegian Ministry of Petroleum and Energy published its Impact Assessment for exploring and extracting deep-sea minerals on the NCS (Ministry of Petroleum and Energy, 2022b). The hearing document and ministerial press release highlight that deep-sea minerals may become pivotal in transitioning towards a low-emission society and an important emerging industry for Norway. The Norwegian Ministry of Petroleum and Energy further states that more knowledge and data about the deep-sea environment and potential mineral resources are required for responsible resource management. The ministry suggests that opening the NCS for commercial mineral exploration is pivotal for acquiring more and better data—as the current state of exploration is limited. The ministry emphasizes that an opening for commercial actors commencing with mineral exploration will significantly increase the data retrieval and knowledge generation across disciplines studying the deep-sea in the relevant region. The Norwegian parliament is scheduled to vote over the opening of the NCS for mineral exploration and extraction in the spring parliamentary session of 2023. Upon a potential opening, commercial entities may apply for exploration licenses. The Norwegian petroleum directorate will administer the licensing process (Ministry of Petroleum and Energy, 2022c, 2022a).

Bang and Trellevik (2022) present a comprehensive stochastic simulation model and analysis of the emergence of a Norwegian deep-sea mining industry targeting SMS. They indicate that the cost of exploration will strongly affect the overall profitability of Norway's emerging deep-sea mineral industry. Furthermore, their findings suggest that net-present value is strongly affected by discounting—as the cost of exploration is substantial and accumulated at a much earlier stage than the income for extracted minerals.

This article explores how three different but established techno-operational concepts for seabed and sub-seabed surveys and exploration may affect the aggregated commercial performance of the emerging SMS industry.

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Specifically, this study simulates how evolving technologies may affect the cost efficiency of SMS mineral exploration, thereby altering the effect of discounting on the net-present value of the aggregated SMS industry on the NCS. This study applies the model developed by Bang and Trellevik but further develops and applies this model framework to test the effect of techno-operational concepts. The concepts are abstracted as alternative parameterization of structural elements already implemented in the model. The parameters are tested separately and in combination, and the sensitivity to the parameterization is analyzed. This provides a methodical and formal approach to disentangle the effect of different techno-operational pathways in the complex and uncertain future of SMS exploration and extraction; as such, this study provides techno-operational policy advice for innovation and development investment in the emerging SMS industry.

The concepts explored in this study are unmanned surface vessels (USVs), fleet or swarm operation of autonomous underwater vehicles (AUVs), and enhanced remote geophysical methodology for assessing mineralization on the seabed. These techno-operational concepts are all recognized as focus areas for innovation and development, currently pursued by the subsea-service and mineral exploration industry (Argeo 2022; ECA Group 2022; Fugro 2022; Konberg Maritime 2022; Malehmir et al. 2012; Ocean Infinity 2022; Sahoo et al. 2013, 2019; Yu et al., 2019).

The contribution of this study is applied insight for policymakers, industry, and research communities involved in deep-sea minerals on the Norwegian continental shelf and beyond. This study does not consider how the projected emergence of DSM on the NCS would affect the economies of local communities. The study assumes a high level of aggregation and is limited to exploring aggregated effects of innovation and the proliferation of specific emerging technologies at the projected industry level. Through stochastic simulation and sensitivity analysis, this study facilitates clear thinking and qualified decision-making in a highly uncertain domain, aligning with Zeckhauser's thoughts on "investing in the unknown and unknowable" (Zeckhauser, 2010). As such, this study also contributes a methodological framework for clear thinking and methodic assessment of emerging technologies of unknown or uncertain effect in industrial domains where a baseline of current technological efficacy may be assessed.

This study suggests that developing a remote geophysical methodology for assessing mineral deposits will significantly improve the economic outlook of deep-sea massive sulfide seamount deposits. USV technology, in combination with geophysical methods, is also a profitable endeavor. At the same time, operating swarms of AUVs during high-resolution surveys may reduce the net present value of SMS exploration and extraction and henceforth be counterproductive.

Methods

This study builds on a published model and implements emerging techno-operational concepts in an established model framework. Information about emerging technologies is drawn from reviewing academic literature, technical and operational information provided by industry stakeholders, and by way of qualitative research.

The qualitative research includes the author's attendance and participation at 11 academic, technical, and industry conferences addressing deep-sea minerals and subsea exploration technology. Several stakeholders have presented techno-operational concepts. Qualitative data is also elicited and qualified through 17 semi-structured, disconfirmatory interviews with diverse stakeholders within the marine minerals and subsea exploration industry and academia.

The academic literature on the three different technologies to be tested is plentiful at engineering research's technical and micro levels. However, the opposite is true for techno-economic analysis at an aggregated industry level; this relates to the novelty inherent in any emerging technology—and the time required for academia to provide empirical observation and evidence of techno-operational performance.

Therefore, the structural abstraction and parameterization of the techno-operational concepts are synthesized through triangulation between qualitative data, academic literature, and data provided openly by commercial stakeholders. In summary, this multi-faceted approach has rendered a well-defined techno-operational understanding of the concepts and their applicability as model abstractions, as well as a range of parameters for cost and expected efficiency of the emerging concepts that enable simulation and policy analysis. It is stressed that these concepts are still under development and far from being supplied at scale—the policy parameters must be considered approximate and uncertain. In acknowledgment of uncertainty—the study assumes an exploratory and conceptual approach. In order to mitigate uncertainty and shed light on the cost efficiency range potential of the different techno-operational concepts under different development trajectories, the study employs sensitivity analysis.

The base model by Bang and Trellevik presents a baseline result where the SMS industry may or may not prove profitable in terms of net-present value depending on ore-grade and investment policy. The ore-grade scenarios are 3, 4, and 5% concentrations of a mineral mix of copper, zinc, and cobalt. The investment policy "Wait and See" requires considerable mineral resources to be confirmed before investment in extraction technology is executed. In contrast, the "Anticipatory" policy commences with investment at an earlier stage and is less risk-averse. The model is simulated stochastically, and results are averaged over 1000 Monte Carlo simulations for each policy configuration. The baseline suggests that with a 3% ore grade and a "Wait and See" investment policy, the NPV is negative 980 million USD, while with a 5% ore grade and "Anticipatory" investment policy, the aggregated industry generates a 2.53 billion USD NPV over the simulated time-horizon. All scenarios with an ore grade above 4% yield positive NPV in the baseline results. The study concludes that discounting and the long time between accruing cost of exploration and retrieving revenue from extracted minerals is the major challenge for the profitability of the industry as, i.e., the net non-discounted value of the 3% "Wait and See" scenario generates a profit of 10.85 billion USD while the NPV value is negative. The "Results" section discusses the baseline results in further detail.

Simulation results presented in this study are generated with the same stochastic parameters, numerical integration method, and Monte Carlo parameters as the simulations presented by Bang & Trellevik. This allows for comparative policy analysis with the baseline results presented and, as such, a relative quantitative framework for understanding the plausible policy impact of the different techno-operational concept scenarios.

As for any study of the future—this study offers little certainty and lays no claim to accurate prediction. No commercial-scale deep-sea SMS industry is currently established anywhere (Bang & Trellevik, 2022; Kaluza et al., 2018). Nautilus Mining Ltd came close to extracting minerals from the Solwara 1 prospect. However, the company filed for bankruptcy in August 2019—and no other initiatives have to date come as close to the commencement of commercial DSM (Gross, 2022). Furthermore, while the techno-operational concepts studied here are well-described and implemented at varying maturity levels, neither of these concepts has been tested at scale for performance in an aggregated deep-sea mineral context. This study, therefore, with the perspective that "structure generates behavior," elicits model structure and parametrization from the established techno-operational concepts and simulates how these may drive behavior and performance in the context of SMS exploration on the NCS (Forrester, 1980; Kwakkel & Pruyt, 2015; Lane, 2000; Lane & Oliva, 1998). Through simulation and sensitivity analysis, meaningful insight and clear thinking on possible future behavior may be obtained as the concepts provide a structural foundation for synthetic analysis. The technological concepts discussed here are all incremental innovations anticipated to materialize for some time. As such, the scope of this study lends itself well to the thesis that "…the future is embedded in the past; it is the projection of the past through the present" (Poli, 2010). This, however, implicitly infers complexity and significant uncertainty. Dynamic simulation is commonly used to analyze complex and uncertain problems, developing over time, and is, therefore, a valuable approach for developing insight in such domains (Pruyt, 2007).

Model structure

The model encompasses five sectors (Fig. 1). (1) "Exploration process" tracks the seabed exploration for minerals from unexplored areas through 3 levels of declining geographic area and increasing levels of data resolution confirming or disconfirming mineral deposits. The final step of the exploration process aggregates area with positive finds going through environmental impact assessments. Areas deemed without commercially viable mineral resources are aggregated in a stock of the discarded area. The exploration process and the area flow through this process are governed by the sector (2) "Exploration technology."

Exploration technology includes the application of four different vessel configurations where regional surveys are executed with relatively small and low-cost vessels, performing seafloor surveys from hull-mounted or towed acoustic and magnetic sensors. These vessels cover large areas of seabed at relatively low cost—and at relatively low data resolution. Areas deemed attractive by exploration companies are then surveyed in greater detail. Finally, high-resolution surveys are executed from relatively large vessels where autonomous or remotely operated vehicles are operated close to the seabed. These operations cost more, as they involve advanced subsea equipment and large ships with considerable crew onboard and onshore support.

The same category of ships is applied to offshore platforms during coring operations and environmental impact assessments. Coring involves drilling into the seabed and retrieving geological core samples of the seabed. This process is tedious, costly, and covers a limited area per time unit. Still, it does provide explorations with high certainty, ground-truth, and data on geological composition and mineralization. Environmental impact assessment involves documenting and assessing the possible environmental impact of mining in areas with confirmed mineral deposits. The model prioritizes the use of these vessels first for environmental impact assessment, second for coring, and third for high-resolution surveys—to pass confirmed mineral deposits through to mining activities.

(3) "Mining process" is the sector in the model where ore is extracted from the seabed, and the pace and magnitude of this activity are governed by the (4) "Mining technology" sector. This model sector includes all logistics, vessels, and subsea equipment involved in bringing ore from the seabed through the water column to the deck and from there to the shore. The model does not include onshore processing or

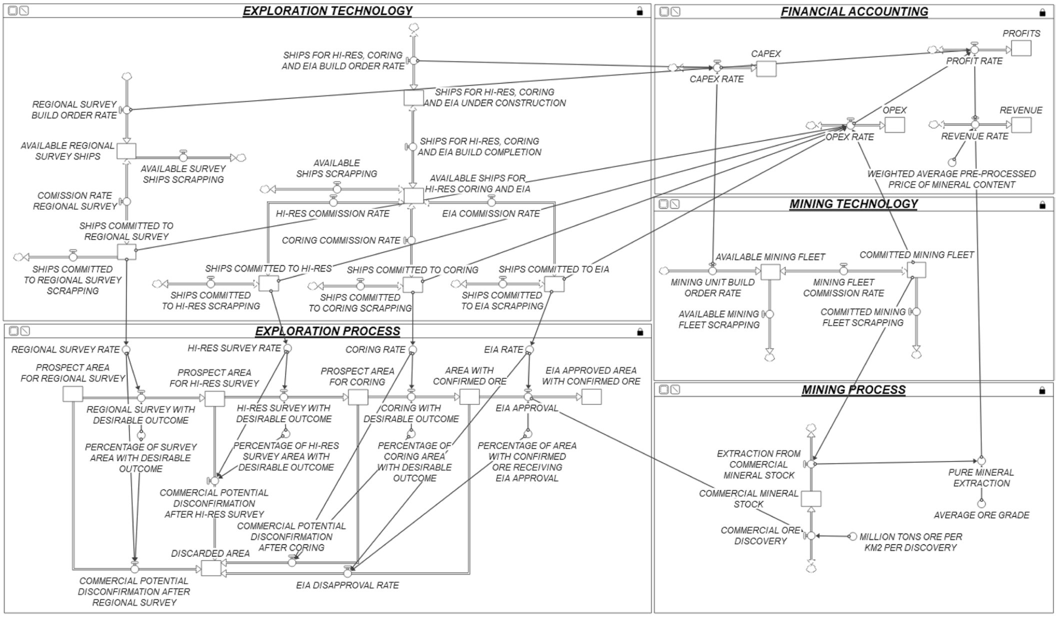

Fig. 1 Simplified high-level model overview (Bang & Trellevik, 2022)

refinement of minerals, which would add considerable complexity to the model and the analysis. This study's scope is to explore the projected efficacy of subsea exploration technology—including onshore processing will not add to the analysis. The study therefore considers ore-value "on deck" rather than value of the refined mineral value in the global commodities market.

The (5) "Financial accounting" sector tracks spending and income for all technology sectors in the model. This sector is essential in that it governs investment in equipment—the model is simulated with two different spending policies where a "Wait and see" policy will have substantial confirmed resources available before investing in more technology. In contrast, the "Anticipatory" policy will show more risk-seeking behavior where investments are made with less confirmed mineral ore on the seabed.

Simulation

Throughout the exploration process, the area considered interesting for further evaluation or impact assessment is governed by four stochastic parameters. This stochasticity is the reason for running 1000 Monte Carlo simulations for every policy scenario and providing the average of this simulation as the result—as stochasticity will generate a distribution of varying results, reflecting the uncertainty related to the distribution of minerals on the seabed.

The model is simulated with three different average mineral mix ore-grade scenarios. These scenarios are simulated to accommodate the uncertainty of what average ore-grades will be proven for SMS deposits on the NCS. The three ore-grade scenarios are the low scenario of 3%, the medium scenario of 4%, and the high scenario of 5%. The mineral mix constitutes copper, zinc, and cobalt—the percentage indicated is the total percentage containing mineral mix in the entire ore body. The mineral mix includes assumptions of 77.8% Cu, 16.7% Zn, and 5.6% Co. It should further be noted that SMS deposits on the NCS have been demonstrated to include cobalt—which is an anomaly when considering SMS deposits studied in other regions (Bang & Trellevik, 2022; Pedersen & Bjerkgård, 2016). The model employs a price matrix based on historical commodity prices for the different commercial minerals in the mineral mix, embedded in the "FINANCIAL ACCOUNTING" sector of the model.

Policies

Three techno-operational concepts are implemented in the model and examined. First, the three concepts identified as *Policies A*, *B*, and *C* are introduced to the model by changing parameters embedded in the model structure in the “Exploration technology,” “Exploration process,” and “Financial accounting” model sectors. Then, the three policies are further tested in all possible combinations.

Policy A: Unmanned surface vessels (USVs)

are ships or crafts able to operate without any personnel onboard. USVs can be either remotely operated via datalink, pre-programmed, or autonomously. USVs can carry any number of sensors or instruments—and be used for a wide array of purposes (Rumson, 2021; Zhang et al., 2019). In the context of this study, USVs are imagined as a replacement for survey vessels employed in regional surveys of deep-sea mineral prospecting. In this context, USVs would be equipped with multi-beam echo sounders, side-scan sonars, and other sensors. The significant impact of replacing a survey vessel with a USV is the removal of all personnel offshore—and the logistics involved in maintaining crews offshore. Removing all offshore crews further affords significant risk mitigation and allows for elongated operating seasons in arctic waters (Rumson, 2021). The USV is henceforth significantly less costly to build and operate, and it can operate for a more extended period of the year and thereby be more productive. There are several companies involved in developing USV technology for this purpose, including Konberg Maritime (Kongsberg Maritime, 2022), ECA Group (ECA Group, 2022), Fugro (Fugro, 2022), Sea-Kit (Sea-Kit, 2022) and Ocean Infinity/Armada (Ocean Infinity, 2022). These companies unanimously claim increased operating windows and fractional cost relative to crewed offshore operations—and there is little reason to doubt that this is the case as remote operations of smaller unmanned crafts and vessels must be more cost-effective than the conventional alternative. It should be noted that also USVs require monitoring, maintenance, and repair—which may amount to considerable cost as they, in this scenario, will be operated far from people and workshops; these costs are included in the aggregated parameterization terms of efficiency and cost. The USV concept is identified in this study as “Policy A”; please refer to Table 1 for policy implementation in simulation runs.

Policy B: Fleet operation of autonomous underwater vehicles (FAUV)

is a technological and operational concept where multiple AUVs are launched and operated from a single crewed surface vessel. Several companies are advancing this concept, most notably Ocean Infinity and Argeo (Argeo, 2022; Ocean Infinity, 2022). This concept

Table 1 Policy parameters

Original Parameter Name	Original Parameter Value	Policy Parameter Value
Policy A		
Regional survey speed per year	REGIONAL_SURVEY_KTS_CONVERTER (converting nautical miles surveyed per day to Km surveyed per day) * 18 (hours operation per day) * 28 (days operation per month) * 6 (months—survey season) km/year	REGIONAL_SURVEY_KTS_CONVERTER (converting nautical miles surveyed per day to km surveyed per day) *18 (hours operation per day) * 28 (days operation per month) * 10 (months—survey season) km/year
Average cost of regional survey ship	35000000 USD (building/procurement cost)	680000 USD (building/procurement cost)
Yearly rate of regional survey ship	82500 (USD day rate) * 365 (operational days) * 0.5 (year—operational season) USD/year	8250 (USD day rate) * 365 (operational days) * 0.83 (year—operational season) USD/year
Policy B		
Yearly rate for hi-res ship	140,000 (day rate USD) * 28 (days operation per month) *6 (months—survey season) USD/year	200000(day rate USD) * 28 (days operation per month) *6 (months—survey season) USD/year
Hi-res survey swath	0.5 km (lateral width of ecco-sounder/sensor footprint per scan)	0.5*8 (multiplicator of footprint by adding AUVs to operation) km (lateral width of ecco-sounder/sensor footprint per scan)
Policy C		
Yearly rate for coring ship	140,000 (day rate USD) * 28 (days operation per month) *6 (months—survey season) USD/year	160000 * (day rate USD) * 28 (days operation per month) * 6 (months—survey season) USD/year
Area concluded per coring campaign	0.2125 km^2 (area concluded by one coring campaign)	0.2125 * 10 (area multiplicator introduced by adding geophysical sensing to coring campaign) km^2 (area concluded by one coring campaign)

significantly increases the seabed survey footprint of a single surface vessel, with marginal increases in vessel crews. The increased efficiency is made possible by advanced robotics and autonomous technology and has been under development for over two decades (Sousa et al., 1997; Wang et al., 2021). The Fleet AUV technology concept has yet to become commercially widespread, but several projects have been completed. Notably, in 2018 Ocean Infinity conducted highly effective seabed surveys employing as many as eight AUVs simultaneously in the search for the lost MH370 flight (Ocean Infinity, 2018, 2022; Xu and Jiang, 2021). This study identifies this concept as "Policy B"; please refer to Table 1 for policy implementation in simulation runs.

Policy C: Geophysical sampling

In Bang & Trellevik's model, coring is a significant cost driver on the exploration side (2022). Coring is a common geological sampling technique on land involving drilling into the ground and retrieving continuous rock samples to identify and classify orebodies. A dense matrix of cores is required to ascertain the ore-grade throughout a deposition. While subsea coring has been executed for many decades, it remains complicated and costly, and there are only a limited number of successful coring campaigns targeted at SMS deposits (Holtedahl, 1959; Murton et al., 2019; Spagnoli et al., 2016). New technological concepts and applications may reduce the reliance on extensive subsea coring for identifying and evaluating deep-sea mineral deposits by supplementing or filling in gaps between physical cores with geophysical data that can be correlated to physical samples. These technologies include, but may not be limited to, modified seismic applications, electro-magnetic sampling, self-potential anomaly measurements, atomic dielectric resonance spectroscopy, and combinations of these technologies (Almqvist and Mainprice, 2017; Biswas 2018; Malehmir et al. 2012; Stove et al. 2013, 2009). Although there is little in the way of proven subsea application of such technologies in this category, this study assumes that these technologies will be adapted, mature, and become available as they are both theoretically possible and under development. These technologies are likely, and expected, to vastly increase the assessment area during a coring campaign—as geophysical sampling will be used to augment physical coring data by providing calibrated remotely measured or sampled data points for interpolation between physical core samples. Geophysical sampling will be executed from the same vessel and parallel with ongoing coring operations. Thus, geophysical sampling will enable surveys of a considerably larger area to be assessed for prospectivity within the same operational time frame as what is obtainable with conventional coring operations alone. To understand the space for innovation, this study includes geophysical sampling as a concept for exploratory model analysis. This study identifies this concept as "Policy C." Please refer to Table 1 for policy implementation in simulation runs.

Policies A, *B*, and *C* are implemented in the following way.

Policy A is modifying the yearly survey speed as the USVs are assumed to be able to operate for a more extended season than conventional survey ships. As a result, the build cost (CAPEX) and operational cost are also significantly reduced.

Policy B is modifying the yearly rate for high-resolution surveys as there is a cost impact for mobilizing and operating 8 AUVs. In addition, the survey footprint, or swath, is also increased by a multiple of eight, aligned with the operational configuration of Ocean Infinity's MH360 search operation (Ocean Infinity, 2018). Thus, *Policy B* still utilizes vessels from the vessel pool included in the model at a different cost.

Policy C is implemented by increasing the operational cost of the coring ship—as there will be a cost impact of mobilizing geophysical sampling in addition to coring equipment. The area covered by coring is increased tenfold. This increase in efficiency is aligned with expectations expressed by interviewed stakeholders engaged with such techno-operational concepts. As mentioned above, Geophysical sampling is expected to operate simultaneously with conventional coring. Geophysical samples will be correlated and calibrated to physical cores retrieved and qualify a larger area with interpolated prospective analysis in between cores based on geophysical sampling samples. This will significantly increase the footprint covered by a coring campaign. Like *Policy B*, *Policy C* still utilizes vessels from the vessel pool included in the model, yet at a different cost.

As described above, the model is simulated with the same stochastic parameters, ore-grade scenarios, and investment policies as in the original model. In addition, each new policy is tested separately and in all possible combinations on top of the original model configurations. This renders the following simulation matrix for innovation policy baseline results (Table 2).

Results

The following section reports the simulation results compared to the baseline results provided by Bang and Trellevik. It should be noted that these results represent prognostic simulated system behavior and not empirical data. The following data is included in all tables in this section.

Table 2 Innovation policy baseline simulation matrix—42 different simulation configurations run across 1000 Monte Carlo simulations each

Policy	Average ore-grade of mineral mix			Average ore-grade of mineral mix		
	"Wait and See"			"Anticipatory"		
Policy A	0.3	0.4	0.5	0.3	0.4	0.5
Policy B	0.3	0.4	0.5	0.3	0.4	0.5
Policy C	0.3	0.4	0.5	0.3	0.4	0.5
Policy A + B	0.3	0.4	0.5	0.3	0.4	0.5
Policy A + C	0.3	0.4	0.5	0.3	0.4	0.5
Policy B +C	0.3	0.4	0.5	0.3	0.4	0.5
Policy A + B + C	0.3	0.4	0.5	0.3	0.4	0.5

(1) Exploration capex, summarizing all capital investment expenditure for the exploration process. (2) Exploration opex, summarizing all operational costs associated with exploration. The policies will directly affect exploration capex and exploration opex. (3) Mining capex summarizes capital investment expenditures for mining units and associated logistical elements. The policies will indirectly affect this cost via efficiency in the exploration process. (4) Mining opex summarizes operational expenditure for the mining activities. Mining opex will only be indirectly affected by the introduced policies. (5) Total extraction is reported in million tons of mineral mix. (6) Total revenue is the aggregated revenue throughout the simulation period. (7) Net non-discounted value reports the aggregated revenue less the aggregated cost. (8) Net present value (NPV) is the profit adjusted for discounting through the simulation horizon. "Baseline results" refer to the results generated by the original model (Table 3).

The baseline results from the original model indicate that it is not given that a deep-sea SMS exploration and extraction industry on the NCS will be profitable. NPV varies from a negative 980 million USD low to a profit of 2.53 billion USD throughout the simulation horizon. The results also indicate that the ore-grade of the extracted minerals is a significant driver for the industry's profitability; however—of significance is also the investment policy pursued. The "Anticipatory" policy generates a significantly higher profit in the high (5%) ore-grade mineral mix than does the "Wait and See" policy, showing an NPV improvement of 1.2 billion USD with the less risk-averse policy. The results further show a significant difference between non-discounted and net-present values, indicating that discounting is a significant challenge for this industry's prospective profitability. This arises from a long temporal horizon between cost propagating throughout the exploration process, and initial investment in the mining process before revenue is generated by bringing mineral commodities to shore. In short, this suggests that reducing the time horizon between initial exploration and minerals reaching markets is essential, as is the cost of exploration. *Policies A*, *B*, and C and their possible combinations explore this assumed room for improvement related to emerging techno-operational concepts (Table 4).

Policy A's results indicate that the net present value is marginally increased across ore-grades and investment policies. However, the exploration capex and exploration opex are only marginally reduced. The regional survey in the original model constitutes a relatively small portion of the total exploration process cost. Therefore, this policy cannot

Table 3 Overview of baseline simulation results. Average values across 1000 Monte Carlo runs (Bang & Trellevik, 2022)

Resource scenario	Policy	Expl. capex (bill. $)	Expl. opex (bill. $)	Mining capex (bill. $)	Mining opex (bill. $)	Total extraction (mill. tons)	Total revenue (bill. $)	Net non-disc. value (bill. $)	Net present value (bill. $)
Low average ore-grade (3% mix of copper, zinc, and cobalt)	Wait and See	3.21	6.96	7.93	6.32	1.82	35.28	10.85	− 0.98
	Anticipatory	3.56	6.96	5.36	6.28	1.81	35.10	12.92	− 0.97
Medium average ore-grade (4% mix of copper, zinc, and cobalt)	Wait and See	3.21	6.96	7.93	6.32	2.42	47.04	22.60	0.17
	Anticipatory	3.56	6.96	5.36	6.28	2.41	46.80	24.61	0.78
High average ore-grade (5% mix of copper, zinc, and cobalt)	Wait and See	3.21	6.96	7.93	6.32	3.03	58.80	34.35	1.33
	Anticipatory	3.56	6.96	5.36	6.28	3.01	58.50	36.30	2.53

Table 4 Overview of simulation results with Policy A. Average values across 1000 Monte Carlo runs with baseline results in brackets

Resource scenario	Policy	Expl. capex (bill. $)	Expl. opex (bill. $)	Mining capex (bill. $)	Mining opex (bill. $)	Total extraction (mill. tons)	Total revenue (bill. $)	Net non-disc. value (bill. $)	Net present value (bill. $)
Low average ore-grade (3% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.87 [6.96]	7.89 [7.93]	6.32 [6.32]	1.81 [1.82]	35.21 [35.28]	10.93 [10.85]	− 0.92 [− 0.98]
	Anticipatory	3.57 [3.56]	6.88 [6.96]	5.36 [5.36]	6.28 [6.28]	1.81 [1.81]	35.08 [35.10]	12.97 [12.92]	− 0.90 [-0.97]
Medium average ore-grade (4% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.87 [6.96]	7.89 [7.93]	6.32 [6.32]	2.42 [2.42]	46.95 [47.04]	22.66 [22.60]	0.24 [0.17]
	Anticipatory	3.57 [3.56]	6.88 [6.96]	5.36 [5.36]	6.28 [6.28]	2.41 [2.41]	46.77 [46.80]	24.65 [24.61]	0.85 [0.78]
High average ore-grade (5% mix of copper, zinc, cobalt)	Wait and See	3.20 [3.21]	6.87 [6.96]	7.89 [7.93]	6.32 [6.32]	3.02 [3.03]	58.68 [58.80]	34.38 [34.35]	1.40 [1.33]
	Anticipatory	3.57 [3.56]	6.88 [6.96]	5.36 [5.36]	6.28 [6.28]	3.01 [3.01]	58.46 [58.50]	36.33 [36.30]	2.60 [2.53]

generate a positive NPV for the lowest ore-grade scenario (Table 5).

Policy B is increasing the exploration capex across all scenarios and investment policies—but is simultaneously reducing the exploration opex. This indicates that the slightly more costly hi-resolution survey configuration, including eight AUVs per vessel, is more efficient in operation but more costly to procure. The same effect can be identified for mining capex and opex; *Policy B* is driving up investment costs but is slightly reducing or neutral on operational costs during the mining operations. As a result, net present value is only marginally affected by *Policy B* and has a neutral or slightly positive effect. Interestingly, NPV with *Policy B* is lower than what is evident with *Policy A* (Table 6).

Policy C is vastly outperforming *Policies A* and *B*. Geophysical sampling technology is generating positive NPV within the lowest ore-grade scenario under the "Wait and See" regime, turning a profit of 1.54 billion USD. The Baseline scenario here is negative 980 million USD. In the 5% ore-grade and "Anticipatory" investment strategy, *Policy C* generates a net present value more than 2.5 times the baseline results. Exploration Capex and Exploration Opex are both significantly lower than what is found in *Policies* A and *B;* this is a significant factor in the overall performance of *Policy* B (Table 7).

Policy A + *B* generated improved NPV results for both simulations in the 3% ore-grade scenario. In the 4 and 5% scenarios, apart from the 4% ore-grade and "Anticipatory" scenario, *Policy A* alone generates a higher Net Present Value than the combined *A* and *B* policies. The combined policy outperforms *Policy B* in terms of NPV across all simulations (Table 8).

The combined *Policy A* + *B* generates significantly lower Exploration Capex and Exploration Opex than *Policies A* or *B* or the combination of the two policies. *Policy A* +*B*

Table 5 Overview of simulation results with Policy B. Average values across 1000 Monte Carlo runs with baseline results in brackets

Resource scenario	Policy	Expl. Capex (bill. $)	Expl. opex (bill. $)	Mining capex (bill. $)	Mining opex (bill. $)	Total extraction (mill. tons)	Total revenue (bill. $)	Net non-disc. value (bill. $)	Net present value (bill. $)
Low average ore-grade (3% mix of copper, zinc, cobalt)	Wait and See	3.24 [3.21]	6.81 [6.96]	8.30 [7.93]	6.31 [6.32]	1.82 [1.82]	35.23 [35.28]	10.56 [10.85]	− 0.98 [− 0.98]
	Anticipatory	3.60 [3.56]	6.80 [6.96]	5.38 [5.36]	6.27 [6.28]	1.80 [1.81]	35.01 [35.10]	12.94 [12.92]	− 0.91 [− 0.97]
Medium average ore-grade (4% mix of copper, zinc, cobalt)	Wait and See	3.24 [3.21]	6.81 [6.96]	8.30 [7.93]	6.31 [6.32]	2.42 [2.42]	46.97 [47.04]	22.30 [22.60]	0.11 [0.17]
	Anticipatory	3.60 [3.56]	6.80 [6.96]	5.38 [5.36]	6.27 [6.28]	2.41 [2.41]	46.67 [46.80]	24.60 [24.61]	0.81 [0.78]
High average ore-grade (5% mix of copper, zinc, cobalt)	Wait and See	3.24 [3.21]	6.81 [6.96]	8.30 [7.93]	6.31 [6.32]	3.03 [3.03]	58.72 [58.80]	34.03 [34.35]	1.19 [1.33]
	Anticipatory	3.24 [3.56]	6.81 [6.96]	6.31 [5.36]	6.28 [6.28]	3.03 [3.01]	58.72 [58.50]	34.03 [36.30]	1.19 [2.53]

generates higher NPV than *Policy C*. Henceforth, combining USVs with geophysical sampling is beneficial (Table 9).

The combined *Policy B* + *C* generates a similar exploration capex to *Policy A* + *C,* yet a slightly lower exploration opex. *Policy B* + *C* produces an exploration opex of 0.88 billion USD across all scenarios, while *Policy A* + *C* shows an exploration opex of 0.95 billion USD across scenarios. Interestingly *Policy B* + *C* renders slightly higher mining capex and mining opex than *Policy A* + *C* Across all scenarios. *Policy B* + *C* produces a lower NPV than *Policy A* + *B*, most notably in the 5% ore-grade and "Anticipatory" scenario where *Policy B* + *C* generates an NPV of 5.70 billion USD, 760 million USD lower than *Policy A* + *C* (Table 10).

Policy A + *B* + *C* Generates a similar exploration capex, but slightly lower exploration opex than *Policy B* + *C*. Exploration opex for *Policy A* +*B* + *C* is also lower than what is seen in *Policy A* + *C* and *Policy C*. *Policy A* + *B* + *C* generates a slightly higher NPV then *Policy B* + *C,* but a lower NPV then *Policy C* and *Policy A* + *C*.

In summary, the baseline policy simulations demonstrate that the most significant techno-operational concept in reducing exploration costs is remote sensing geophysical data collection. Any combination of policies, including geophysical sampling, will by far outperform both baseline results and the techno-operational policy scenarios where the exploration process is confided by conventional coring. The data further shows that introducing *Policy B*, FAUVs for Hi-Resolution surveys, does not improve the NPV from the baseline scenarios—except for the 4% ore-grade and "Anticipatory" configuration. *Policy A* demonstrates improved NPV, but not substantially so. The combined *Policy A* + *B* produces lower NPV than the baseline scenarios. The best-performing policy is the combined *Policy A* + *C* with NPV of 6.46 billion USD in the 5% ore-grade and "Anticipatory" scenario. This is a substantial increase in NPV relative to the baseline scenario of 2.53 billion USD.

Sensitivity analysis

The results of the baseline policy simulation nominate *Policy C*, or the introduction of geophysical sampling, as the most significant driver for increased profitability within deep-sea SMS mining. This techno-operational concept is not mature, and the parameterization of the policy is, therefore, subject to deep uncertainty. Sensitivity analysis of *Policy C*, in isolation from other policies, is therefore of value. To reduce complexity and, as such, provide more clarity on results, sensitivity is only tested for 3% ore-grade in the "Wait and See" configuration. This configuration does not generate a positive NPV in the baseline results, yet it does so with the same configuration under *Policy C*. It is, therefore, interesting to identify a lower limit of efficiency for the policy's ability to turn a profit and, as such, de-risk the deep-sea SMS mining industry at large. Two parameters govern *Policy C*: the area concluded per coring campaign and the annual cost of coring operations. Both parameters are tested in isolation.

Table 11 indicates that by increasing the coring efficiency by 82.5%, deep-sea SMS mining will be marginally profitable, with an NPV of 1 million USD, in the lowest ore-grade and passive investment regime. In the original model, a coring campaign is, on average, estimated to cover an area of 0.2125 km^2. The sensitivity results of *Policy B* suggest that by increasing the area to 0.387 km^2 the industry would, on an aggregated level, be profitable at a 3% average ore-grade and risk-averse investment regime. The sensitivity analysis of *Policy B* further indicates that the policy is not very sensitive to the annual cost of the operation; at 9.5 times

Table 6 Overview of simulation results with Policy C. Average values across 1000 Monte Carlo runs with baseline results in brackets

Resource scenario	Policy	Expl. capex (bill. $)	Expl. opex (bill. $)	Mining capex (bill. $)	Mining opex (bill. $)	Total extraction (mill. tons)	Total revenue (bill. $)	Net non-disc. value (bill. $)	Net present value (bill. $)
Low average ore-grade (3% mix of copper, zinc, cobalt)	Wait and See	0.33 [3.21]	1.03 [6.96]	7.17 [7.93]	6.27 [6.32]	1.81 [1.82]	35.03 [35.28]	20.21 [10.85]	1.54 [− 0.98]
	Anticipatory	0.35 [3.56]	1.03 [6.96]	5.23 [5.36]	6.26 [6.28]	1.80 [1.81]	34.94 [35.10]	22.05 [12.92]	2.42 [− 0.97]
Medium average ore-grade (4% mix of copper, zinc, cobalt)	Wait and See	0.33 [3.21]	1.03 [6.96]	7.17 [7.93]	6.27 [6.32]	2.41 [2.42]	46.71 [47.04]	31.88 [22.60]	3.07 [0.17]
	Anticipatory	0.35 [3.56]	1.03 [6.96]	5.23 [5.36]	6.26 [6.28]	2.40 [2.41]	46.59 [46.80]	33.69 [24.61]	4.41 [0.78]
High average ore-grade (5% mix of copper, zinc, cobalt)	Wait and See	0.33 [3.21]	1.03 [6.96]	7.17 [7.93]	6.27 [6.32]	3.01 [3.03]	58.39 [58.80]	43.54 [34.35]	4.59. [1.33]
	Anticipatory	0.35 [3.56]	1.03 [6.96]	5.23 [5.36]	6.26 [6.28]	3.00 [3.01]	58.23 [58.50]	45.32 [36.30]	6.39 [2.53]

Table 7 Overview of simulation results with Policy A + B. Average values across 1000 Monte Carlo runs with baseline results in brackets

Resource scenario	Policy	Expl. capex (bill. $)	Expl. opex (bill. $)	Mining capex (bill. $)	Mining opex (bill. $)	Total extraction (mill. tons)	Total revenue (bill. $)	Net non-disc. value (bill. $)	Net present value (bill. $)
Low average ore-grade (3% mix of copper, zinc, cobalt)	Wait and See	3.24 [3.21]	6.72 [6.96]	8.30 [7.93]	6.31 [6.32]	1.82 [1.82]	35.23 [35.28]	10.65 [10.85]	− 0.91 [− 0.98]
	Anticipatory	3.60 [3.56]	6.72 [6.96]	5.38 [5.36]	6.27 [6.28]	1.80 [1.81]	35.01 [35.10]	13.03 [12.92]	− 0.84 [− 0.97]
Medium average ore-grade (4% mix of copper, zinc, cobalt)	Wait and See	3.24 [3.21]	6.77 [6.96]	8.30 [7.93]	6.31 [6.32]	2.42 [2.42]	46.97 [47.04]	22.33 [22.60]	0.14 [0.17]
	Anticipatory	3.60 [3.56]	6.76 [6.96]	5.38 [5.36]	6.27 [6.28]	2.41 [2.41]	46.67 [46.80]	24.64 [24.61]	0.84 [0.78]
High average ore-grade (5% mix of copper, zinc, cobalt)	Wait and See	3.24 [3.21]	6.77 [6.96]	8.30 [7.93]	6.31 [6.32]	3.03 [3.03]	58.72 [58.80]	34.06 [34.35]	1.22 [1.33]
	Anticipatory	3.60 [3.56]	6.76 [6.96]	5.38 [5.36]	6.27 [6.28]	3.01 [3.01]	58.34 [58.50]	36.30 [36.30]	2.55 [2.53]

the annual cost, the industry generates a negative NPV of 2 million USD—at nine times the annual cost, it generates a profit of 7 million USD. The ability to effectively confirm or disconfirming mineral prospects as commercially viable appears to be of greater importance than the annual cost of these operations.

Policy B, fleet-operated AUVs for high-resolution surveys, is the techno-operational policy of the poorest performance. In order to establish limit values for this policy to yield positive results in the lowest ore-grade and passive investment regime is therefore interesting. *Policy B* is governed by the yearly cost of high-resolution survey vessels and by the swath, or footprint on the seabed, obtained by the AUVs. To test the sensitivity of *Policy B*, these two parameters are tested in isolation (Table 12).

The model is not sensitive to high-resolution survey swath. Even with 40 times the swath, the NPV is largely unaffected, as is mining opex, total extraction, and total revenue. exploration capex is marginally higher, and exploration opex is marginally lower in this extreme configuration, as is net non-discounted value. The same tendency is evident also for significant changes in the yearly rate of high-resolution surveys. The model behavior is insensitive to vastly reduced rates of high-resolution surveys. The efficiency of high-resolution surveys does not affect model behavior to any considerable extent, nor does the cost of this step in the exploration process.

Discussion and policy analysis

This study indicates that their innovation and development in the exploration processes for deep-sea SMS deposits on the Norwegian Continental Shelf may significantly reduce the commercial risk and boost

Table 8 Overview of simulation results with policy A + C. Average values across 1000 Monte Carlo runs with baseline results in brackets

Resource scenario	Policy	Expl. capex (bill. $)	Expl. opex (bill. $)	Mining capex (bill. $)	Mining opex (bill. $)	Total extraction (mill. Tons)	Total revenue (bill. $)	Net non-disc. value (bill. $)	Net present value (bill. $)
Low average ore-grade (3% mix of copper, zinc, cobalt)	Wait and See	0.33 [3.21]	0.95 [6.96]	7.17 [7.93]	6.27 [6.32]	1.81 [1.82]	35.03 [35.28]	20.29 [10.85]	1.61 [− 0.98]
	Anticipatory	0.35 [3.56]	0.95 [6.96]	5.23 [5.36]	6.26 [6.28]	1.80 [1.81]	34.94 [35.10]	22.13 [12.92]	2.49 [− 0.97]
Medium average ore-grade (4% mix of copper, zinc, cobalt)	Wait and See	0.33 [3.21]	0.95 [6.96]	7.17 [7.93]	6.27 [6.32]	2.41 [2.42]	46.71 [47.04]	31.96 [22.60]	3.13 [0.17]
	Anticipatory	0.35 [3.56]	0.95 [6.96]	5.23 [5.36]	6.26 [6.28]	2.40 [2.41]	46.59 [46.80]	33.77 [24.61]	4.47 [0.78]
High average ore-grade (5% mix of copper, zinc, cobalt)	Wait and See	0.33 [3.21]	0.95 [6.96]	7.17 [7.93]	6.27 [6.32]	3.01 [3.03]	58.39 [58.80]	43.63 [34.35]	4.66 [1.33]
	Anticipatory	0.35 [3.56]	0.95 [6.96]	5.23 [5.36]	6.26 [6.28]	3.00 [3.01]	58.23 [58.50]	45.41 [36.30]	6.46 [2.53]

Table 9 Overview of simulation results with Policy B + C. Average values across 1000 Monte Carlo runs with baseline results in brackets

Resource scenario	Policy	Expl. capex (bill. $)	Expl. opex (bill. $)	Mining capex (bill. $)	Mining opex (bill. $)	Total extraction (mill. tons)	Total revenue (bill. $)	Net non-disc. value (bill. $)	Net present value (bill. $)
Low average ore-grade (3% mix of copper, zinc, cobalt)	Wait and See	0.32 [3.21]	0.88 [6.96]	7.81 [7.93]	6.30 [6.32]	1.81 [1.82]	35.30 [35.28]	19.87 [10.85]	1.15 [− 0.98]
	Anticipatory	0.36 [3.56]	0.88 [6.96]	5.35 [5.36]	6.28 [6.28]	1.81 [1.81]	35.09 [35.10]	22.19 [12.92]	2.19 [− 0.97]
Medium average ore-grade (4% mix of copper, zinc, cobalt)	Wait and See	0.32 [3.21]	0.88 [6.96]	7.81 [7.93]	6.30 [6.32]	2.42 [2.42]	46.94 [47.04]	31.59 [22.60]	2.32 [0.17]
	Anticipatory	0.36 [3.56]	0.88 [6.96]	5.35 [5.36]	6.28 [6.28]	2.41 [2.41]	46.78 [46.80]	33.88 [24.61]	3.95 [0.78]
High average ore-grade (5% mix of copper, zinc, cobalt)	Wait and See	0.32 [3.21]	0.88 [6.96]	7.81 [7.93]	6.30 [6.32]	3.02 [3.03]	58.67 [58.80]	43.31 [34.35]	3.49 [1.33]
	Anticipatory	0.36 [3.56]	0.88 [6.96]	5.35 [5.36]	6.28 [6.28]	3.01 [3.01]	58.48 [58.50]	45.56 [36.30]	5.70 [2.53]

profitability. It should be noted that these simulation runs include uncertain parameters, certainly pertaining to the efficacity of the emerging technologies being projected. By employing broad arrays of sensitivity analysis on the stochastic model—the uncertainty is included and explored in the analysis. The simulation results identify that the successful development of geophysical sampling tecno-operational concepts will significantly impact the profitability of this emerging industry on an aggregated level. The Policy Simulation Baseline results indicate that at the high (5%) ore-grade, under the "Anticipatory" investment scenario—a geophysical sampling technology applied to enhance the footprint of conventional coring may produce about 250% improvement of NPV. Sensitivity analysis furthermore shows that scaling up the area confirmed or disconfirmed by geophysical sampling enhanced coring by 82.5% will render a positive NPV also in the low ore-grade (3%) and risk-averse ("Wait and See") policy scenario. The sensitivity analysis demonstrates that the increased cost of geophysical sampling is less critical. This is a significant finding for a budding industry—as it suggests a distinct focus on research and development and indicates that considerable budgets for developing and scaling up such techno-operational concepts may be beneficial as the resulting operational cost efficiency may be significant.

The results also demonstrate that developing and scaling up fleet AUV techno-operational concepts may be of little value in terms of the aggregated profitability of the industry over time. The sensitivity analysis furthermore indicates that neither the cost nor the actual efficiency of FAUV is of considerable importance to the deep-sea SMS exploration and extraction industry on the NCS. This is also an interesting find, as this is a techno-operational concept currently receiving much attention and investment in the subsea industry (Argeo, 2022; Ocean Infinity, 2022). There may be several reasons for this, but it is likely related to the ship utilization—and the size of areas expected to require

Table 10 Overview of simulation results with Policy A + B + C. Average values across 1000 Monte Carlo runs with baseline results in brackets

Resource scenario	Policy	Expl. capex (bill. $)	Expl. opex (bill. $)	Mining capex (bill. $)	Mining opex (bill. $)	Total extraction (mill. tons)	Total revenue (bill. $)	Net non-disc. value (bill. $)	Net present value (bill. $)
Low average ore-grade (3% mix of copper, zinc, cobalt)	Wait and See	0.32 [3.21]	0.80 [6.96]	7.81 [7.93]	6.30 [6.32]	1.81 [1.82]	35.20 [35.28]	19.95 [10.85]	1.21 [− 0.98]
	Anticipatory	0.36 [3.56]	0.80 [6.96]	5.35 [5.36]	6.28 [6.28]	1.81 [1.81]	35.09 [35.10]	22.27 [12.92]	2.25 [− 0.97]
Medium average ore-grade (4% mix of copper, zinc, cobalt)	Wait and See	0.32 [3.21]	0.80 [6.96]	7.81 [7.93]	6.30 [6.32]	2.42 [2.42]	46.94 [47.04]	31.68 [22.60]	2.39 [0.17]
	Anticipatory	0.36 [3.56]	0.80 [6.96]	5.35 [5.36]	6.28 [6.28]	2.41 [2.41]	46.78 [46.80]	33.96 [24.61]	4.01 [0.78]
High average ore-grade (5% mix of copper, zinc, cobalt)	Wait and See	0.32 [3.21]	0.80 [6.96]	7.81 [7.93]	6.30 [6.32]	3.02 [3.03]	58.67 [58.80]	43.40 [34.35]	3.56 [1.33]
	Anticipatory	0.36 [3.56]	0.80 [6.96]	5.35 [5.36]	6.28 [6.28]	3.01 [3.01]	58.48 [58.50]	45.64 [36.30]	5.77 [2.53]

high-resolution surveys. By the time the exploration process moves into high-resolution surveys, earlier survey initiatives dramatically reduce the area of interest. Therefore, increasing the footprint on the seabed by adding several AUVs may not offer much benefit as the conventional footprint in the original model is already sufficient—and, indeed, relatively efficient as it is.

The introduction of Unmanned Surface Vessels for regional surveys is likely to positively affect aggregated NPV, although the impact is mainly marginal. This can be directly related to regional surveys already being relatively cost-efficient in comparison with the other stages of the exploration process. It should, however, be noted—that removing conventional regional survey vessels is likely to have a positive impact on risk to personnel and emissions to the environment while operating in the Arctic, as the USVs will not be crewed—and will consume considerably less fuel (Rumson, 2021). On the other hand, removing crews will hurt the employment rates in the subsea industry. This study considers neither of these effects as they lie beyond the model boundaries.

The policy combination that generates the highest NPV is *Policy A + C.* This policy combination generates a net present value of 6.46 billion USD in the high ore-grade, "Anticipatory" scenario and an NPV of 1. 61 billion USD in the low ore-grade, "Wait and Wait and See" scenario. These are considerable improvements to the 2.53 billion USD and − 0.98 billion USD results produced by the original model and, as such, indicate a considerable innovation space for these two techno-operational concepts within the realm of SMS mining on the NCS.

It is simultaneously interesting to note that *Policy A + B + C* generates an NPV of 760 million USD below *Policy A + C* in the high ore-grade (5%) and "Anticipatory" scenario—while it demonstrates a 40 million lower NPV in the low ore-grade (3%) and risk-averse scenario ("Wait and See"). Similarly, *overall, Policy B + C* performs poorer in terms of NPV than *Policy C* alone. Furthermore, *Policy A + B* renders lower NPV across all scenarios than *Policy A* alone. It appears that focusing on developing and scaling up fleet-operated AUVs is not only moot but counterproductive for the aggregated deep-sea SMS industry on the Norwegian continental shelf. This is also a significant finding—as it informs stakeholders developing new techno-operational concepts within this emerging industrial segment in which concepts to allocate a low priority or to avoid altogether.

Table 11 Overview of sensitivity results with Policy C at 3% average ore-grade and "Wait and See" setting, average values across 1000 Monte Carlo runs with *Policy C* baseline results in brackets

Sensitivity scenario	Expl. capex (bill. $)	Expl. opex (bill. $)	Mining capex (bill. $)	Mining opex (bill. $)	Total extraction (mill. tons)	Total revenue (bill. $)	Net non-disc. value (bill. $)	Net present value (bill. $)
2 × coring area	1.59 [0.33]	4.08 [1.03]	7.63 [7.17]	6.29 [6.27]	1.81 [1.81]	35.12 [35.03]	15.52 [20.21]	0.14 [1.54]
1.5 × coring area	2.13 [0.33]	5.36 [1.03]	7.74 [7.17]	6.30 [6.27]	1.81 [1.81]	35.17 [35.03]	13.63 [20.21]	− 0.31 [1.54]
1.75 × coring area	1.82 [0.33]	4.63 [1.03]	7.68 [7.17]	6.29 [6.27]	1.81 [1.81]	35.14 [35.03]	14.70 [20.21]	− 0.06 [1.54]
1.825 × coring area	1.75 [0.33]	4.45 [1.03]	7.66 [7.17]	6.29 [6.27]	1.81 [1.81]	35.13 [35.03]	14.97 [20.21]	0.01 [1.54]
2 × yearly rate coring vessel	0.33 [0.33]	1.80 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.03 [35.03]	19.45 [20.21]	1.36 [1.54]
4 × yearly rate coring vessel	0.33 [0.33]	3.32 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.03 [35.03]	17.93 [20.21]	0.99 [1.54]
6 × yearly rate coring vessel	0.33 [0.33]	4.48 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.03 [35.03]	16.40 [20.21]	0.62 [1.54]
7 × yearly rate coring vessel	0.33 [0.33]	5.61 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.03 [35.03]	15.64 [20.21]	0.44 [1.54]
8 × yearly rate coring vessel	0.33 [0.33]	6.37 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.03 [35.03]	14.88 [20.21]	0.26 [1.54]
9 × yearly rate coring vessel	0.33 [0.33]	7.13 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.03 [35.03]	14.12 [20.21]	0.07 [1.54]
9.5 × yearly rate coring vessel	0.33 [0.33]	7.51 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.03 [35.03]	13.74 [20.21]	− 0.02 [1.54]
10 × yearly rate coring vessel	0.33 [0.33]	7.89 [1.03]	7.17 [7.17]	6.27 [6.27]	1.81 [1.81]	35.36 [35.03]	13.36 [20.21]	− 0.11 [1.54]

Table 12 Overview of sensitivity results with Policy B at 3% average ore-grade and "Wait and See" setting. Average values across 1000 Monte Carlo runs with Policy B baseline results in brackets

Sensitivity scenario	Expl. capex (bill. \$)	Expl. opex (bill. \$)	Mining capex (bill. \$)	Mining opex (bill. \$)	Total extraction (mill. tons)	Total revenue (bill. \$)	Net non-disc. value (bill. \$)	Net present value (bill. \$)
2 × swath	3.26 [3.24]	6.79 [6.81]	8.37 [8.30]	6.31 [6.31]	1.82 [1.82]	35.24 [35.23]	10.49 [10.56]	– 0.98 [– 0.98]
10 × swath	3.27 [3.24]	6.78 [6.81]	8.45 [8.30]	6.31 [6.31]	1.82 [1.82]	35.23 [35.23]	10.41 [10.56]	– 0.99 [– 0.98]
20 × swath	3.28 [3.24]	6.78 [6.81]	8.46 [8.30]	6.31 [6.31]	1.82 [1.82]	35.23 [35.23]	10.40 [10.56]	– 0.99 [– 0.98]
40 × swath	3,28 [3.24]	6.78 [6.81]	8.47 [8.30]	6.31 [6.31]	1.82 [1.82]	35.23 [35.23]	10.39 [10.56]	– 0.99 [– 0.98]
2 × yearly rate hi.res survey	3.24 [3.24]	6.82 [6.81]	8.30 [8.30]	6.31 [6.31]	1.82 [1.82]	35.23 [35.23]	10.54 [10.56]	– 0.98 [– 0.98]
0.5 × yearly rate hi.res survey	3.24 [3.24]	6.80 [6.81]	8.30 [8.30]	6.31 [6.31]	1.82 [1.82]	35.23 [35.23]	10.57 [10.56]	– 0.97 [– 0.98]
0.25 × yearly rate hi.res survey	3.24 [3.24]	6.79 [6.81]	8.30 [8.30]	6.31 [6.31]	1.82 [1.82]	35.23 [35.23]	10.28 [10.56]	– 0.97 [– 0.98]
0.175 × yearly rate hi.res survey	3.24 [3.24]	6.79 [6.81]	8.30 [8.30]	6.31 [6.31]	1.82 [1.82]	35.23 [35.23]	10.58 [10.56]	– 0.97 [– 0.98]
0.0875 × yearly rate hi.res survey	3.24 [3.24]	6.79 [6.81]	8.30 [8.30]	6.31 [6.31]	1.82 [1.82]	35.23 [35.23]	10.58 [10.56]	– 0.97 [– 0.98]
0.04375 × yearly rate hi.res survey	3.24 [3.24]	6.79 [6.81]	8.30 [8.30]	6.31 [6.31]	1.82 [1.82]	35.23 [35.23]	10.58 [10.56]	– 0.97 [– 0.98]

Conclusion

This study has explored the possible impact of three emerging techno-operational concepts within the subsea and sub-seabed survey as these apply to the nascent SMS industry on the Norwegian continental shelf. These concepts are unmanned surface vessels for regional surveys, fleet operation of AUVs for high-resolution surveys, and geophysical sampling in conjunction with geological core samples for resource evaluation of mineral deposits.

Significant possible gains are available in the techno-operational innovation space within SMS exploration on the Norwegian continental shelf. Most predominantly stand for developing a geophysical methodology that enhances the area covered and qualified, or disqualified, by geological core sampling. This process's cost is less significant—the cost of the combination of coring and geophysical sampling can be increased by about nine times and still yield profits in a low ore-grade and risk-averse investment scenario. By only increasing the area covered by a coring and geophysical campaign by 82% relative to the baseline scenarios produced by the original model—profits may be generated. This appears amply possible within the offshore industries. Gains are also likely by the introduction of unmanned surface vessels for regional surveys—but these gains are less significant. The most profitable endeavor is developing USVs for regional surveys and geophysical sampling. Simultaneously, the emergence of fleet-operated AUVs is less beneficial to the SMS mining industry on the NCS. In fact—not only does this concept appear pointless, but it is also counterproductive as it may reduce the aggregated net present value of the industry. Nevertheless, these findings are of value to an emerging industry currently placing its bets on techno-operational concepts and gearing up for a possible opening of the Norwegian continental shelf (Energi24.no, 2021; Ministry of Petroleum and Energy, 2022a).

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Declarations

Conflict of interest The author, who has 15 years of onshore and offshore industry experience with deep water subsea operations, works as an external technical consultant for a company that aims to take part in the potential future marine mineral industry in Norway. The author also represents the University of Bergen as a board member of the Norwegian Marine Minerals forum (NMM).

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11. Appendix V

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